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ENERGY AND GREENHOUSE GAS IMPACTS OF SUBSTITUTING WOOD PRODUCTS FOR NON-WOOD ALTERNATIVES IN RESIDENTIAL CONSTRUCTION IN THE UNITED STATES

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PRESIDENT'S NOTE

Substitution effects occur when one product is substituted for another with different life cycle environmental attributes. Substitution effects associated with different types of building materials have been the focus of a number of studies in recent years, notably the studies by the Consortium for Research on Renewable Industrial Materials (CORRIM). None of the studies performed to date, however, has attempted to estimate the national-level effects of using wood-based building products. Working with the USDA Forest Service with funding from its Resources Planning Act (RPA) Assessment Program, NCASI used data generated by CORRIM and information from other sources to characterize the effects of using wood-based building materials on U.S. energy consumption and greenhouse gas emissions.

NCASI's analysis indicates that on an annual basis, the greenhouse gas benefits of using wood-based building systems amount to 9.6 million tonnes of CO_2 equivalents per year. The corresponding energy benefit is approximately 132 million gigajoules per year. These figures represent approximately 22% of the energy and 27% of the greenhouse gas emissions associated with the pre-occupancy stages of the life cycle of residential structures in the U.S. (i.e., 22% of the embodied energy and 27% of the embodied greenhouse gas emissions in residential structures).

These estimates have been found to be very sensitive to a number of assumptions about the rate at which carbon accumulates in forest ecosystems and the fate of carbon in forests that are no longer needed for production of wood building materials. In addition, the analysis requires extrapolation from only a few types of structures in a limited number of climates to the entire country. Additional research is warranted to reduce the uncertainty associated with these aspects of the analysis.

Ronald A. Yeske

November 2006

MOT DU PRÉSIDENT

Des effets occasionnés par la substitution surviennent lorsqu’un produit est substitué par un autre dont les caractéristiques environnementales du cycle de vie sont différentes. Les effets associés à la substitution de différents types de matériaux de construction ont fait l’objet d’une attention soutenue dans plusieurs études depuis les dernières années, notamment les études réalisées par le Consortium pour la recherche sur les matériaux industriels renouvelables (*Consortium for Research on Renewable Industrial Materials, CORRIM*). Cependant, aucune des études effectuées jusqu’à maintenant n’a tenté d’estimer les effets, au niveau national, de l’utilisation des produits de construction à ossature de bois. En collaboration avec le service forestier USDA (*USDA Forest Service*), et financé par son programme d’évaluation inclus dans la Loi sur la planification des ressources (*Resources Planning Act -RPA- Assessment Program*), NCASI a utilisé les données générées par le CORRIM et des informations provenant d’autres sources pour caractériser les effets de l’utilisation de matériaux de construction de bois sur la consommation d’énergie et les émissions de gaz à effet de serre (GES) des États-Unis.

L’analyse de NCASI indique que, sur une base annuelle, les bénéfices de réduction des GES associés à l’utilisation des systèmes de construction à ossature de bois totalisent 9,6 millions de tonnes équivalent de CO_2 par année. Le bénéfice énergétique correspondant totalise approximativement 132 millions de gigajoules par année. Ces chiffres représentent approximativement 22% de l’énergie et 27% des émissions de GES associées aux stages précédant la prise de possession, dans le cycle de vie des structures résidentielles aux États-Unis (c.-à-d., 22% de l’énergie intrinsèque et 27% des émissions intrinsèques de GES dans les structures résidentielles).

NCASI a observé que ces estimés sont très sensibles à un certain nombre d’hypothèses relatives au taux d’accumulation du carbone dans les écosystèmes forestiers et au devenir du carbone dans les forêts qui ne sont plus utilisées pour la production de matériaux de construction de bois. De plus, l’analyse implique l’extrapolation à partir de seulement quelques types de structures et ce, pour un nombre restreint de climats, afin de couvrir le pays entier. Des recherches additionnelles seraient justifiées afin de réduire l’incertitude associée à ces aspects de l’analyse.

Ronald A. Yeske

Novembre 2006

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ABSTRACT

In this study, NCASI worked with the USDA Forest Service with funding from its Resources Planning Act (RPA) Assessment Program to estimate the effects of using wood-based building materials on national energy use and greenhouse gas emissions. Data developed by the Consortium for Research on Renewable Industrial Materials (CORRIM) were used in an analytical framework that allowed carbon in forests and forest products to be tracked over large areas and long time frames. In addition, NCASI developed a module to follow the fate of carbon in discarded building materials. To ensure that short-term and transient effects did not bias the findings, a time horizon of 100 years was used.

The results indicate that houses with wood-based wall systems required about 15 to 16% less total energy for non-heating/cooling purposes than thermally comparable houses employing alternative steel- or concrete-based building systems. The results for non-renewable energy consumption were essentially the same as those for total energy, reflecting the fact that most of the displaced energy was in fossil fuels. Net greenhouse gas emissions associated with wood-based houses were 20 to 50% lower than those associated with thermally comparable houses employing steel- or concrete-based building systems. Only a small fraction of the building materials need to be changed to accomplish these improvements. In the Atlanta example, the additional wood used in the wood-based house represented only 2.3% of the mass of the house, while in the Minneapolis example, the additional wood used in the wood-based house represented 7.7% of the mass.

On an annual basis, considering 1.5 million housing starts a year, the difference between wood and non-wood building systems is about 9.6 million tonnes of CO_2 equivalents per year, and the corresponding energy benefit associated with wood-based building materials is approximately 132 million GJ per year. These figures represent approximately 22% of the embodied energy and 27% of the embodied greenhouse gas emissions in the residential sector of the economy.

The estimates developed in this study were found to be very sensitive to assumptions about carbon accumulation in forests and about the fate of carbon in forests no longer needed for production of wood building materials. Future studies would benefit from a more refined analysis of these issues as well as an analysis of the benefits of producing energy from forest biomass under a variety of scenarios. In addition, the estimates would be improved if data were available for houses representative of regions not included in the CORRIM Phase I work.

KEYWORDS

building materials, energy, greenhouse gases, life cycle studies, substitution effects, wood products

RELATED NCASI PUBLICATIONS

Special Report No. 04-03 (August 2004). *An analysis of the methods used to address the carbon cycle in wood and paper product LCA studies*.

Technical Bulletin No. 872 (March 2004). *Critical review of forest products decomposition in municipal solid waste landfills*.

IMPACTS DE LA SUBSTITUTION DE PRODUITS (PRODUITS NON DÉRIVÉS DU BOIS REMPLACÉS PAR PRODUITS DU BOIS) SUR L'ÉNERGIE ET LES GAZ À EFFETS DE SERRE DANS LA CONSTRUCTION RÉSIDENTIELLE AUX ÉTATS-UNIS

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RÉSUMÉ

Dans cette étude, NCASI a collaboré avec le service forestier USDA, et a reçu des fonds de son programme d'évaluation contenu dans la Loi sur la planification des ressources (*Resources Planning Act -RPA- Assessment Program*), afin d'estimer les effets de l'utilisation des matériaux de construction de bois sur l'utilisation d'énergie et les émissions de gaz à effet de serre (GES) au niveau national. Les données développées par le Consortium pour la recherche sur les matériaux industriels renouvelables (*Consortium for Research on Renewable Industrial Materials, CORRIM*) ont été utilisés dans un cadre analytique permettant de suivre la trace du carbone dans les forêts et les produits forestiers sur de grandes surfaces et de longues périodes de temps. De plus, NCASI a développé un module pour suivre le devenir du carbone dans les matériaux de construction éliminés. Afin de s'assurer qu'aucun biais associés aux effets court terme et aux effets de transition n'affecte les résultats, on a utilisé un horizon de 100 ans.

Les résultats indiquent que les résidences comportant des systèmes muraux de construction à ossature de bois requièrent environ 15 à 16% moins d'énergie totale pour les besoins autres que le chauffage et les besoins de refroidissement, par rapport aux résidences thermiquement comparables, construites avec des systèmes de construction à ossature métallique ou avec du béton. Les résultats reliés à la consommation d'énergie non renouvelable étaient essentiellement les mêmes que ceux reliés à l'énergie totale, ce qui montre que la majeure partie de l'énergie déplacée se trouvait dans les combustibles fossiles. Les émissions nettes de GES associées aux résidences avec ossature de bois étaient de 20 à 50% inférieures à celles associées aux résidences thermiquement comparables et construites avec ossature métallique ou avec du béton. Seule une petite fraction des matériaux de construction doit être modifiée pour réaliser ces améliorations. Dans l'exemple d'Atlanta, l'utilisation additionnelle de bois dans la résidence avec ossature de bois représentait seulement 2,3% de la masse de la résidence tandis que dans l'exemple de Minneapolis, l'utilisation additionnelle de bois dans la résidence avec ossature de bois représentait 7,7% de la masse.

Sur une base annuelle, en considérant 1,5 million de mises en chantier dans le secteur résidentiel par an, la différence entre les systèmes de construction à ossature de bois et les autres systèmes est d'environ 9,6 millions de tonnes équivalent de CO_2 par an et le bénéfice énergétique correspondant associé aux matériaux de construction de bois est d'approximativement 132 millions de GJ par an. Ces chiffres représentent approximativement 22% de l'énergie intrinsèque et 27% des émissions de GES intrinsèques au niveau du secteur résidentiel de l'économie.

NCASI a observé que les estimés développés dans cette étude sont très sensibles aux hypothèses reliées à l'accumulation du carbone dans les forêts et celles associées au devenir du carbone dans les forêts qui ne sont plus utilisées pour la production de matériaux de construction de bois. Les recherches futures bénéficieraient d'une analyse plus approfondie de ces enjeux ainsi qu'une analyse des bénéfices générés lors de la production d'énergie à partir de la biomasse forestière, selon une variété de scénarios. Enfin, ces estimés pourraient être améliorés si les données pour des résidences représentatives de régions qui ne font pas partie de la phase I des travaux du CORRIM étaient disponibles.

MOTS CLÉS

Matériaux de construction, énergie, gaz à effet de serre (GES), études du cycle de vie, effets occasionnés par la substitution de produits, produits du bois

AUTRES PUBLICATIONS DE NCASI DANS CE DOMAINE

Rapport spécial no. 04-03 (août 2004). *An analysis of the methods used to address the carbon cycle in wood and paper product LCA studies*.

Bulletin technique no. 872 (mars 2004). *Critical review of forest products decomposition in municipal solid waste landfills*.

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ENERGY AND GREENHOUSE GAS IMPACTS OF SUBSTITUTING WOOD PRODUCTS FOR NON-WOOD ALTERNATIVES IN RESIDENTIAL CONSTRUCTION IN THE UNITED STATES

1.0 INTRODUCTION

Over a period of decades, significant effort has been directed at reducing residential energy requirements and greenhouse gas emissions by improving the thermal performance of buildings, primarily through improved insulation. This effort has achieved impressive results. Energy requirements for space heating and air conditioning declined by more than 40% between 1978 and 1997 from 95 to 55 million British thermal units (BTUs) per unit, in spite of increasing housing sizes and more widespread use of air conditioning (NAHB 2005; EIA 1997).

