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Energy and CO_2 analysis of wood substitution in construction

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Abstract Comparative analysis of the energy and carbon balances of wood vs. non-wood products is a complex issue. In this paper we discuss the definition of an appropriate functional unit and the establishment of effective system boundaries in terms of activity, time and space, with an emphasis on the comparison of buildings. The functional unit can be defined at the level of building component, complete building, or services provided by the built environment. Energy use or carbon 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, we suggest that 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 we suggest that using marginal production data is 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. 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 approaches to meet this challenge, including the intensification of land use to increase the time rate

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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.

1 Introduction

We face a major challenge to transition from a society driven by stored solar energy, in the form of fossil fuels, to one driven by active solar energy exploited at a sustainable rate. Forest biomass can play a dual role in this transition, serving as an industrial material as well as a fuel source, both produced from solar energy captured in forest ecosystems. There is growing recognition of the potential for substituting wood-based materials in place of other materials as a means of reducing the environmental impacts of product use. In particular, using wood instead of concrete, steel, and other non-renewable materials results in less greenhouse gas (GHG) emissions, and can play an important role in a strategy to mitigate climate change (IPCC 2007).

There exists a range of mechanisms by which wood product substitution affects energy and carbon balances (Lippke et al. 2004; Gustavsson et al. 2006b). These include the fossil energy used to manufacture wood products compared with alternative materials; the avoidance of industrial process carbon emissions from e.g. cement manufacture; the physical storage of carbon in forest ecosystems 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 residues deposited in landfills.

Efficient use of wood products involves material and energy flows in different economic sectors, including forestry, manufacturing, construction, energy, and waste management. The closer integration of these flows can significantly improve the overall life cycle environmental performance of wood-based products, though accurate analysis across this broad range of natural and technological processes can be problematic (Sathre 2007). A thorough understanding of the relative impacts caused by the different products over their entire life cycles is needed to design effective wood substitution that minimizes the environmental impacts of the products.

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. 2005a).

In recent years, methodological approaches have been developed by various authors to explore the energetic and climatic implications of wood substitution. Koch (1992) estimated the carbon balance implications of a proposed reduction in timber harvest from US forests. Using data from an earlier study (Boyd et al. 1976) comparing production energy use of wood products and functionally equivalent non-wood materials like steel, aluminium, concrete and brick, the author concluded that if non-wood materials were used instead of structural wood products, net CO_2 emissions would increase substantially. Künniger and Richter (1995) used life cycle analysis (LCA) methodology to determine the environmental impacts of wood, concrete and steel utility poles. They compared the global warming potential and primary energy use of the different materials, as well as other impact categories including acidification, nitrification, and photochemical ozone creation.

Buchanan and Honey (1994) calculated the CO_2 emissions from fossil fuel combustion and process emissions from the production of building materials in New Zealand. They compared wood-framed versions to steel or reinforced concrete versions of several different types of buildings, and found that in all cases the wood buildings emitted less fossil and process CO_2 emissions during material production. Buchanan and Levine (1999) later used building emissions data from Buchanan and Honey (1994) in a scenario analysis of the carbon balance implications of an increased use of wood-based building materials. They included the carbon storage in wood products as well as reduced fossil carbon emissions, but did not consider the differing dynamics of these carbon pools over time.

The conceptual basis of the climate benefits of wood substitution was advanced by Schlamadinger and Marland (1996), who provided a comprehensive theoretical analysis of the role of wood products in the global carbon cycle. Based on computer modelling of carbon flows associated with various land use strategies, they concluded that using biomass for direct substitution of fossil fuels or fossil fuel-intensive materials is an important means of reducing net CO_2 emissions because it provides permanent and cumulative emissions reduction, whereas sequestration or conservation of carbon is typically limited or temporary. They estimated the “displacement factor” of wood products, defined as the amount of fossil carbon not oxidised because wood products are used instead of more energy-intensive materials, and acknowledged that additional research is needed to better quantify the displacement factor and its variability.

Schlamadinger et al. (1997) developed a standard methodology to compare the greenhouse gas balances of fossil fuel and biofuel energy systems. Many of the methodological issues examined by these authors are equally relevant to the comparison of wood-based and non-wood-based material use. There are strong parallels between the cyclical flow of carbon in sustainably produced biofuels and wood building materials, versus the linear flows associated with fossil fuels and energy-intensive mineral materials. Furthermore, the life cycle of wood-based materials is linked to biofuel availability and its impact on the use of fossil fuels.

