CHARACTERIZING THE IMPORTANCE OF CARBON STORED IN WOOD PRODUCTS

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Abstract. Carbon emissions and stores are increasingly important as solutions are sought to address climate change. Focusing on some forest-related carbon pools but omitting product carbon frequently results in invalid conclusions. This study examined carbon emissions and stores in the life cycle of wood products in comparison with alternative materials. Emissions were established from a sustainably managed, carbon-neutral forest through processing to wood product use in residential structures and their eventual disposal. A life-cycle inventory was developed to establish the quantity of emissions from each stage of processing, and a life-cycle assessment of a representative residential building was made of its impact on global warming potential. The carbon stored in wood products as an offset to emissions was shown to be significant. Comparison of various building materials—wood, steel, and concrete—showed that wood was more environmentally friendly because of reduced carbon emissions because of fossil fuel combustion, carbon stored in products, permanent avoidance of emissions from fossil fuel-intensive products, and use of a sustainable and renewable resource.

Keywords: Carbon emissions, carbon storage, global warming, wood products, forests, life-cycle inventory and assessment (LCI/LCA).

INTRODUCTION

Over the last decade, the Consortium for Research on Renewable Industrial Materials (CORRIM 2005) has researched life-cycle inventory (LCI) and life-cycle assessment (LCA) methods for tracking inputs and outputs across every stage of wood processing and its use as a way to measure environmental burdens. LCIs developed by CORRIM for structural wood products has conformed to rigorous research guidelines

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(Briggs 2001), including measures of every input and output per unit of product and coproduct for each structural wood production process (ie inputs of materials, energy, water, and land use and output emissions to air, water, and land per product and coproduct produced). The initial protocol adopted for the emissions from manufacturing activities was to provide a common frame of reference across wood and nonwood material processes and thus did not include the carbon that is stored in wood products as an offset (negative) emission. This separation in accounting has led to errors by users as they compare the carbon emissions from the manufacture of wood products directly with the carbon emissions from the manufacture of fossil fuel-intensive products without noting the substantial carbon that is stored in wood products. CORRIM has now changed that protocol to show that the carbon stored in products is functionally equivalent to a negative carbon emission produced in the manufacture of those products (Puettmann et al 2010). The impacts are substantial and are detailed here for each stage of processing as well as analyzed for their integrated impact across forest, product, and product displacement carbon pools. Carbon pools include both carbon stores (the forest and wood products) as well as carbon offsets (displaced fossil fuel emissions from burning biomass for energy and displaced emissions from substituting wood products for fossil fuel-intensive products).

It is important to begin with a definition of sustainable forestry. In sustainable forests, removals plus decomposition of dead and dying residuals do not exceed growth from one rotation to the next. Hence, forest carbon across a sustainably managed forest is stable over time, ie remains carbon-neutral. Carbon that is released through the decomposition of slash or dead trees after harvest, plus the carbon in logs that are processed in mills, is offset by the forest uptake of carbon dioxide through new growth over time in a sustainably managed forest.

The carbon that is exported from the forest and remains in products can be considered an addition to the carbon stored in the forest. Unlike the forest carbon stock, which remains stable, the carbon stored in products continues to increase with every harvest and is an increasing stock of carbon that is reduced only by the product volumes that have reached the end of their useful life. When products reach the end of their useful life, they may be recycled (extending their life), reclaimed for energy (displacing fossil energy emissions), decomposed quickly by burning as waste, or landfilled, resulting in a slow decomposition process. Because the products in buildings have lives of 80 yr or more (Winistorfer et al 2005), the cumulative carbon stored in these products is a significant store of carbon.

When measuring carbon in the forest, the usual convention is to measure carbon in units of C (reflecting a store of carbon). Once outside the forest, the focus is generally on greenhouse gas emissions (a loss in stored C) and this is expressed in units of CO_2 with a molecular weight conversion of 44/12 that of C. The CO_2 taken from the atmosphere by forest growth creates a new store of C, but in a sustainably managed forest, this will be balanced by the transfer of C to products and the decomposition of any dead wood left behind.