Nonetheless, the residential sector of the economy remains a significant contributor to national energy requirements and emissions of greenhouse gases. In 2001, the residential sector required approximately 17.6 quadrillion BTUs of energy and was responsible for the emission of 1155 million tonnes of CO_2 (EIA 2001, 2002). These represented 18% of national energy requirements (estimated to be 96.47 quadrillion BTUs) and 20% of national CO_2 emissions (estimated to be 5789 million metric tonnes CO_2) (EIA 2001, 2002, 2006). Within the residential sector, heating and cooling accounted for 41% of the primary energy requirements and 36% of the CO_2 emissions, representing, in both cases, about 7% of the corresponding national figures.

While the importance of residential heating and cooling is well understood, a less obvious source of residential energy and emissions impacts is associated with the manufacture, transport, and recycling or disposal of the materials used in construction, renovation, and maintenance. This report examines the significance of these other energy requirements and greenhouse gas emissions and how they vary among different building materials.[1]

2.0 EMBODIED ENERGY AND CO_2 EMISSIONS

The embodied energy and emissions of residential structures usually include those associated with obtaining raw materials, manufacturing the building materials, transporting materials to the construction site, and building the structure. Some studies also include energy and emissions associated with recycling or disposing of construction and demolition debris. Embodied energy and emissions can represent a significant component of the overall energy and emissions footprint of residential structures. Estimates of embodied energy relative to operational energy (primarily for heating and cooling) vary over a wide range—from less than 5% of operational energy to 50% or more over the lifetime of a structure. Some of the important factors influencing these estimates are a) local climate; b) building design; c) assumed building lifetime; d) whether the estimates include maintenance activities; e) whether the estimates include energy used for purposes other than heating and cooling; and f) the methods and boundary conditions used in the analysis.

A number of U.S.-based studies have suggested that embodied energy and CO_2 emissions can be approximated by assuming that embodied values for homes in the United States are one-tenth of the energy and emissions associated with heating and cooling (Lippke et al. 2004; Pierquet, Bowyer, and

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[1] Although this study is limited to greenhouse gas and energy impacts, it is important to note that life cycle assessment of buildings deals with a much larger range of resource demands and environmental loads. A number of other releases to air, water and land occur during a building's life cycle, and these can constitute an important set of embodied effects (e.g., Lippke et al. 2004; Petersen and Solberg 2005).

Huelman 1998; Marceau and Van Geem 2002a, 2002b, 2002c).[2] Using this approximation and the information above, it appears that the embodied energy in residential construction materials is between 0.5 and 1 quadrillion BTUs per year and that the embodied CO_2 emissions are between 30 to 60 million tonnes per year (not including the effects of carbon sequestration).

In most cases, embodied energy requirements and CO_2 emissions are much smaller than the operational energy and emissions associated with the occupancy of a building over its lifetime. Nonetheless, embodied energy and emissions are important because with proper building design they can be reduced without adversely affecting operational energy and emissions. Indeed, in some cases it may be possible to reduce both operational and embodied energy and emissions. In addition, as the thermal performance of structures continues to improve, the relative contribution of embodied energy and emissions can be expected to increase (e.g., Thormark 2006). Ideally, houses should be designed to minimize total energy (embodied plus operating) and GHG emissions over the lifecycle of the house.

3.0 REVIEW OF PAST STUDIES

A review of the literature reveals that a large number of studies have been conducted to examine opportunities to reduce the amount of embodied energy and CO_2 emissions in residential building materials. The research on this topic is distributed throughout the world, with a large fraction of such studies coming from outside North America. Because of differences in climate and building practices, care must be exercised in applying the results of these studies to the North American situation. Nonetheless, such studies are important because they provide insights into the robustness of findings regarding the relative advantages and disadvantages of different building materials.

Studies of embodied energy are useful only if they compare multiple materials using consistent methods and assumptions. Especially important is the decision on whether to compare materials based on structures that represent particular construction methods or to compare structures that have comparable thermal performance. Differences in thermal performance can easily overwhelm comparisons of the life cycle energy requirements and emissions of structures. Thus, this examination focuses on studies of structures with comparable thermal performance. Studies where comparable thermal performance was accomplished by employing building designs that are uncommon in practice due to cost were excluded.

In addition, attempts have been made to rely primarily on studies containing adequate detail on boundary conditions and assumptions. The importance of study assumptions is illustrated in work by Borjesson and Gustavsson (2000), who examined the net life cycle carbon emissions associated with a multi-story apartment building. That study found that the net embodied emissions calculated for a wood frame structure varied from -5 to +38 metric tonnes of CO_2 equivalents, depending on assumptions about how demolition debris was managed. Other researchers have emphasized that embodied energy estimates can vary by up to 50%, depending on how far upstream the analysis extends (Lawson 1996). The Australian Greenhouse Office has observed that estimates of embodied energy can vary by a factor of 10 (Milne and Reardon 2004).[3]

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[2] The estimates contained in these references have been adjusted to represent a building lifetime of 75 to 100 years and to include only operational energy required for heating and cooling. The relative contribution of embodied parameters to life cycle values will, of course, vary between regions and building designs.

[3] Much smaller differences than those cited here are expected among studies that adhere to accepted standards for conducting LCIs, particularly with regard to pre-combustion loads from energy use (W.B. Trusty, pers. comm.).

Such considerations greatly limit the ability to compare the performance of one material to another based on separate studies of each material. In spite of the limitations on comparing materials across different studies, embodied energy and emissions comparisons made within individual studies can provide useful insights as long as the comparisons are based on systems with comparable thermal performance.

In the studies identified in this review that were designed to compare embodied energy in systems with comparable thermal performance, wood-based wall systems and buildings were almost always found to have lower embodied energy and CO_2 emissions than comparable building systems using concrete, steel, or brick (Borjesson and Gustavsson 2000; Athena 2004; Scharai-Rad and Welling 2002; Pierquet, Bowyer, and Huelman 1998; Lenzen and Treloar 2002; Gustavsson and Sathre 2006; Richter and Sell 1993; Gustavsson, Pingoud, and Sathre 2006; Consortium for Research on Renewable Industrial Materials (CORRIM) studies described in Lippke et al. 2004, Perez-Garcia et al. 2005a, Puettmann and Wilson 2005). In one study, the wood-based system contained more embodied total energy than the steel-based system, but embodied non-renewable energy and CO_2 emissions for the wood-based system were lower than for steel-, brick-, or concrete-based systems (Sarri 2001). In most, but not all, of these studies thermal performance was measured in terms of conventional insulation properties, i.e., steady-state R or U values.

A number of studies examined lifetime energy requirements and life cycle loads, but many did not separate operating loads from embodied loads and did not compare systems designed to have comparable thermal performance. A series of studies focusing on concrete-based wall systems, for instance, was either limited to operational energy (Gajda 2001) or characterized performance in terms of aggregated life cycle indicators which combined embodied and operational energy and emissions (Marceau and Van Geem 2002a, 2002b, 2002c). In several cases, these studies found that many of the concrete-based walls had lifetime operational energy requirements and greenhouse gas emissions (or related life cycle indicators) comparable to or lower than those associated with wood frame walls. (Marceau and Van Geem 2002a, 2002b, 2002c; Gajda 2001). Because embodied energy and emissions were not reported and because the studies were not designed to compare structures with comparable thermal performance, the significance of these studies to comparisons of embodied energy and emissions is not known. These studies suggest, however, that in some situations concrete-based wall systems may provide benefits in operational energy and emissions that are difficult for wood-based systems to match.

Where concrete-based systems have been found to have lower operational energy and emissions, this has generally been attributed to thermal mass (AGO 1999; Milne and Reardon 2004; Marceau and Van Geem 2002a, 2002b, 2002c; Gajda 2001; Kosny et al. 2001). Studies at Oak Ridge National Laboratory have demonstrated that the importance of thermal mass depends on local climate, with most benefits occurring in places with large diurnal temperature changes that encompass the human comfort zone. In Phoenix, for instance, steady-state R-values may need to be multiplied by as much as 2.5 to correctly estimate heating and cooling loads for high thermal mass wall systems. The benefits of high mass wall systems, however, are modest in places where differences between daytime and nighttime temperatures are smaller and average daily temperatures are outside the human comfort zone during the peak heating or cooling season. For some wall systems in certain locations, high thermal mass can even reduce thermal performance (Kosny et al. 2001). Two studies have been identified where the modeling was done with tools that allow comparisons of embodied energy, and in some cases embodied emissions, for structures with approximately comparable thermal performance, including considerations of thermal mass for concrete-based systems. Both studies found that the embodied energy for the wood-based systems was lower than that of concrete-based systems, even over a 75- to 100-year building life (Athena 2004; Pierquet, Bowyer, and Huelman 1998). Because these studies were based on conditions in Minnesota, Illinois, and Toronto, caution is warranted in extrapolating the results to regions where the benefits of thermal mass would be expected to be more significant.

The benefits of steel-based construction systems are highlighted in a number of reports. These studies usually focus on a) the recyclability of steel studs; b) the fact that embodied energy and CO_2 emissions are much smaller than the life cycle energy and emissions associated with heating and cooling;(c) the lower lifetime maintenance requirements for steel; and d) the land area (and implied ecological impacts) associated with wood-based systems (SCI 1998; Adalberth, Almgren, and Petersen 2001; Anderson 1998; SCSSC n.d.; de Spot 1999). In studies comparing embodied metrics for thermally comparable systems, however, wood-based systems are generally found to have lower embodied energy and CO_2 emissions than comparable steel-based systems (Athena 2004; Sarri 2001; Pierquet, Bowyer, and Huelman 1998; CORRIM studies reported in Lippke et al. 2004, Perez-Garcia et al. 2005a, Puettmann and Wilson 2005).

Finally, a number of studies are available that compare the embodied energy in different types of structures either as normally built or without adequate information to know whether the structures being compared had comparable thermal performance. Consequently, the results of these studies should be used with caution. Nonetheless, it is notable that in almost all cases these studies found wood-based systems to have lower embodied energy (Milne and Reardon 2004; Lawson 1996; BRE 2004; Howard, Edwards, and Anderson 2004; Anderson and Howard 2000; Buchanan and Levine 1999; Eriksson 2003; AFIA 2003; Sakai, Urushizaki, and Nakahara 1997; Meil 1995; Baird, Alcorn, and Haslam 1997; Trusty and Meil 1999; Crane Environmental 1999; Arima 1993; Petersen and Solberg 2005). In one case, steel-based systems were suggested to be superior with respect to embodied energy, although this finding was based on a comparison of data from two other studies that may have involved different assumptions and boundary conditions (de Spot 1999).