A comprehensive study by Börjesson and Gustavsson (2000) brought together issues of land use, biofuel supply, and end-of-life alternatives of building materials. The authors compared a multi-storey building in Sweden built with either a wood frame or a concrete frame, and found that the primary energy used for the production of building materials was about 60–80% higher for the concrete construction than for the wood construction. This study considered the use of forest and processing residues as well as wood-based demolition waste as substitutes for fossil fuel, and considered alternative land uses and their effect on carbon balances. The net GHG emission, while generally more favourable for the wood-framed building, depended strongly on how the wood was handled after demolition of the building. The study highlighted the complexity of comparing different alternatives for utilising forest biomass for climate change mitigation, and the effect that the time perspective has on the results.

Pingoud and Perälä (2000) estimated the maximum wood substitution potential in new building construction in Finland. The total amount of materials used during 1 year in various building parts in new construction of different building types was estimated, and the commercial potential for increased wood use in each building part was assessed. Scharai-Rad and Welling (2002) analysed single-family houses constructed in central Europe made with either wood or brick. They considered the utilisation of processing and demolition residues to replace fossil fuels, and found that net GHG emission decreased as the volume of recovered wood increased.

In a series of articles, Petersen and Solberg (2002, 2003, 2004) analysed the use of various wood materials in place of non-wood materials in Norway. They employed a methodology that discounted emissions and costs that occur at different times during the material life cycles, and calculated an index of the cost-efficiency of material substitution. They also linked the analyses to the carbon fixation dynamics of forests. They found wood construction to have consistently lower GHG emissions than non-wood material, with the amount depending largely on waste material management and how forest carbon flows are considered.

Lippke et al. (2004) reported results from the Consortium for Research on Renewable Industrial Materials (CORRIM). The consortium analyzed all stages of the wood-based building materials chain, from forest production, harvest, processing, construction, use, and demolition. They compared concrete- and steel-framed houses to functionally-equivalent wood-framed houses. Additional articles by various CORRIM member scientists confirmed and expanded upon the initial 2004 results (Johnson et al. 2005; Lippke et al. 2005; Perez-Garcia et al. 2005a, b; Puettmann and Wilson 2005; Winistorfer et al. 2005; Lippke and Edmonds 2006; Meil et al. 2007). Upton et al. (2008) expand these case studies of individual houses to a national scale, over a time period of 100 years. The authors develop models that link the CORRIM data on construction materials in 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.

Werner et al. (2005) conducted a scenario analysis of the GHG emissions impact of an increase in wood product use in Switzerland through the year 2130. They estimated substitution potentials for different wood-based materials used in construction and interior finishing, and calculated changes in carbon stock and GHG emissions if these wood materials were used instead of non-wood materials. They distinguished between the effects occurring within the Swiss border and those in other countries.

Gustavsson et al. (2006b) compared the energy use and CO_2 emissions of producing functionally-equivalent apartment buildings made with wood or concrete frames, finding the wood buildings to have lower energy use and CO_2 emissions. They calculated the energy available from biomass residues from logging, processing, construction, and demolition, finding it to be greater than the energy used to produce the wood buildings. They also considered CO_2 emissions and uptake due to process reactions that occur during the life cycle of concrete. Gustavsson and Sathre (2006) studied the variability of energy use and CO_2 emissions of buildings with wood or concrete frames. They found that recovery of biomass residues 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.

Eriksson et al. (2007) conducted a broad system analysis of carbon stocks and flows in trees, soil, wood products, and substitutable materials and fuels, finding that overall CO_2 emissions were lower when forests were managed more intensively to produce timber for use as construction material. The substitution effect of using wood construction material instead of non-wood materials had the greatest single impact on the overall carbon balance. Removing harvest residues and stumps for use as biofuel led to avoided fossil carbon emissions that were 7 to 10 times greater than the reduction in soil carbon stock due to the biomass removal, depending on the fossil fuel replaced.

A review of these previous studies of the energy and carbon balances 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 space. In the present paper, we discuss these issues and suggest appropriate methodological approaches to analyse the energy and carbon implications of substituting wood in place of non-wood materials. Defining the functional unit and system boundaries is a necessary part of analyzing energy and 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. 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.