The transfer of C from the forest to products is a negative emission relative to the positive emissions from the processing energy required to produce the products and hence becomes an offset against other carbon emissions during the product life cycle. Emissions are assigned based on mass allocation to the various products and coproducts, including biofuels.

To establish the importance of carbon storage in wood products, we start by showing the energy involved in producing structural wood products and their carbon emissions. We then add back the carbon stored in wood products and compare the results with nonwood substitutes. We show these impacts at the product level followed by the impact on completed houses comparing the use of different framing materials. Finally, we show the integration of all carbon pools back to the raw material source (a unit of forest with forest carbon, short- and long-lived products carbon, bioenergy displacement, and displacement from product substitution) for conservative end-of-life assumptions before summarizing the importance of these observations.

ENERGY REQUIRED AND EMISSIONS PRODUCED IN PROCESSING

Energy Used by Stages of Processing

Based on the stage of processing survey data collected by CORRIM for forest management and processing into structural materials (Johnson et al 2005; Kline 2005; Milota et al 2005; Puettmann and Wilson 2005; Wilson and Sakimoto 2005), Fig 1 shows the LCI measure of total energy required to produce various wood products from resources in the forest. Green lumber is the only product in which the processing energy does not completely dwarf the energy used in harvesting and transportation. The energy includes that for all fuels, including wood and feedstock; for resins from in-ground resources through extraction, processing, delivery, and combustion; and the energy used to produce electricity (Puettmann and Wilson 2005). Products that are dried and/or use resins such as plywood and oriented strandboard (OSB) require more energy but much of the drying energy is supplied by biofuels (bark and mill residues).

Carbon Dioxide Emissions and Carbon Storage

Figure 2 shows the carbon emissions for three of the more common wood products, in which the emissions produced by biofuels are offset by an equivalent amount of carbon removed from the atmosphere by forest growth. The use of biofuel and the storage of carbon in products is a unique attribute of renewable, bio-based resources. To understand the importance of these attributes relative to alternative materials, we use similar LCI measures for nonwood materials. The National Renewable Energy Lab (NREL) and its partners created the USLCI Database (NREL 2003) to help LCA experts answer questions about environmental impacts. This database provides an accounting of all the energy sources and material flows that are associated with producing primary products from raw materials. The LCI profiles for primary products can then in turn be used to construct the LCI measures for components or assemblies based on the LCI measures for their bill of materials. The database provides

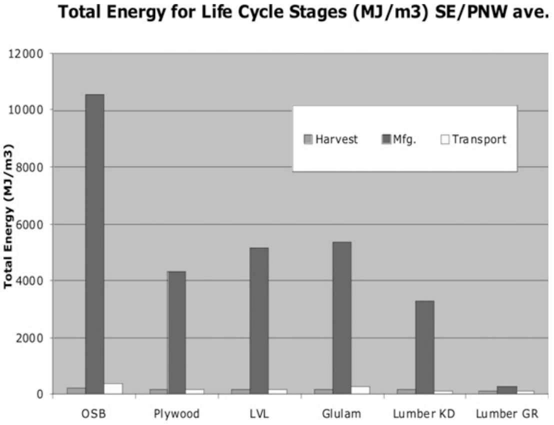

Figure 1. Total energy use, from in-ground resources through production, of structural wood materials for the average of southeast (SE) and northwest (NW) mills. LVL is laminated veneer lumber, glulam is laminated timber, and lumber is either kiln dried (KD) or green (GR). From Puettmann and Wilson (2005).

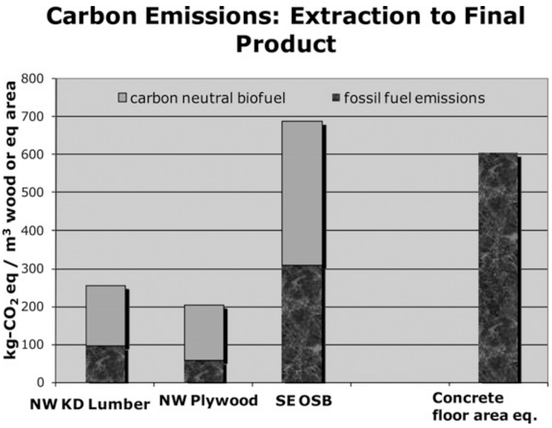

Figure 2. Carbon emissions (as CO_2 equivalents) of a wood floor, from in-ground resources through product manufacturing, compared with a concrete floor of the same area. From Puettmann and Wilson (2005) and Lippke and Edmonds (2006) based on ATHENA EIE analysis of different flooring materials.

an online storeroom of data collected on commonly used wood and nonwood materials, products, and processes. The critically reviewed LCI database procedures (NREL 2004) are consistent across all materials based on a common research protocol with international standards.