In summary, studies of alternative building systems demonstrate the importance of residential heating and cooling to life cycle energy requirements and CO_2 emissions associated with residential structures. For systems with comparable heating and cooling requirements, however, wood-based building systems are generally agreed to contain lower embodied energy and CO_2 emissions than steel-, concrete-, and brick-based systems.

It is important to note that none of the U.S.-based studies identified in the literature examined the impacts of different building materials on all of the carbon pools in the building products value chain. A number of U.S. studies examined the fate of carbon in products during use and at the end of life, but they did not examine the carbon implications in the forest. The U.S. study that most carefully examined forest carbon is the CORRIM study (Lippke et al. 2004; Perez-Garcia et al. 2005b), but the CORRIM study did not consider the fate of carbon at the end of life. Several European studies of substitution effects have also examined forest carbon, but none have included end-of-life carbon pools that are representative of those in the U.S. (e.g., Gustavsson and Sathre 2006). The work described below includes all carbon pools in the value chain as they exist in the U.S.

4.0 APPROACH TO ESTIMATING POTENTIAL SUBSTITUTION EFFECTS IN THE U.S.

Attempts have been made to estimate the potential impacts of substituting one type of building system for another in, for instance, Finland, New Zealand, the EU, and the world (Pingoud and Perala 2000; Buchanan and Levine 1999; Eriksson 2003). None of the studies identified in this review attempted such estimates for the U.S. The results to date of the Consortium for Research on Renewable Industrial Materials (CORRIM) program, however, provide much of the information needed to develop these estimates (see detailed information at www.corrim.org and summary reports in Lippke et al. 2004; Perez-Garcia et al. 2005a, 2005b; Puettmann and Wilson 2005). The CORRIM research is useful because it is specific to U.S. building practices and climates. It includes extensive documentation, allowing the underlying data to be used (www.corrim.org). In addition, the CORRIM study specifically includes carbon sequestration within the scope of the assessment—an important element of the substitution effects of wood-based construction materials for non-wood materials. For these reasons, the CORRIM work was selected as the basis for examining the potential impacts on energy and CO_2 emissions of using wood-based residential construction methods.

It was necessary to expand the scope of the assessment conducted by CORRIM in two areas. First, an end-of-life module was developed to examine the energy, carbon, and greenhouse gas impacts associated with building materials at the end of a structure's life. Second, the framework and data used to examine forest and forest product carbon were changed to examine cumulative national-level effects over long periods.

5.0 DESCRIPTION OF THE CORRIM ASSSESSMENT

In 1996, the Consortium for Research on Renewable Industrial Materials (CORRIM)[4] was formed by 15 research institutions as a nonprofit entity that would undertake research on the use of wood as a renewable material. In 1998, CORRIM published a 22-module research plan and protocol (CORRIM 1998) to develop a life cycle assessment (LCA) for residential structures and other wood uses. The research plan required development of a complete life cycle inventory (LCI) of all environmental inputs and outputs from forest regeneration through product manufacturing, building construction, use, maintenance, and disposal.

CORRIM later published a summary and a Phase I Interim Report on the progress with a provisional LCI database to evaluate the environmental performance of building materials (Bowyer et al. 2001, 2002). The report also contained an LCA for residential structures focusing on energy use, air and water emissions, global warming potential (GWP), and solid waste production from resource extraction through construction. These five key performance indices were chosen to simplify the assessment. The Phase I Final Report, along with 15 modules containing detailed information on the CORRIM assessment and input data, have since been issued and are available for download (http://www.corrim.org/reports/). The results were summarized by Lippke et al. (2004).

The CORRIM research involved collection of primary data on all inputs and outputs associated with the production of lumber, plywood, oriented strand board (OSB), glulam, laminated veneer lumber (LVL), and I-joists. The data were collected using surveys of a range of mill types within the processing regions. The two primary U.S. wood processing regions studied were the Pacific Northwest (PNW) and the Southeast (SE). Recent studies of harvesting activities (secondary data) were used to gather forest regeneration, growth, and log production data.

CORRIM constructed LCIs from the collected data using SimaPro[5] software for each wood product. CORRIM then incorporated the LCIs into the Athena™ Environmental Impact Estimator (EIE)[6] model. The EIE also contains more than 50 assemblies that incorporate combinations of concrete, steel, and wood products LCIs for materials used in construction. CORRIM developed representative bills of construction materials based on the architectural designs for the representative residential structures. The EIE model generates a bill of materials and identifies LCI measures based on the design developed for each house.

To study the use of alternative building materials, typical residential designs were used for each climate type: a) a wood frame design and a steel frame design for the cold Minneapolis, Minnesota, climate; and b) a wood frame design and a concrete design for the hot, humid Atlanta, Georgia, climate. The

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[4] The description of the CORRIM analysis was drawn primarily from Lippke et al. 2004.

[5] SimaPro is a professional software data analysis package designed for life cycle analysis, licensed from Pré Consultants, Amersfoort, Netherlands.

[6] The Athena Sustainable Materials Institute, Ottawa, Canada, is a cooperator with CORRIM on its research and provided software for simulating building construction to generate LCI and environmental impact measures.

configuration of the structures developed by CORRIM was based on the most recent surveys conducted by the U.S. Census Bureau and the National Association of Home Builders (NAHB 2005). The average size of a new house in the United States is about 2225 square feet. The designs analyzed by CORRIM reflected local building codes with matched thermal properties, including building envelope designs.

The Minneapolis structure was designed as a two-story building with a basement, representing typical construction in the area. The total floor area of the structure was 2062 square feet. The base case design consisted of solid wood framing members (2-by-6-inch wall studs) except for the floor joists, which were composite I-joists. Other wood structural components consisted of OSB sheathing for roof, walls, and floor, and pre-engineered roof trusses for the roof system. Alternative wood materials studied were a) solid wood joists in place of I-joists; and b) plywood in place of OSB. As a non-wood alternative, steel floor joists and wall studs were substituted for wood I-joists and 2-by-6 wall studs, with an extra layer of exterior insulation to meet code requirements.

The wood and concrete Atlanta structures were a slab-on-grade single story design with an area of 2153 square feet. The wood design incorporated 2-by-4 inch wood wall studs. The concrete design consisted of a concrete slab floor, a concrete block wall system with furred-out wood stud walls, and a wood truss roof with OSB sheathing.

Flows of materials used in residential houses and associated environmental burdens were tracked by CORRIM using the completed LCIs for forest resources, wood products, and associated transportation data. These data were introduced into the Athena EIE model, which integrates the various combinations of products into functionally equivalent assemblies and completed structures, and reports five environmental performance indices to summarize the many output measures for the LCI on the building shell. Flows of mass, energy, and emissions are reported for extraction and manufacturing activities, transport to site, and construction activities. So, for example, the activities associated with construction (i.e., activities in which building materials and energy are consumed and solid wastes and emissions are produced) include those activities involved in producing building materials as well as those associated with the construction activities themselves.

6.0 ADDITIONAL ANALYTICAL WORK NEEDED TO DEVELOP NATIONWIDE ESTIMATES

Several additional steps were required to develop nationwide estimates from the CORRIM studies. The most important of these are described here.

The CORRIM assessment follows a single plot of managed forest over the lifetime of a house. The analysis described herein, however, is based on calculations performed over a large land base of sustainably managed forest so that it can be assumed that the forest carbon stocks are, for all practical purposes, constant.[7] The basis for the nationwide assessment is the production of a specified number of houses annually for a long period, usually 100 years. This is done to capture the cumulative long-term and large-scale impacts associated with using renewable wood resources. Specifically, this framework allows examination of the cumulative impacts of using a forested land base, where carbon stocks are essentially constant, to continuously convert atmospheric carbon into building materials that displace energy- and carbon-intensive alternatives and contribute to a growing stock of stored carbon in housing.

The modeling of substitution effects requires an assessment of the fate of what has been termed "surplus forest" (Gustavsson and Sathre 2006). Surplus forest is the forest that is no longer required for wood

[7] The USDA Forest Service reports that carbon stocks on private timberland are increasing by more than 200 million tonnes of carbon per year, so an assumption of constant carbon stocks probably understates the carbon benefits of the forest products industry value chain (Smith, Woodbury, and Heath 2004).

production when non-wood building materials are substituted. Surplus forest is not considered in some studies. Other studies have modeled forest growth under an alternative "no harvest" scenario (e.g., Lippke et al. 2004; Perez-Garcia et al. 2005b) or have assumed that carbon stocks in surplus forest will increase by a specified amount (e.g., by 50% in 100 years, as in Gustavsson and Sathre 2006). In at least two studies of substitution effects the benefits of using surplus forest to sequester carbon have been compared to the benefits of using it to supply biomass fuels (Gustavsson and Sathre 2006; Gustavsson, Pingoud, and Sathre 2006). In both cases the production of biomass fuels has proven to provide greater carbon benefits than using forests to sequester carbon. This result is generally consistent with earlier work done on the topic, although it has been found that in some circumstances the use of forests for carbon sequestration may be preferred (Marland and Schlamadinger 1995, 1997; Schlamadinger et al. 1997; Schlamadinger and Marland 1996).

For the estimates described in this report it is assumed that 80% of the surplus forest remains in forest and continues to accumulate carbon to a maximum carbon capacity, where it remains indefinitely. The details of the calculations are described in Appendix B. It should be recognized, however, that considerable uncertainty is associated with assumptions about what happens to forests if the demand for wood products is reduced.

The apparent carbon benefits of construction methods that use less wood will be diminished as some of the sequestration benefits attributed to the surplus forest are lost due to "leakage" (i.e., increased sequestration will be partially offset by losses in forest carbon through other means). Market effects associated with depressed demand and prices for wood are of critical importance in determining leakage. Over time, if reduced demand diminishes the economic incentive to keep land in managed forests it will become more likely that the land will be used for other purposes. Many of these other uses involve removing much or all of the forest biomass, resulting in permanent losses of stored carbon. In addition, shifts in the demand for building materials can affect the demand and supply conditions for other forest products. A reduced demand for building materials, for instance, may cause a shift in management from saw timber production to pulpwood, which can result in shorter rotation times and reductions in forest carbon. Unmanaged forests may also be more prone to damage by insects and catastrophic carbon loss in fires. Unfortunately, it is difficult to quantify these effects. In this study, all the various types of carbon leakage associated with forest preservation are dealt with by assuming that 20% of surplus forest will be converted to non-forest. The basis for this assumption is explained later in this report. Because the assumption is highly uncertain, the effects of a range of leakage assumptions are examined in a sensitivity analysis described below.

Instead of assuming a value for leakage, an alternative approach to examining the land use and carbon storage implications of a large-scale shift in residential construction practices would be to model a gradual erosion in market share for wood-based systems using a framework capable of addressing the probable market-based impacts on forest management and land use practices over time. This was not possible, however, within the time and resource constraints of this study.