2 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 et al. 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 1 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 (Sathre and Gustavsson 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 and 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 et al 2006b; 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 (see Section 3.2).

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 perform 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 all 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.

3 System boundaries: activities

There exists a range of mechanisms by which wood product substitution affects energy use and CO_2 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.

3.1 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 primary 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.

3.1.1 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 (see Section 3.5.1).

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).

3.1.2 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

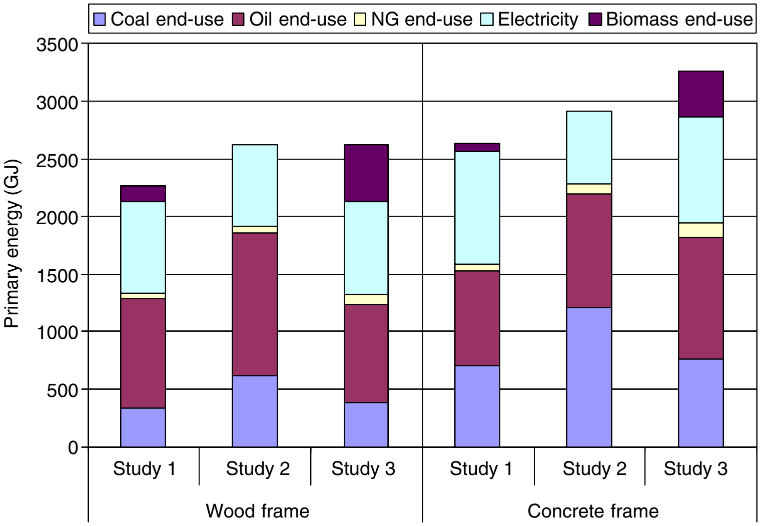

Fig. 1 Primary energy used for production of materials for wood- and concrete-framed versions of a building, using specific energy use data from three different process analyses. Study 1 is Fossdal (1995), Study 2 is Worrell et al. (1994) and Study 3 is Björklund and Tillman (1997). (Adapted from Gustavsson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

biological materials include the carbon fluxes that occur during the life cycle of the plants.

There is an inherent variability in the quality 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.

3.1.3 Cement process reactions

Manufacture of cement-based products result in industrial process carbon emissions. CO_2 emissions are inherent to the cement production process, due to chemical reactions (calcination) during the transformation of raw materials into cement clinker. Process emissions can be a significant part of the GHG emissions from manufacturing concrete and other cement-based materials. While calcination reaction emissions are well quantified, there is some uncertainty regarding the net effect of cement process emissions, due to subsequent CO_2 uptake by carbonation reaction. This slow reaction occurs over the life cycle of cement products, and reabsorbs from 8% to 57% of the CO_2 that was initially emitted (Dodoo et al. 2009). Nevertheless, as carbonation uptake is less than calcination emission, process reaction emissions can be a significant part of the GHG emissions of cement products, and should be included in the analysis.

3.2 Operation phase

The operation phase generally contributes the greatest share of life cycle energy use and CO_2 emissions of a building. As the emphasis of a wood substitution study is on the energy and carbon balances of building materials, the impacts from *operating* the buildings are of interest only to the extent that they are affected by the choice of material. Numerous studies have analysed wood and non-wood building versions that are designed to be thermally equivalent. The functional unit of the comparative analysis is chosen so as to give the same services, resulting in no differences in the operation impacts. Some studies do not include impacts that occur during the operation phase, reasoning that the impacts are the same in both building versions, thus do not affect the relative environmental impacts of the wood and non-wood building (e.g. Gustavsson et al. 2006b; Upton et al. 2008). 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. In such cases, adding the operational energy use would increase the total primary energy use for both the wood and non-wood alternative, but the difference between them would remain the same. The thermal mass of building materials may in some cases affect the heating or cooling energy requirements of a building, depending on climate, building size, configuration, and orientation.

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 need to be considered.

3.3 Co-products

Biomass flows over the life cycle of a wood-based building material are shown schematically in Fig. 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 as biofuel. Residues are generated during primary processing when logs are reduced to lumber, as well as in secondary processing industries that provide manufactured products such as doors, windows and glue-laminated beams. Some residues from wood processing are also used as a raw material for particleboard or other composite wood products.