In comparison with the carbon impact from the three common wood products in Fig 2, the equivalent emissions from producing a concrete slab floor of the same area as can be produced by a cubic meter of wood is also shown. The processing emissions from the concrete floor are roughly four times greater than for wood floor options. All source data are available from the USLCI database managed by NREL. The cradle-to-production gate LCI data for wood products in the all-products USLCI database were produced by CORRIM (Puettmann and Wilson 2005) and input to the USLCI database. The data for a concrete slab floor were used in the ATHENA Environmental Impact Estimator (EIE) to construct a floor area equivalent to a wood floor from 1 m^3 of wood products (ATHENA 2004). It is important that comparisons across materials are made for functionally equivalent uses because the weight of different materials can vary substantially for equal functional use.

The carbon emissions generated from the use of biofuel reduces the carbon storage potential that was available in the harvested log, but the carbon in the products more than offsets the emissions from processing energy, as shown in Fig 3. Included in this offset is that the carbon store in wood fuels is equivalent to the CO_2 emissions because of its combustion. The wood products in a wood floor store about as much carbon over their life cycle as is emitted from constructing a concrete floor (including cradle-to-construction gate emissions). The construction of the wood floor stores carbon for the life of the product and avoids fossil fuel-related carbon emissions that would be produced by constructing the more energy-intensive concrete floor. It also offsets much of the emissions from the construction of concrete foundations in which wood and concrete are used as complements rather than substitute products. As the quality of the USLCI database improves, some reduction in carbon emissions over the life of the concrete product should be expected given some absorption of CO_2 in concrete over time.

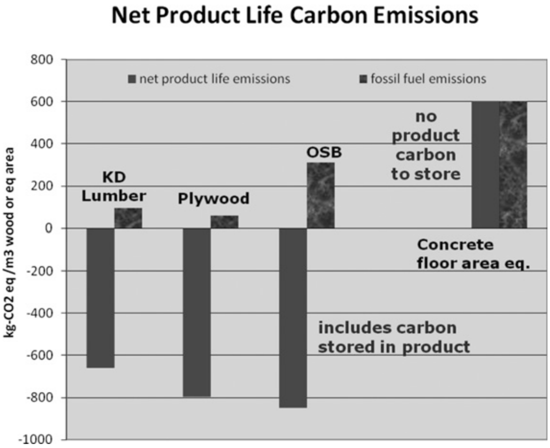

Figure 3. Net carbon emissions, including stored carbon, of a wood floor compared with a concrete floor of the same area. Based on stored product carbon CO_2 equivalent calculated at 1.83 times the dry wood mass.

At the end of their useful product lives, if the wood products are recycled for their energy value as fuel, the carbon offset becomes essentially permanent because it displaces the emissions that would have otherwise been generated from burning coal or other fossil fuels for that energy. If the wood is recycled, using the waste as a raw material for products like fiberboard, the useful life is extended. If the used wood products are landfilled, they will decompose slowly, extending the carbon storage period beyond the useful life of the product (but not indefinitely). Whereas this comparison is limited to a cradle to end-of-product-life analysis, the expected life of the buildings in which products are used is very long and the impacts of building maintenance are generally small (Winistorfer et al 2005). Postproduct life impacts involve a transfer of product carbon to many different possible alternatives, much like the transfer of forest carbon to products carbon, and will be considered as a last step when integrating the impact of all product carbon pools.