Although the estimates in this report are based on CORRIM carbon data for products in use, the data are handled differently than in the CORRIM assessment. The nationwide analysis described herein assumes a constant annual output of products and a first order decay equation with generally accepted product half-lives to estimate how much of the carbon in various annual product cohorts (i.e., groups of products of the same age) remains in use over time. This approach is patterned on that used by the U.S. government to prepare the annual forest products carbon inventory in that it follows each year's production over time based on time-in-use equations and accepted product half-lives (USEPA 2005). The method is described in detail elsewhere (IPCC 2003). The cumulative amount of carbon remaining in use across all products is calculated for every year into the future.

In addition, an end-of-life module has been added to the CORRIM assessment. Based on time-in-use information, the amounts of carbon leaving the products in use pool annually are calculated for each cohort and summed. The base case scenario assumes that all discarded material is landfilled. However, other fates for demolition debris are investigated in the sensitivity analysis (e.g., recovered and recycled or recovered and burned for energy production). In addition, some of the building material for new construction is assumed to be discarded at the construction site and managed in the same way as end-of-life waste.

Carbon sequestration in the landfill is estimated based on the approach used by the U.S. government to develop the national inventory of harvested wood products carbon in landfills (USEPA 2005). The method is described by the Intergovernmental Panel on Climate Change (IPCC 2003), and the specific parameter values are primarily from EPA (USEPA 2002). Some of the carbon is assumed to remain in the landfill indefinitely and the rest decays according to first order kinetics. The calculations are repeated annually for all cohorts (a cohort consists of all waste deposited in a given year) and for each year into the future so that at any point in time one can calculate the carbon stocks in landfills.

The end-of-life analysis also estimates methane emissions from discarded wood-based building materials in landfills. EPA information is used to calculate the amount of methane generated from the decay of wood products in landfills and to estimate the amount of methane released to the atmosphere. A detailed description of how landfill deposition rates, carbon sequestration, and methane emissions were estimated is provided in Appendix A.

The amounts of methane released by wood-based material are larger than those in the non-wood cases, representing a greenhouse gas advantage for the non-wood alternatives. The advantage for non-wood products would be less if it were assumed that some of the landfill gas was being burned to displace fossil fuels, but at present it is assumed that collected methane is burned and then vented as carbon-neutral CO_2.

The end-of-life assessment sensitivity analysis also considers the impacts of burning demolition and construction debris for energy. The displaced fossil fuel is assumed to be natural gas.

7.0 DESCRIPTION OF BASE CASE SCENARIO

The assumptions herein are incorporated into the base case scenario for GHG emissions associated with wood-based and alternative construction techniques.

- When non-wood building materials are used and the production of wood-based building materials is reduced, it is assumed that the co-products associated with wood-based building materials will continue to be produced at some other location in the same quantities as before the production of wood-based building materials was reduced.

- Eighty percent of surplus forest[8] is assumed to remain forested and not be managed for wood production. This forest is allowed to grow to steady-state maturity with high carbon storage and is never harvested or cut for other purposes. The remaining 20% is assumed to be cleared of forest to accommodate other uses (e.g., agriculture or other development). A land use-based leakage rate of 20% is near the lower end of the range suggested by the work of Murray, McCarl, and Lee (2002, 2004). Carbon accumulation in the non-harvested "preservation forest" is modeled using Forest Inventory and Analysis (FIA) data as compiled and summarized by the USDA Forest Service Carbon On-Line Estimator (COLE; http://www.fs.fed.us/ne/durham/4104/products/cole.html) (Proctor et al.

[8] Surplus forest is forest that is no longer needed for wood production due to decreased consumption of wood when non-wood alternatives are used (Gustavsson and Sathre 2006).

2005) for the two regions included in the CORRIM study. A description of the approach used to characterize carbon accumulation is included in Appendix B.

- Residual construction materials and demolition debris are not recovered for recycling (however, they may be landfilled or burned for energy recovery, scenarios investigated in the sensitivity analysis).
- At the beginning of the analysis period, 49% of the debris placed in landfills is assumed to go to landfills equipped with systems for collecting and destroying methane generated from decaying wood materials. This is consistent with current practice (USEPA 2002). This percentage is assumed to increase linearly to 75% by the end of the analysis period.
- In landfills equipped with covers and gas collection systems, 75% of generated landfill gas is collected, whereas 10% of the uncollected landfill gas becomes oxidized to carbon dioxide in the landfill cap material. These assumptions are consistent with the default assumptions used by EPA in its assessments of landfill gas releases (USEPA 2002).

Two building technique comparisons based on the CORRIM assessment were investigated. The first comparison was between same sized houses (2062 square feet floor area, two-story) in Minneapolis, one built using a wood frame design and the other built using a steel frame design. Details of the house designs are provided in CORRIM Module J, Table 2.2. The other building comparison was between same sized houses (2153 square feet, single-story) in Atlanta, one built using wood-based walls and the other built using concrete block walls (further house design details are in CORRIM Module J, Table 2.3). The accuracy of the estimates made in this report would be improved by additional research involving other regions of the country and product substitutions not examined in the CORRIM work to date.

8.0 RESULTS

Greenhouse gas (GHG) emissions and energy impacts were modeled over a 100-year period on the basis of the construction of a constant annual output of homes, usually 1 or 1.5 million homes per year.[9] The analysis incorporated a 100-year house half-life (Skog and Nicholson 1998), with all construction and demolition debris landfilled (versus recycled or recovered for other purposes). The GHG considerations included embodied emissions (from fuels burned in creating and transporting the materials and energy needed to construct the homes); carbon sequestration in the forest, in wood products in use, and in wood products in landfills; and emissions of methane from decaying wood debris in landfills, all expressed as equivalent amounts of carbon dioxide. The net energy analysis considered embodied energy consumption (from fuels consumed in creating and transporting construction materials and in actual construction of the home). Maintenance activities were not included. Net energy is presented both in terms of total energy and as non-renewable energy (non-renewable energy equals total energy minus hydro and biomass energy).

Tables 8.1 and 8.2 show the results at the end of 100 years, while Figures 8.1 and 8.2 show the changes in emissions and sequestration over time. Tables 8.1 and 8.2 include results presented in terms of cumulative differences (over a 100-year period) between the building techniques (i.e., emissions from steel frame house construction minus those from wood frame house construction in the Minneapolis case and emissions from concrete wall house construction minus those from wood wall house construction in the Atlanta case). GHG emission differences (including methane emissions from landfills, with one tonne of methane equivalent to 21 tonnes of carbon dioxide) are presented in terms of carbon dioxide equivalents (CO_2 Eq.) in units of million metric tonnes. Sequestration differences are also expressed in terms of million metric tonnes of CO_2 Eq. (1 tonne of carbon is equivalent to 3.67 tonnes of CO_2 Eq.). Energy differences are expressed in units of billions of gigajoules.

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[9] Since 2000, single family residence housing starts have averaged about 1.5 million per year, but in the 1990s averaged about 1.1 million per year (NAHB 2005; United States Census Bureau 2006).

Table 8.1 Minneapolis (PNW) Design Cumulative Emission Differences (millions of tonnes CO_2 Eq.) and Cumulative Net Energy Impacts (billions of gigajoules) [after 100 years for 1 million housing starts per year (based on a 100-year house half-life)]

		Wood Frame	Steel Frame	Difference[c] (steel – wood)
Wood content of house	(% by mass)[a]	15.1	7.4	-7.7
Embodied emissions	(10^6 t CO_2 Eq.)	3705	4683	977.9
Product sequestration	(10^6 t CO_2 Eq.)	-1367	-737.5	629.6
Forest sequestration[b]	(10^6 t CO_2 Eq.)	0	-1310	-1310
Landfill sequestration	(10^6 t CO_2 Eq.)	-553.9	-298.8	255.1
Landfill methane	(10^6 t CO_2 Eq.)	279.3	150.7	-128.7
Net emissions	(10^6 t CO_2 Eq.)	2063	2487	423.6
Net energy (total energy)	(10^9 GJ)	65.06	76.36	11.30
Net energy (non-renewable energy)	(10^9 GJ)	62.17	74.80	12.63

[a] Lippke et al. 2004
[b] assuming loss of 20% of surplus forest; this is near the lower end of leakage range suggested by Murray, McCarl, and Lee 2002, 2004
[c] negative number indicates emissions are less for steel frame case than for wood frame case

Table 8.2 Atlanta (SE) Design Cumulative Emission Differences (millions of tonnes CO_2 Eq.) and Cumulative Net Energy Impacts (billions of gigajoules) [after 100 years for 1 million housing starts per year (based on a 100-year house half-life)]

		Wood Wall	Concrete Wall	Difference[c] (conc. – wood)
Wood content of house	(% by mass)[a]	10.1	7.8	-2.3
Embodied emissions	(10^6 t CO_2 Eq.)	2137	2800	663.7
Product sequestration	(10^6 t CO_2 Eq.)	-1082	-891.9	189.9
Forest sequestration[b]	(10^6 t CO_2 Eq.)	0	-37.85	-37.85
Landfill sequestration	(10^6 t CO_2 Eq.)	-438.3	-361.3	76.94
Landfill methane	(10^6 t CO_2 Eq.)	221.1	182.3	-38.80
Net emissions	(10^6 t CO_2 Eq.)	837.6	1692	853.9
Net energy (total energy)	(10^9 GJ)	39.79	46.11	6.32
Net energy (non-renewable energy)	(10^9 GJ)	37.87	44.33	6.45

[a] Lippke et al. 2004
[b] assuming loss of 20% of surplus forest; this is near the lower end of leakage range suggested by Murray, McCarl, and Lee 2002, 2004
[c] negative number indicates emissions are less for concrete wall case than for wood wall case