Recovered woody material can be either burned as biofuel, or used as input for further processing into other wood products. Such 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). Various alternative uses for

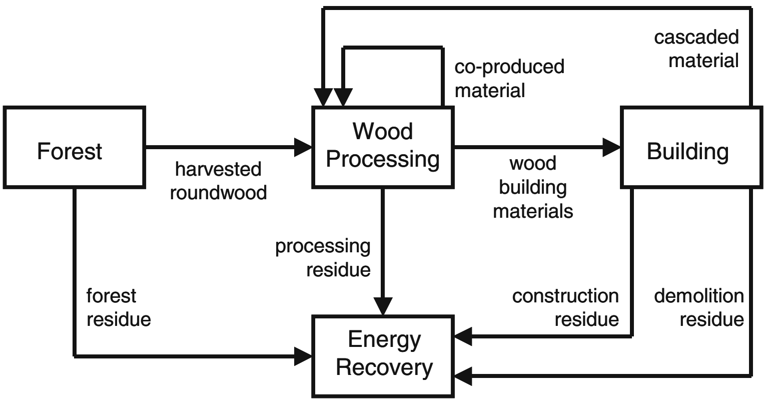

Fig. 2 Schematic diagram of forest biomass flows over the life cycle of a wood-based building material

recovered wood lumber are possible, including re-use as lumber, and re-processing into particleboard or pulp. 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 (Gartner 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.

3.4 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 in Section 3.5.3.

European studies have often concluded that burning wood waste to replace fossil fuel is the best post-use management option (see e.g. Scharai-Rad and Welling 2002; Börjesson and Gustavsson 2000). North American studies have generally considered landfilling as a more suitable option (see e.g. Upton et al. 2008). 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).

3.5 Energy supply system

3.5.1 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 et al. 2006b).

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 (Section 3.5.2) or that is replaced by biomass residues (Section 3.5.3), 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.

3.5.2 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 (Sjödin and Grönkvist 2004). 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 northern Europe, 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. Over the coming decades in northern Europe, the marginal electricity production would appear to be from coal-fired power plants, or less likely from fossil gas-fired power plants.

3.5.3 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 of biofuel obtained from sustainably managed forests is generally assumed to have zero net emission. 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 (see Section 3.5.1).

The carbon balance effect of fossil fuel substitution will depend on the extent of biomass residue recovery (Sathre and O'Connor 2010). Recovery and utilisation of forest residue is becoming more common. 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 is quite widespread. Some byproducts are not directly used as biofuel but instead for pulp or particleboard production, though eventually these materials also can be used for energy purposes. The recovery of wood-based construction waste for use as biofuel is becoming more widespread, with source separation of different types of construction wastes occurring on many construction sites. Utilisation of wood-based demolition waste has a significant impact on the energy balance of wood construction, and has the potential to increase. 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. Policy measures, including landfill dumping fees and regulations, affect the amount of wood that is recovered from building 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 so-called "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.

4 System boundaries: temporal

The time at which energy and carbon flows occur can affect the outcome of wood substitution analyses, depending on the system boundaries and assumptions used. Important temporal aspects of the wood life cycle include the dynamics of forest growth including regeneration and 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.

4.1 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 (Sathre and O'Connor 2008).

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).

4.2 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 et al. 2006b). 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 (see Section 3.4).

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 (Gustavsson et al. 2006b). 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.

4.3 Fossil fuel use

Fossil fuels are used at different times over the life cycle of a building, as discussed in Section 3. 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 fuel results in carbon emissions occurring at different times throughout the life cycle of the material.

4.4 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.

4.5 Cement process reactions

As discussed in Section 3.1.3, chemical reactions affecting the net carbon balance occur continuously 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 depends on several factors including the exposed uncoated surface area of the concrete, the composition of the cement used to make the concrete, and the relative humidity and temperature of the environment (Gajda and Miller 2000). 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).

5 System boundaries: spatial

5.1 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/year (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.

5.2 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).

5.3 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 et al. 2006a). 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%. 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 complicates 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. The inter-European and intercontinental 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 in northern Europe 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 is small in relation to the total quantities of biomass potentially available. If the export potential was ignored, the additional biomass would then be used for other uses 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 buildings 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). In an analysis 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. Other wood 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.

6 Conclusions

Analysis of the energy and carbon balances of wood substitution is a complex issue. In this paper 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 we suggest that using marginal production data is a 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 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 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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