GLOBAL WARMING POTENTIAL IMPACTED BY PRODUCT CARBON

The Impact of Product Carbon on Residential Buildings

The impact of product selection on the total emissions from resource extraction through processing (Lippke et al 2004) as well as the impact of carbon storage in the products used to build a complete house is shown in Fig 4 for virtual houses framed in steel or wood for Minneapolis building codes (cold climate) and concrete or wood wall framing in an Atlanta house (a warm climate). The ATHENA EIE was used to develop the bill of materials linked to their LCI burdens for comparable virtual houses differentiated by the choice of materials used for framing. The Minneapolis house uses 2 × 6 wood wall studs or 2 × 4 steel studs with vinyl cladding and steel or wood floor joists. The Atlanta house uses wood stud walls with vinyl siding or concrete block covered with stucco for wall framing and a concrete slab floor. Each structure used a wood-framed roof with asphalt shingles.

Although the carbon substitution impact of a single wood product vs a nonwood product was shown to be potentially very high, as in the substitution for a concrete floor in Fig 2, changing the wall framing from wood to steel for the complete house reduces total wood use by only about 7% of the mass of the house. The vast majority of materials used is common to both designs. Despite this small total mass difference, the Global Warming Potential emissions (measured as CO_2 equivalents including CO_2, methane, and nitrous oxide) from the steel-framed house was 26% greater than the house with wood-framed walls and floors (Lippke et al 2004) without considering the carbon stored in wood products. This becomes a 120% difference when the carbon stored in the wood products for the life of the house is included. Emissions from the completed, concrete wall-framed house were 31% greater than the wood-wall house without considering the carbon stored in wood products and are 156% greater when these carbon stores are included in the calculation.

Using more wood in construction has the potential to store more carbon in the building materials than is emitted, ie better-than-carbon-neutral construction is possible. The carbon stored in products is not permanent, but the carbon offset

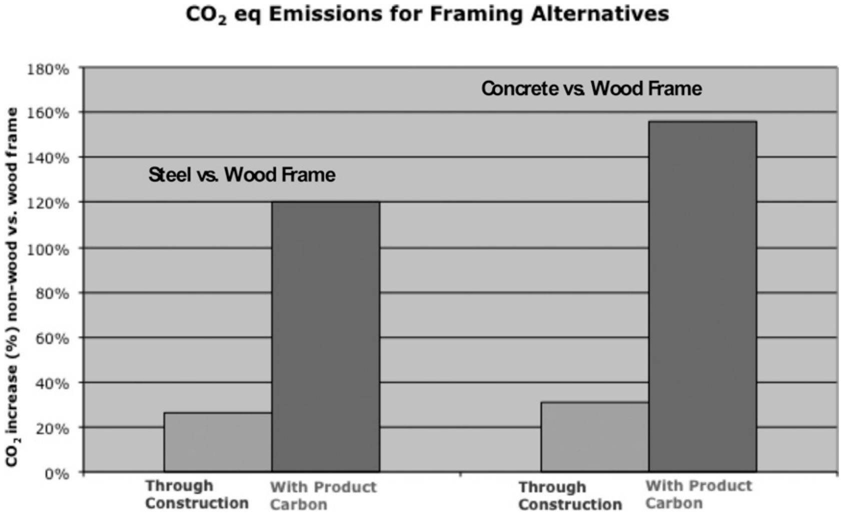

Figure 4. Global Warming Potential carbon equivalent emissions through residential construction for steel and concrete frame vs wood frame ignoring and including the carbon stored in wood products. Based on stored product carbon CO_2 equivalent calculated at 1.83 times the dry wood mass.

may become permanent by recycling or the collection of the discarded wood for biofuel processing or may appear nearly permanent with the slow decay in a modern landfill relative to the 100-yr accounting period used by some registries. The carbon emissions displaced by using wood instead of fossil fuel-intensive products is permanent from the time of initial substitution.

Carbon Emissions Across the Forest and Products Pools

Although the LCI for each stage of wood processing are derived as cross-sectional snapshots of a point in time, when considered as a series of epochs over time, they can be used to link the product impacts back to each unit of forest (Bowyer et al 2004). Figure 5, a version of the forest and product carbon pools resulting from sustainably managing a single forest unit developed by Perez-Garcia et al (2005), illustrates the export of the carbon at harvest to long- and short-lived product pools with the emissions associated with harvesting and processing as a negative carbon pool. This shift of focus to a hectare of managed forest demonstrates the integration of both forest and product carbon. The product pools characterized for representative residential structures are scaled to the amount of product carbon resulting from the management of a hectare of forest.