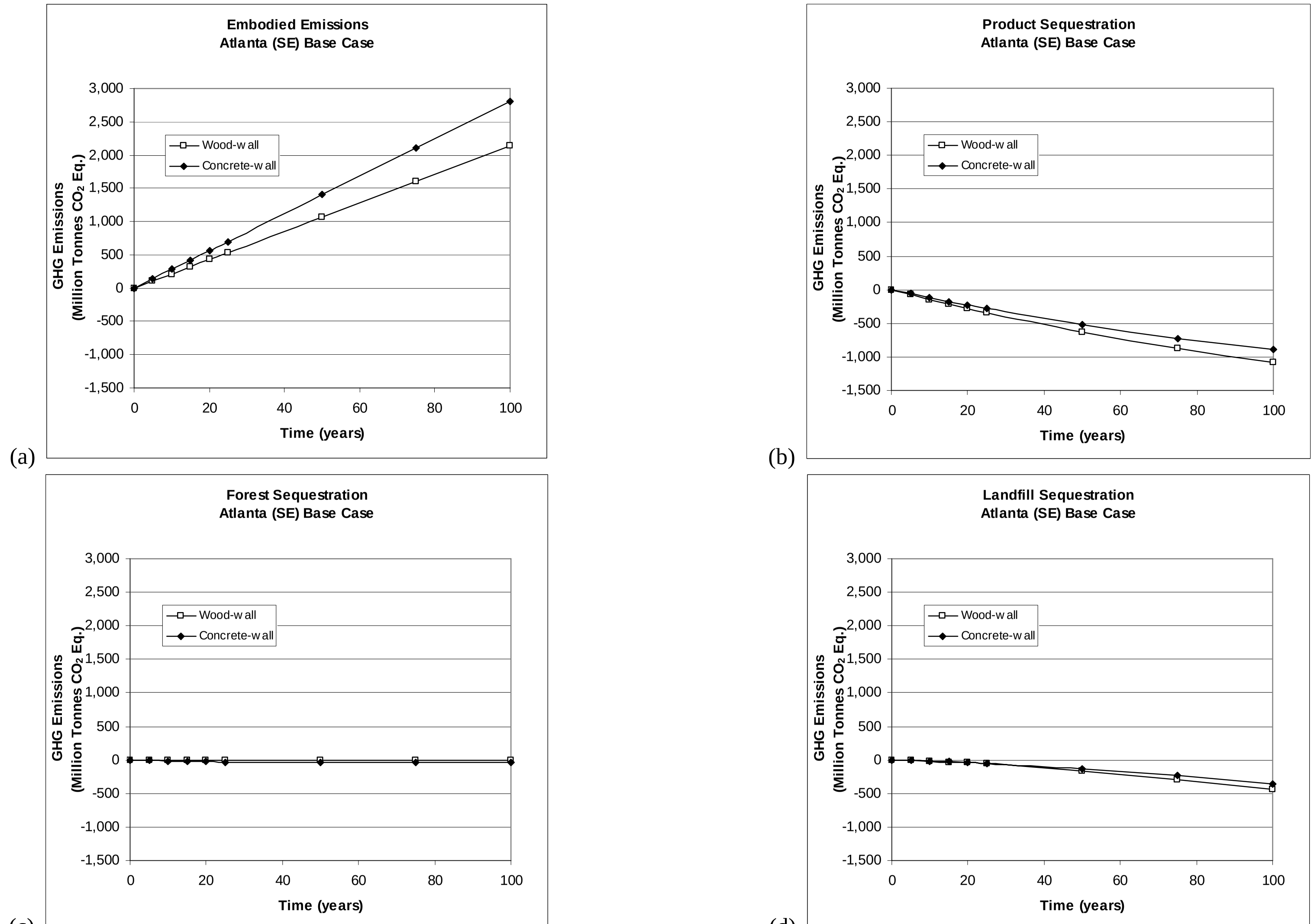

Figure 8.1 a through d. Emissions, Sequestration (carbon removed from the atmosphere – i.e., negative emissions), and Energy Consumption Over Time, Atlanta (SE) Case

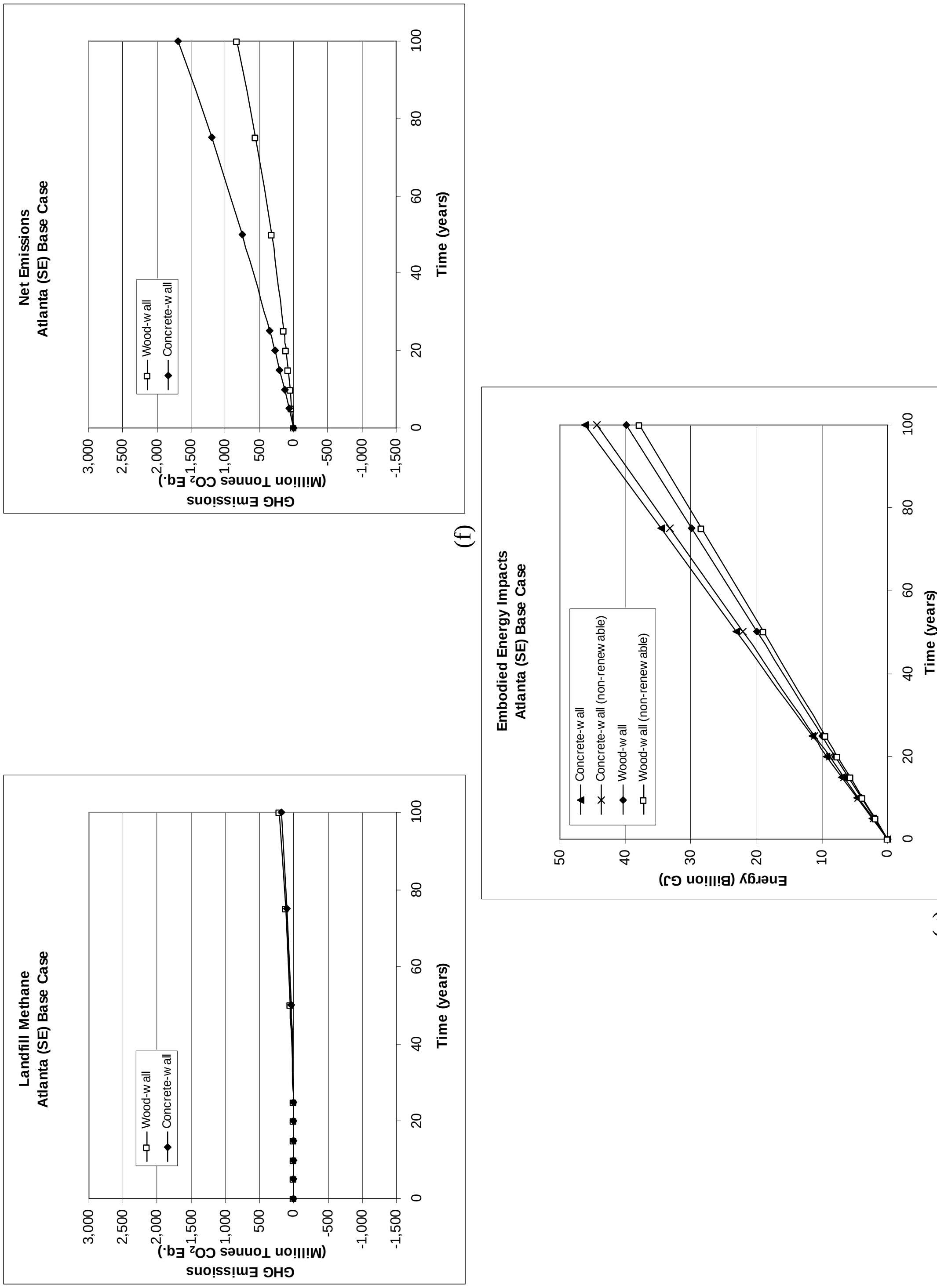

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Figure 8.1 e through g. Emissions, Sequestration (carbon removed from the atmosphere – i.e., negative emissions), and Energy Consumption Over Time, Atlanta (SE) Case

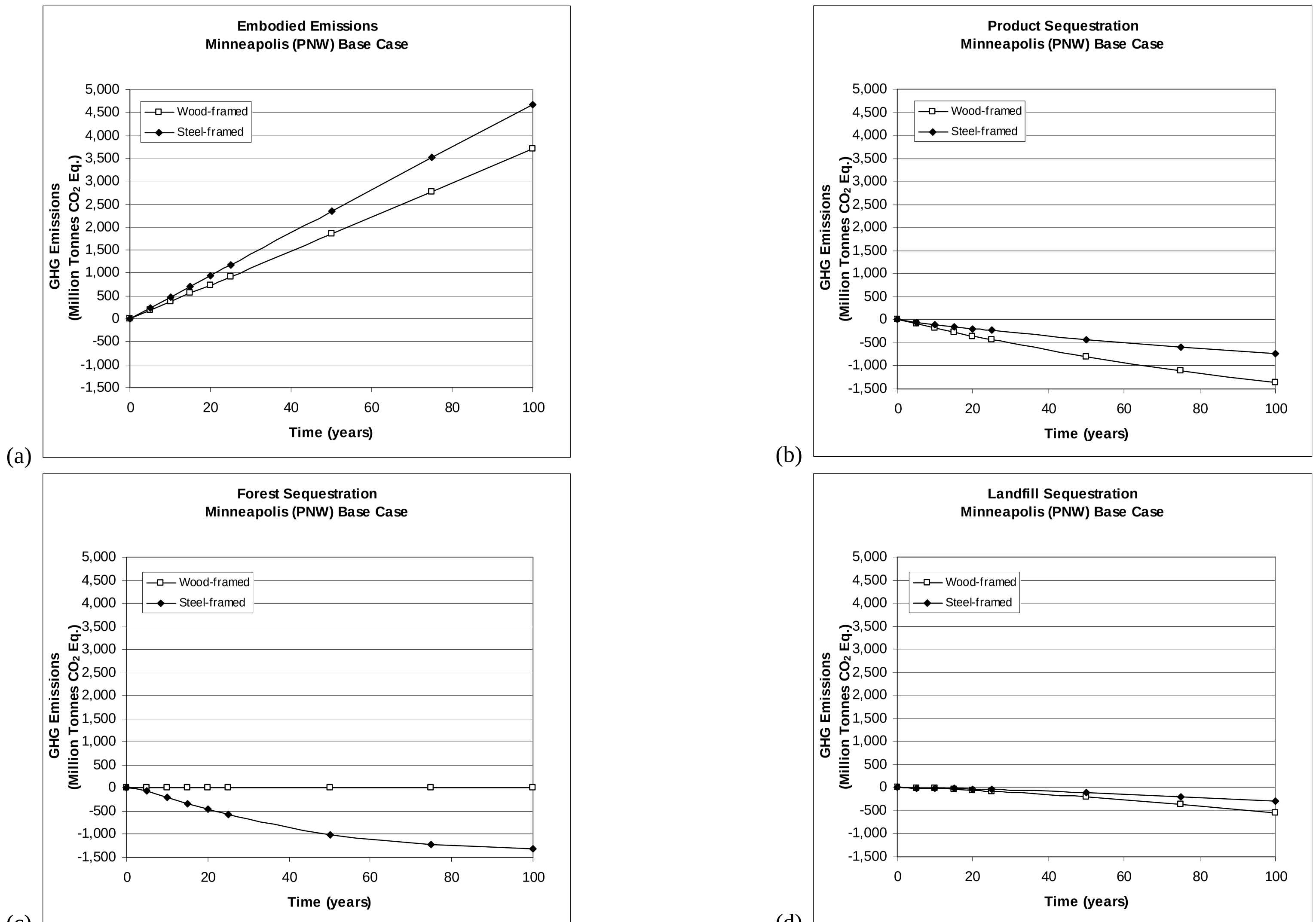
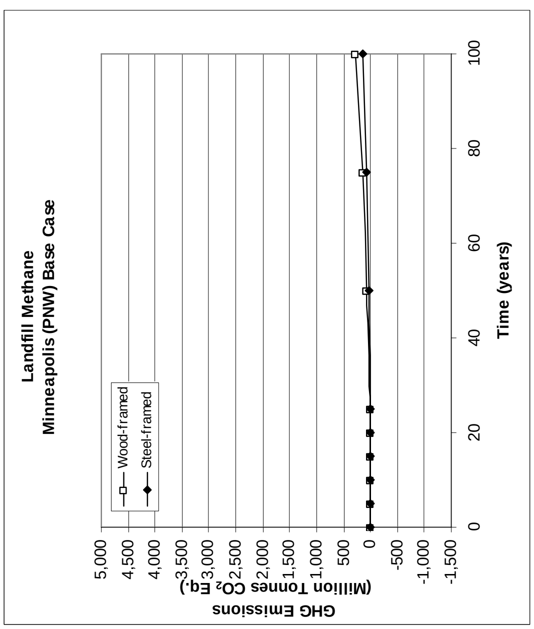


Figure 8.2 a through d. Emissions, Sequestration (carbon removed from the atmosphere – i.e., negative emissions), and Energy Consumption Over Time, Minneapolis (PNW) Case



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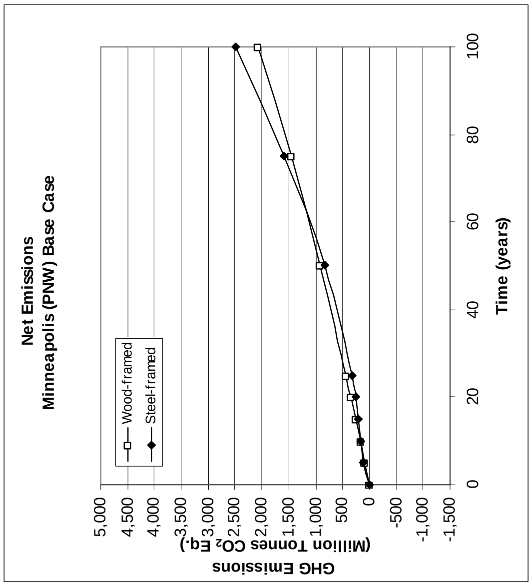

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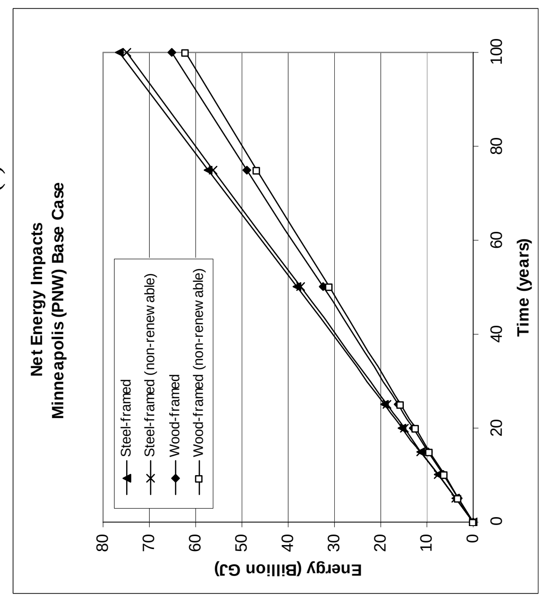

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Figure 8.2 e through g. Emissions, Sequestration (carbon removed from the atmosphere – i.e., negative emissions), and Energy Consumption Over Time, Minneapolis (PNW) Case

9.0 DISCUSSION

In considering the effects of substituting wood for non-wood, it is important to realize that the amount of wood in the Atlanta house is only increased from 7.8% to 10.1% of the total mass and the amount in the Minneapolis house is only increased from 7.4% to 15.1% of the total mass (Lippke et al. 2004). Thus, a relatively small fraction of the mass in a residential structure can represent a significant opportunity for improving the structure's embodied energy and greenhouse gases.

9.1 Embodied Emissions

The results presented in Figures 8.1 and 8.2 illustrate that the difference in embodied GHG emissions between construction techniques increases linearly over time as houses are constructed. Embodied emissions are a function of the number of homes built and the emissions per home (from the CORRIM assessment). The results indicate that annual construction of one million steel frame houses is associated with greater embodied GHG emissions than construction of the same number of wood frame houses (approximately 978 million metric tonnes CO_2 Eq. difference over the 100-year analysis period). Similar results were obtained for the concrete wall versus wood wall houses in the Atlanta case (a cumulative difference of approximately 664 million metric tonnes CO_2 Eq. greater GHG emissions for the non-wood construction method for a million housing starts per year over a 100-year period). The GHG emissions difference is greater for the Minneapolis case due to the greater degree of substitution in the steel frame house than in the concrete wall house of the Atlanta case, and due to the high embodied emissions associated with steel.

9.2 Product Sequestration

More carbon is stored in houses built using wood-based construction techniques than in steel- or concrete-based techniques. Product sequestration results are influenced by the assumed house half-life, with longer half-lives resulting in more carbon stored in products in use. There is a greater difference in product sequestration between wood-based construction and steel-based systems (about 630 million metric tonnes CO_2 Eq. for 100-year house half-life and a million housing starts per year) than between the wood- and concrete-based systems evaluated (approximately 190 million metric tonnes CO_2 Eq. for house half-life of 100 years). This is because there is more wood involved in the substitution for the steel frame (Minneapolis) house. In the Atlanta example the additional wood used in the wood-based house represented only 2.3% of the mass of the house, while in the Minneapolis example the additional wood used in the wood-based house represented 7.7% of the mass.

These results reflect the fact that wood-based building materials store biomass carbon, while alternative building materials do not.[10] Because sequestration of carbon is the opposite of an emission, the positive differences in product sequestration between the construction techniques reflect greater sequestration (i.e., lower emissions) of the wood-based construction techniques.

9.3 Forest Sequestration

The alternative building materials (steel or concrete) are associated with increased sequestration of carbon in surplus forest. In this analysis, the forest land base was defined by forest production rates and wood requirements of the conventionally constructed houses. Houses built using non-wood materials incorporate less wood; therefore, less forest land is needed to provide the construction

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[10] This study did not consider the long-term uptake of atmospheric carbon dioxide by concrete, i.e., "carbonization." Carbonization of concrete is not usually encouraged because it can ultimately lead to corrosion of reinforcing steel used in concrete construction. Under some circumstances, however, this uptake can offset enough of the CO_2 released in lime production to represent a significant component of the carbon profile of concrete structures (Borjesson and Gustavsson 2000).

materials. The difference in required forest land is assumed to comprise surplus forest in which active management for forest products is assumed to terminate and the forest is allowed to accumulate carbon as trees grow to maturity. Under the baseline assumptions used in this study, 20% of the preservation forest would be cleared for other uses (e.g., agriculture or development, as the demand for wood building materials declines, representing a form of land use leakage). The forest sequestration difference between construction techniques is greater for the Minneapolis case (steel frame versus wood frame, with a sequestration difference of approximately -1310 million metric tonnes CO_2 Eq. for one million housing starts per year over 100 years) than for the Atlanta case (concrete wall versus wood wall, with a difference of approximately -38 million metric tonnes CO_2 Eq.). The difference is due to the greater degree of alternative building material substitution for wood in the Minneapolis case and the much greater carbon storage capacity of the PNW forests assumed to supply wood for construction of houses in Minneapolis. The PNW forests modeled in the analysis are some of the highest carbon capacity forests in the U.S. and therefore represent the upper end of the range of potential benefits associated with preservation of surplus forest.

9.4 Landfill Sequestration

As houses age and are maintained or demolished, much of the construction material is disposed of in landfills. Furthermore, as new houses are built or existing houses are renovated or expanded, a portion of the material used in fabrication is disposed of in landfills. Therefore, construction and demolition of houses typically result in debris being placed in landfills. Because wood decays very slowly in landfills, the carbon in landfilled wooden building materials tends to accumulate, contributing to long-term sequestration. Houses constructed from wood-based materials incorporate more wood than houses built using non-wood alternative materials, and therefore are associated with more wood-based construction and demolition debris. The results in Tables 8.1 and 8.2 and Figures 8.1 and 8.2 illustrate that wood-based houses are associated with a greater degree of carbon sequestration in landfills than houses built using non-wood materials. Furthermore, the difference in landfill sequestration between the different construction techniques is more pronounced in the Minneapolis case than in the Atlanta case due to the greater building material substitution occurring in the Minneapolis case. In the Minneapolis case (steel frame houses versus wood frame houses for one million housing starts per year over a 100-year period), landfill sequestration differences between construction techniques are predicted to be about 255 million metric tonnes CO_2 Eq. In the Atlanta case the corresponding landfill sequestration difference is about 77 million metric tonnes CO_2 Eq.

9.5 Landfill Methane

Methane is generated as cellulosic materials degrade in landfills, where conditions are typically anaerobic. Methane is a potent GHG with a global warming potential (GWP) of 21, indicating that a pound of methane is equivalent, from a global warming perspective, to 21 pounds of carbon dioxide. Methane can also be used as a fuel for energy production. In order to capture landfill-generated methane rather than allowing it to vent to the atmosphere, some landfills are designed with covers and landfill gas combustion systems. This analysis incorporates the premise that 49% of current landfills receiving construction and demolition debris are equipped with these covers and that the portion of landfills with collection/combustion systems will increase to 75% by the end of the analysis period. The landfill methane emission estimates in Tables 8.1 and 8.2 indicate that the non-wood building material techniques are associated with lower landfill methane emissions than wood-based, conventionally built houses due to the greater amount of wood debris disposal from wood-based houses.

9.6 Net Emissions

The net emission difference results presented in Tables 8.1 and 8.2 and Figures 8.1 and 8.2 were calculated by adding the individual component GHG differences between wood-based and non-wood construction techniques (sum of embodied emissions; product, forest, and landfill sequestration; and landfill methane emissions). Wood-based construction techniques are associated with lower net GHG emissions than the alternative material construction techniques. For the Atlanta design, the cumulative net GHG emissions difference is approximately 854 million metric tonnes of CO_2 Eq. for one million housing starts per year over a 100-year period. This represents a reduction of approximately 50% in net emissions for the wood-based house compared to the concrete-based house. For the Minneapolis design, the net GHG emissions difference of 424 million metric tonnes CO_2 Eq. represents a reduction of about 20% in net emissions for the wood-based system compared to the steel-based system. The benefits are less in the Minneapolis case primarily because of the assumptions regarding forest carbon sequestration.