The total processing energy emissions shown as losses of carbon after each harvest are shown at the bottom of the figure and are offset partially by the energy from using wood processing residues as a fuel source (shown as the top carbon pool in the graph). The figure assumes that the long-lived products are burned at the end of the life of a house (shown at 80 yr for tutorial purposes), although they may last much longer by recycling or even disposal in a landfill. Short-lived products (paper or fiberboards made from chips and residuals) are shown to decompose rapidly. Assessments on the life of pulp or fiberboard products through recycling and the landfill are lacking. Similarly, forest residuals left after harvest decompose quickly (shown in black). Some of these short-lived products, when used in flooring and furniture, have intermediate lifespans and could also be recycled, thus increasing their contribution to carbon stores. These assumptions intentionally provide a conservative estimate for integrated carbon pools.

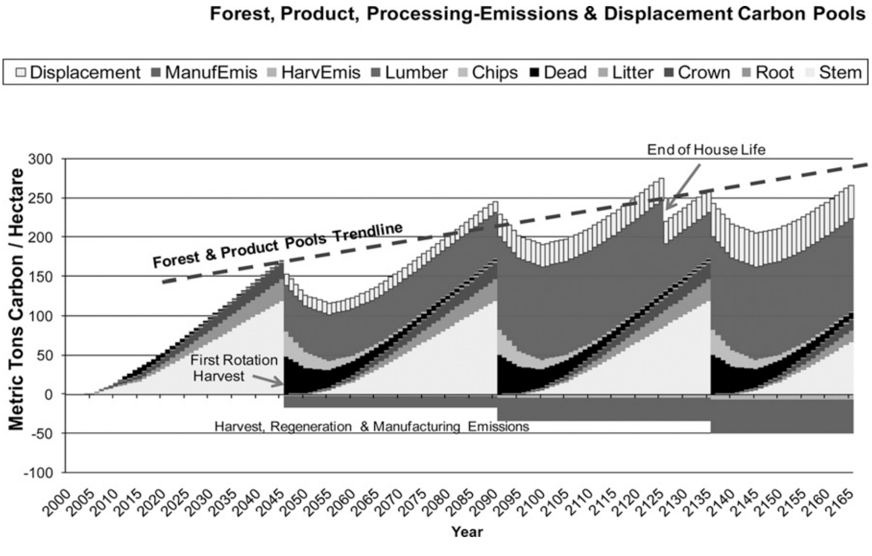

Figure 5. Carbon pools from a sustainably managed forest and its wood products, including biofuel displacement, under conservative end of life assumptions. From Perez-Garcia et al (2005).

More detailed treatment of the carbon stored beyond a product's life requires redistributing the end-of-life product carbon among 1) recycling pools that extend the carbon storage indefinitely; 2) demolition and burning resulting in an immediate carbon release; 3) demolition and collection for energy production that permanently offsets fossil fuel emissions; and 4) landfilling that results in a complex decomposition process with half of the biomass not decomposing and the other half contributing to methane emissions if the landfill is not equipped to capture the methane (Skog 2008). Any landfills that release methane offset some of the benefit of the carbon stored in the landfill.

Unfortunately, the precision of estimates for impacts beyond end-of-product life are of a different character than for the CORRIM product life-cycle data. Landfill emissions are analyzed across inputs with many different ages, unlike product LCIs. Also, with substantial technologic improvements in recycling and landfill management already underway such as recapturing methane releases, a reduction in landfill emissions is anticipated. Depending on assumptions on product life, estimates have shown landfill carbon reaching 40% of the carbon stored in products with the methane emissions offsetting 50% of the landfill carbon store over 100 yrs (Upton et al 2008). Thus, the beyond-product-life product carbon pool decreases slowly but, at the same time, the product supply from the forest replaces the products with sustainable harvests such that each hectare of forest contributes to both the products pools and postproduct life pools, increasing sustainably. Although it is essential to understand the impact of products carbon, ultimately it is the resource supply that drives the sustainable growth and cumulative impact.