Only a small fraction of the building materials needs to be changed to accomplish these improvements. In the Atlanta example, the additional wood used in the wood-based house represented only 2.3% of the mass of the house, while in the Minneapolis example, the additional wood used in the wood-based house represented 7.7% of the mass. There are additional opportunities for substituting wood for non-wood building materials that would probably increase these GHG differences.

9.7 Embodied Energy

Embodied energy, computed as total embodied energy and as non-renewable embodied energy (total minus hydro and biomass), increases linearly as the number of houses increases. The difference in embodied energy between the wood and concrete wall houses (Atlanta designs) over the 100-year analysis period, based on 1 million housing starts per year, is 6.32 billion GJ (total energy) or 6.45 billion GJ (non-renewable energy). For the Minneapolis designs (wood versus steel frame houses), the difference in embodied energy between the construction techniques is 11.3 billion GJ (total energy basis) or 12.6 billion GJ (non-renewable energy basis).

These embodied energy differences correspond to an approximate 15% greater energy demand associated with construction of concrete wall houses compared to that associated with wood wall houses (Atlanta designs). The embodied energy differences between steel frame and wood frame houses (the Minneapolis designs) is slightly greater, with about 16% more total energy and 19% more non-renewable energy required to construct steel frame houses than required to construct wood frame houses. These results are consistent with the results from Lippke et al. (2004), which is expected because the energy impacts are associated primarily with differences in embodied energy and the data for embodied energy were from the CORRIM study described by Lippke et al.

10.0 SENSITIVITY ANALYSIS

A sensitivity analysis was performed in order to characterize the relative importance of the various input parameters on the overall results of the analysis. The sensitivity analysis also illustrates how inaccuracies or inappropriate assumptions may have affected the calculated GHG and energy benefits of using wood-based building materials rather than non-wood alternative materials. Tables 10.1 and 10.2 present the results of the GHG impacts sensitivity analysis for the two scenarios investigated in this study, steel frame versus wood frame houses (Minneapolis case) and concrete wall versus wood wall houses (Atlanta case), respectively. Tables 10.3 and 10.4 present the results of the energy impacts sensitivity analysis (performed on total energy, not non-renewable energy).

Table 10.1 GHG Impacts Sensitivity Analysis Results for Minneapolis (PNW) Case (steel frame vs. wood frame houses)

Parameters Evaluated	(base value shown)	Variation in Parameter (test value in parentheses)	Impact on Result Absolute (tonne CO_2 Eq.) (base case result = 423.6)	Impact on Result Percent
Period of analysis – years	(100)	+150% (250 years)	2292	441
Land-use leakage – fraction	(0.2)	-50% (0.1)	220.2	-48
		+350% (0.9)	1734	309
Co-product leakage – fraction	(1.0)	-25% (0.75)	-8.0	-102
Rate of carbon accumulation in forest (615 tonne carbon/ha asymptote)		-25% (461 tonne carbon/ha asymptote)	860.6	90
		+25% (768 tonne carbon/ha asymptote)	60.0	-86
Landfill methane generation parameters (57% permanent storage, .03/yr rate const.)		(50% permanent storage, .04/yr rate const.)	356.3	-16
		(85% permanent storage, .02/yr rate const.)	577.6	36
Half-life of house – years	(100)	-50% (50 years)	328.4	-22
		+50% (150 years)	463.6	9
Recovery and recycling of construction/demolition debris – fraction	(0.0)	(0.5)	360.4	-15
Energy recovery from non-recycled construction/demolition debris – fraction	(0.0)	(0.25)	425.1	0.4
		(1.0)	429.6	1.4

NOTE: Results are expressed as the net emission difference between steel and wood frame houses in millions of tonnes carbon dioxide equivalents over the analysis period (positive values represent higher emissions for steel frame houses).

Table 10.2 GHG Impacts Sensitivity Analysis Results for Atlanta (SE) Case (concrete wall vs. wood wall houses)

Parameters Evaluated	(base value shown)	Variation in Parameter (test value in parentheses)	Impact on Result Absolute (tonne CO_2 Eq.) (base case result = 853.9)	Impact on Result Percent
Period of analysis – years	(100)	+150% (250 years)	1990	133
Land-use leakage – fraction	(0.2)	-50% (0.1)	841.1	-1.5
		+350% (0.9)	891.8	4.4
Co-product leakage – fraction	(1.0)	-25% (0.75)	851.5	-0.3
Rate of carbon accumulation in forest	(85.1 tonne carbon/ha asymptote)	-25% (63.9 tonne carbon/ha asymptote)	879.5	3.0
		+25% (106 tonne carbon/ha asymptote)	828.4	-3.0
Landfill methane generation parameters	(57% permanent storage, .03/yr rate const.)	(50% permanent storage, .04/yr rate const.)	833.6	-2.4
		(85% permanent storage, .02/yr rate const.)	900.3	5.4
Half-life of house – years	(100)	-50% (50 years)	825.2	-3.4
		+50% (150 years)	865.9	1.4
Recovery and recycling of construction/ demolition debris – fraction	(0.0)	(0.5)	834.8	-2.2
Energy recovery from non-recycled construction/demolition debris – fraction	(0.0)	(0.25)	854.3	0
		(1.0)	855.2	0.2

NOTE: Results are expressed as the net emission difference between concrete and wood wall houses in millions of tonnes carbon dioxide equivalents over the analysis period (positive values represent higher emissions for concrete wall houses).

Table 10.3 Energy Impacts Sensitivity Analysis Results for Minneapolis (PNW) Case (steel frame vs. wood frame houses)

Parameters Evaluated	(base value shown)	Variation in Parameter (test value in parentheses)	Impact on Result Absolute (billion GJ) (base case result = 11.30)	Impact on Result Percent
Period of analysis – years	(100)	+150% (250 years)	28.24	150
Energy recovery from non-recycled		(0.25)	11.98	6.0
construction/demolition debris – fraction	(0.0)	(1.0)	14.03	24

NOTE: Results are expressed as the net energy consumption difference between steel and wood frame houses in billions of gigajoules over the analysis period (positive values represent higher energy consumption for steel frame houses).

Table 10.4 Energy Impacts Sensitivity Analysis Results for Atlanta (SE) Case (concrete wall vs. wood wall houses)

Parameters Evaluated	(base value shown)	Variation in Parameter (test value in parentheses)	Impact on Result Absolute (billion GJ) (base case result = 6.32)	Impact on Result Percent
Period of analysis – years	(100)	+150% (250 years)	15.80	150
Energy recovery from non-recycled		(0.25)	6.52	3.2
construction/demolition debris – fraction	(0.0)	(1.0)	7.13	13

NOTE: Results are expressed as the net energy consumption difference between concrete and wood wall houses in billions of gigajoules over the analysis period (positive values represent higher energy consumption for concrete wall houses).

10.1 Period of Analysis

In this study, the GHG benefits of the various construction techniques were evaluated over a 100-year period (one million homes built per year for 100 years). The period of analysis affects the results because any per-house difference in embodied GHG emissions increases linearly with increasing analysis period. Furthermore, several carbon storage or GHG emission components do not change linearly with time (e.g., landfill carbon storage, forest carbon storage, landfill methane emissions). To evaluate these influences, the analysis was repeated based on a 250-year period (maintaining the basis of 1 million homes built per year).

Changing the period of analysis from 100 years to 250 years increased the net GHG benefit of using wood-based construction materials by over 400% for the Minneapolis case. Expressed on an annual basis, the net GHG benefit more than doubled (from 4.2 to 9.2 million tonnes CO_2 Eq. per year). The analysis period has a very large impact on the Minneapolis case results due to the relationship used to characterize carbon accumulation in PNW forests. For short analysis periods, the lower embodied GHG emissions associated with wood frame houses are diminished by the rapid accumulation of carbon in PNW surplus forests which were assumed to result from the lower wood demand of building houses with steel framing. As the analysis period is increased, the embodied GHG benefit of wood-based houses continues to increase linearly as more houses are constructed, whereas the surplus forest tends to reach a carbon accumulation ("saturation") asymptote by 150 years and therefore does not continue to diminish the embodied emission impacts.

For the Atlanta case, changing the period of analysis increased the net GHG benefit of using wood-based construction by 133%. Averaged over the period of analysis, the net annual GHG benefit changed from 8.5 to 8.0 million tonnes CO_2 Eq. per year, a 6% decrease primarily reflecting increased methane releases from landfills in later years. Although the total GHG benefit of wood-based housing materials can change drastically when the analysis period is adjusted, the annual changes in the Atlanta case are quite modest. The difference between the concrete wall and the wood wall houses (Atlanta design) actually decreased from about 50% to 38% when increasing the analysis period from 100 to 250 years. Figure 10.1 graphically depicts the impact of analysis period on results.

The results obtained by varying the period of analysis illustrate an important point. Even in cases where non-wood construction systems show net benefits in early years of the analysis, as the period lengthens, the benefits associated with wood-based systems eventually overtake those of the non-wood systems. This is because benefits associated with allowing carbon to remain in the forest eventually saturate (the forest has a maximum carbon storage capacity), whereas the benefits associated with using the wood to construct houses do not saturate.

Embodied GHG emissions associated with house construction increased linearly at the same rate as the analysis period (i.e., by 150%). Sequestration in products in use increased by 65%. Landfill sequestration increased by 260%, while landfill methane emissions increased by almost 500% (however, in all cases landfill sequestration remained higher than landfill methane emissions expressed as equivalent amounts of carbon dioxide). Sequestration of carbon in the forest was not strongly affected by increasing the analysis period from 100 to 250 years, because the curves used to characterize carbon accumulation in the forest reach a plateau by about 150 years in the Pacific Northwest case. In the Southeast case the plateau is reached at ages less than 100 years. The impacts of different forest carbon accumulation assumptions are examined below.

Changing the period of analysis from 100 to 250 years (a 150% change) increased the total energy consumption benefit associated with the wood-based construction techniques by 150%, and had no impact on annual energy consumption.