Looking across the forest and product carbon pools, it should be noted that the early decomposition of the short-lived product uses and decaying forest residuals results in a net decline in total carbon stores after harvest before increasing over subsequent harvest rotations. The total carbon in forest, product, and fossil-fuel displacement pools grows over time, unlike the forest pool, which remains neutral over the long term. Although Fig 5 shows the use of wood residuals for fuel as a permanent displacement of fossil-fuel energy emissions, it does not yet show the impact of the wood being used displacing the emissions from substitute materials when wood products are not used.

WOOD PRODUCT SUBSTITUTION FOR FOSSIL FUEL-INTENSIVE PRODUCTS

When wood is not used, alternatives are substituted. Wood framing can be replaced by steel or concrete, wood siding by vinyl, cellulose insulation by fiberglass or polystyrene insulation, wood panels by gypsum board, etc. Each substitute material results in a different emission profile. Generally, nonwood substitutes are several times more fossil fuel-intensive to produce and do not provide the carbon storage offset that is found in wood products.

Because the substitution of wood products for fossil fuel-intensive structural products has a higher "carbon leverage" than any other use of wood, it offers the greatest potential for global climate change mitigation. Substitution for wood products by fossil fuel-intensive products has taken place in the historical context of low fossil-fuel prices. As fossil-fuel prices or carbon credit trading values rise, we can anticipate the increased substitution of wood products for the most fossil fuel-intensive products.

The most frequent form of wood substitution is the use of concrete instead of wood. Figure 6 (Perez-Garcia et al 2005) includes the substitution impact on carbon emissions of substituting concrete block and stucco-walled houses with wood-framed and vinyl-sided houses. The combined forest and product carbon pools and displaced fossil fuel-carbon emission pools when substituting wood for concrete (or steel) grow continuously.

As the value of carbon rises with policy changes designed to reduce emissions, there will be greater motivation to substitute wood for the most fossil fuel-intensive products. At the end

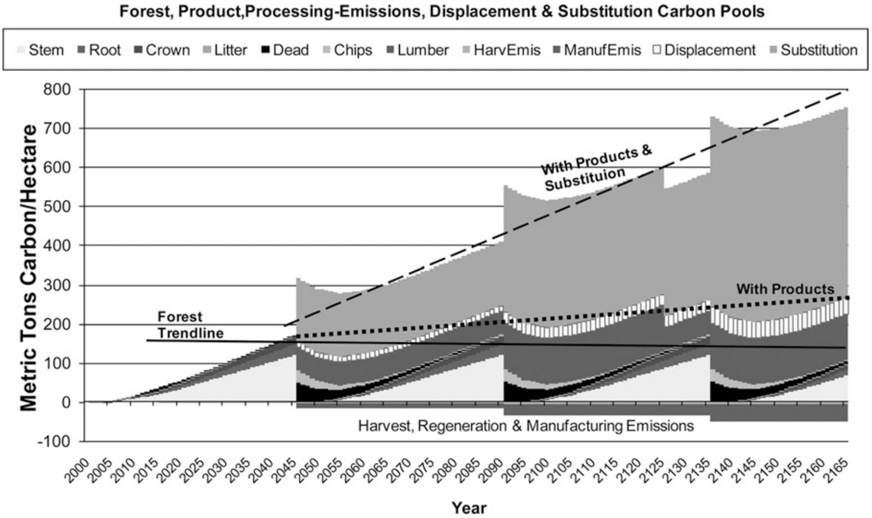

Figure 6. Carbon pools from a sustainably managed forest and its wood products, including biofuel displacement and product-substitution displacement. From Perez-Garcia et al (2005).

of the useful life for wood products, there will be increased efforts to collect the wood for recycled products or for its energy value. Unlike earlier times, the value of the carbon offset in forest residuals (that are now left in the forest to decompose) may pay their way to energy collection facilities. Each of these impacts will raise the slope (eg growth rate) of the combined total of carbon pools. As a consequence, Fig 6 demonstrates sustainable forest management with increasing carbon stored in products as a sustainable economic contribution and increasing displacement of carbon emissions as a sustainable environmental contribution. Concerns over lack of permanence in product carbon are allayed when the focus is shifted from individual products to the stream of products being produced by a sustainably managed forest.

Many More Uses of Wood

Although wood is the dominant framing material in North American residential building construction, there are many ways wood could see greater use in both residential and nonresidential structures. Figure 7 provides direct carbon emission comparisons for wood vs steel wall studs and the more complex substitution of wood studs with

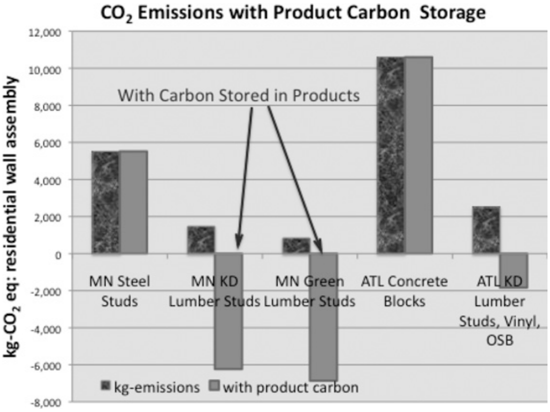

Figure 7. Impact of product carbon store on emissions for wall products and assemblies.

OSB sheathing and vinyl siding compared with concrete block and stucco.

The direct substitution of steel for wood studs results in almost 6 tonne of extra emissions, although wood studs store more than 6 tonne CO_2 equivalent. The steel studs also require extra insulation to have thermal equivalence (not shown), which would increase steel wall emissions. The more complex concrete block substitution emits almost 11 tonne of emissions, whereas the wood wall, even with vinyl siding,

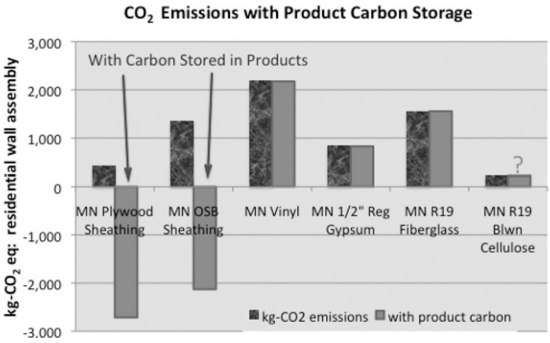

Figure 8. Impact of product carbon store on emissions for sheathing and insulation.

stores almost 2 tonne equivalent (the wood storage more than offsets the vinyl emissions).

Comparisons of siding and sheathing are shown in Fig 8. Whereas OSB is more energy-intensive to manufacture, its greater density stores more carbon, offsetting much of the energy used. Wood panels store carbon, whereas vinyl siding and gypsum are emitters. The recycled fiber paper coating on gypsum, although of little mass, could be credited with the carbon in the paper vs landfilling after the first cycle (not shown). Fiberglass also contributes to emissions, whereas the emissions from the production of cellulosic insulation is very low and would be largely offset by the extended carbon stored in the product relative to rapid decomposition if landfilled after the first life cycle (not shown).

CONCLUSIONS

LCA assessment helps to characterize the opportunities for reducing emissions of carbon to the atmosphere. Life-cycle methods also allow for the evaluation of other environmental burdens such as air and water pollution, solid waste, and ecosystem impacts. The manufacture of wood products results in low emissions compared with other materials and carbon emissions can be lowered further by the increased use of biofuels. In addition, the carbon stored in wood products is substantially greater than the emissions from their initial manufacture. That surplus offsets much of the emissions from the nonwood products that are used along with wood in the construction in typical residential structures. Designs that use more wood should be able to offset all the emissions from the nonwood products that may be required, resulting in "carbon-negative" structures. Looking only at current low levels of substitution associated with framing, and not including the carbon stored in products, hides the many opportunities that exist for reducing carbon emissions from building construction. When the carbon impacts in construction are integrated back to the forest hectare, they provide a convincing characterization of sustainable forest management that includes the harvest and use of wood products to extend the carbon stored in the forest to all the wood uses in society.

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