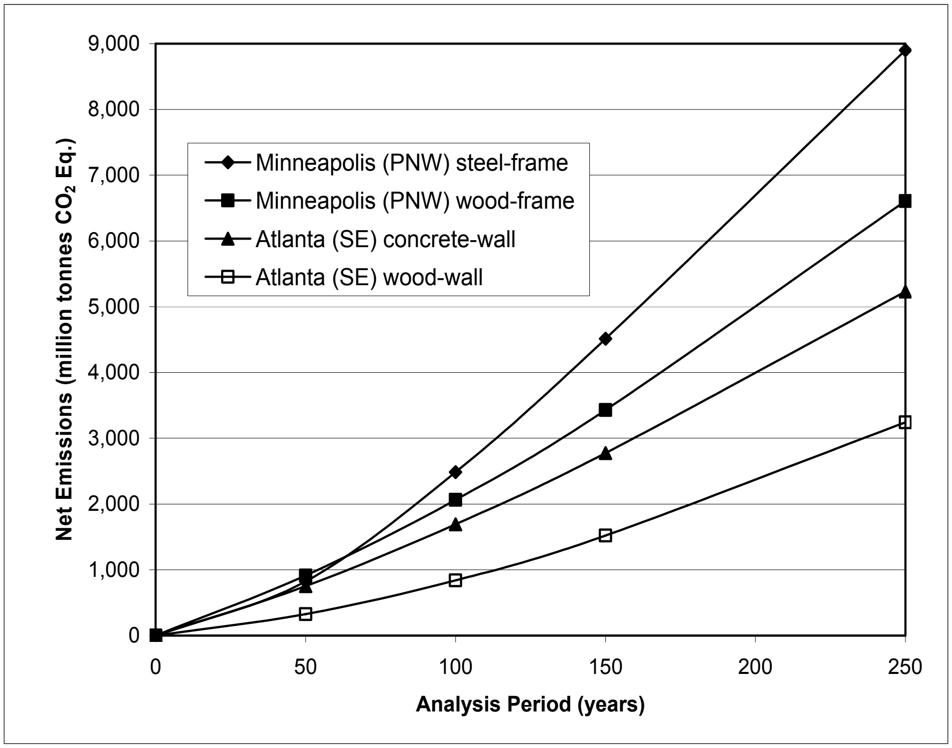

Figure 10.1 Net Emissions versus Time of Analysis for the Base Case

10.2 Leakage of Forest Carbon Sequestration Benefits

In the base case scenario, 80% of the surplus forest (i.e., land no longer needed for wood production due to the substitution of steel or concrete) was assumed to remain in forest without management or cutting, whereas the other 20% was assumed to be cleared and converted to non-forest uses. This assumed degree of leakage is near the lower bounds of the range suggested by the work of Murray, McCarl, and Lee (2002, 2004). Carbon stored in the preserved surplus forest was assumed to grow to some maximum level and remain at that level indefinitely. The occurrence of land use leakage would tend to decrease the extent of potential carbon sequestration in surplus forest, but increase the carbon benefits of using wood-based construction materials.

Research by Murray, McCarl, and Lee (2004) indicated that land use leakage in the U.S. might be expected to range from less than 10% to greater than 90%, but these researchers noted that the extent of leakage depends upon the type of activity that causes land set-asides and the region of the country in which they occur. They primarily studied carbon impacts and leakage associated with forest carbon sequestration programs, which typically involve establishing forest areas where harvest is no longer allowed (i.e., “artificial” restrictions on harvest activities in specified forest areas). The researchers noted that “demand [for forest products] that is more elastic diminishes leakage.” The substitution of concrete or steel for wood-based building products represents a highly elastic situation because demand for wood is decreased due to the availability of viable alternatives (e.g., concrete and steel). Therefore, it is likely that land use leakage due to building material substitution would be lower than leakage resulting from forest set-asides, which is why in the base case a value near the lower end of the range suggested by Murray, McCarl, and Lee (2004) was used.

To address the large uncertainty associated with forest carbon leakage, the analysis was repeated assuming that 10% and 90% of the surplus forest would be lost to other uses. This encompasses the range of leakage indicated by Murray, McCarl, and Lee to be likely in forest sequestration programs. Changing land use leakage from 20% to 10% resulted in a 48% decrease in the net GHG benefit of wood-based building materials for the Minneapolis case (wood frame versus steel frame) and a 1.5% decrease for the Atlanta case (wood wall versus concrete wall). The decrease is due to higher carbon sequestration in forests, compared to a 20% base case leakage scenario, under a reduced demand situation (as wood is replaced by steel or concrete). Under a 90% leakage scenario, the GHG benefit for wood-based building methods tripled for the Minneapolis case and increased by 4% for the Atlanta case relative to the 20% leakage base case scenario. The difference between the impacts of land use leakage on the Minneapolis and Atlanta analyses is primarily a result of the much lower extent of forest carbon sequestration in the Atlanta scenario, which is due to two factors. First, the degree of substitution (concrete wall materials for wood wall materials) is not as great in the Atlanta case as it is in the Minneapolis case, so the degree of forest sequestration due to substitution is lower. Second, the forests assumed to provide wood for the Atlanta case homes are located in the southeastern U.S., and available data indicate that these forests are not characterized by as high a carbon density at maturity as the forests assumed to provide the wood for the Minneapolis case (coastal Pacific Northwest forests). Figure 10.2 graphically depicts the impact of leakage on results, demonstrating that assumptions regarding the extent of forest carbon sequestration and leakage can have overwhelming impacts on the characterization of GHG impacts of different building materials.

Land use leakage assumptions have no impact on the energy consumption differences between the building material choices.

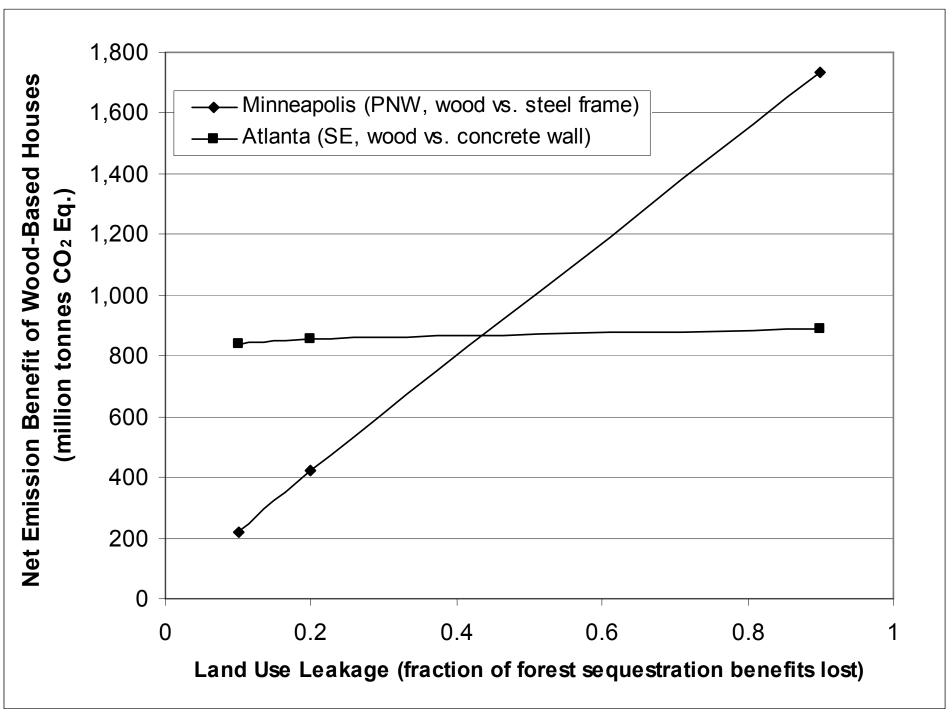

Figure 10.2 Net Emission Difference between Construction Techniques versus Land Use Leakage Assumptions

10.3 Co-Product Leakage

In the analysis, it was assumed that all the co-products produced and shipped off-site during production of wood-based building materials (e.g., wood chips and peeler cores from making plywood) would still be manufactured from forest products regardless of decreasing production of wood-based building materials (the primary product) as steel or concrete is substituted for wood. The ramification of this assumption is that wood is still harvested for manufacturing these co-products. The opposite assumption, that the co-products would no longer be manufactured, is associated with the potential for the forests supplying the raw material to grow to maturity rather than be harvested, potentially sequestering additional carbon.

In the sensitivity analysis, the co-product leakage was changed from a baseline assumption of 100% to a value of 75%, meaning that instead of assuming that all co-products would continue to be produced, it was assumed that only 75% of these would be produced.[11] This change shifted the 424 million tonne CO_2 Eq. net GHG benefit of the wood-based houses to an 8 million tonne CO_2 Eq. benefit for the steel-based houses in the Minneapolis case over the 100-year analysis period (although when considered over a longer time period the wood-based house would eventually regain the advantage due to the saturation of forest carbon benefits). This was due to increased sequestration of carbon in the forest associated with lower production of co-products in the non-wood case. For the Atlanta case (wood wall versus concrete wall), almost no change (less than 1%) in the net GHG benefit of wood-based houses resulted from the same reduction in co-product leakage due to the lower difference in the quantity of wood-based co-products in the two home construction techniques and the much lower carbon storage potential of Southeast forests relative to those in the Pacific Northwest.

Co-product leakage assumptions have no impact on the energy consumption differences between the building material choices.

10.4 Rate of Carbon Accumulation in Forests

As described in Appendix B, this study characterized carbon accumulation in the forest based on FIA data compiled and summarized by the Carbon On-line Estimator, COLE for the two regions included in the CORRIM study. Carbon accumulation was calculated in terms of carbon density over time for the major timber-producing forest type for the two regions.

It is well understood that the ability of a forest to sequester carbon over time is affected by a number of factors. Forest types differ greatly in their rates of carbon accumulation and their ultimate carrying capacities for carbon. Douglas fir forests of the coastal Pacific Northwest have some of the highest capacities of any forests in the U.S. Even within forest types, carbon sequestration rates and ultimate capacities vary significantly depending on site conditions. In addition, a number of factors keep forests from attaining their ultimate capacity. Natural disturbances such as fire and insects kill trees and reduce carbon stocks. Such disturbances are generally less frequent on managed land than on unmanaged land. These and other factors make it difficult to predict, over large aerial scales, the rate at which carbon will accumulate on managed and, especially, unmanaged land. To examine the potential importance of the significant uncertainties surrounding the estimates of forest carbon sequestration, the carbon accumulation rates were subjected to a sensitivity analysis.

To characterize the potential impacts of uncertainty regarding carbon accumulation in forests, the sensitivity analysis included evaluation of two additional carbon accumulation relationships for each

[11] The study did not consider the impacts associated with production of other materials to meet the demand that had been satisfied by the displaced 25%. Clearly, the non-wood products that move into this market would have energy and emissions impacts. Ignoring these impacts tends to understate the benefits of the wood-based building materials in this study.

of the regions in this study (Atlanta–SE, and Minneapolis–PNW). One of the relationships for each region represented increased carbon storage in the forest (by increasing maximum carbon storage of very old forests by 25%) and one represented decreased carbon storage in the forest (by decreasing maximum carbon storage by 25%). These relationships maintained the base case rate of carbon accumulation in young forests (i.e., the shape of the sensitivity analysis relationships is very similar to the base case relationships at early forest ages but the asymptotes approached at old forest ages were increased or decreased by 25%). Figure 10.3 graphically depicts the carbon accumulation relationships used in the base case and sensitivity analyses. Utilization of forest carbon accumulation relationships which predict higher quantities of carbon sequestration tend to diminish the net GHG benefits of using wood-based construction materials due to the greater potential degree of carbon sequestration as less wood is harvested from forests for home construction. Similarly, relationships which predict lower degrees of carbon storage increase the net GHG benefit of wood-based materials.

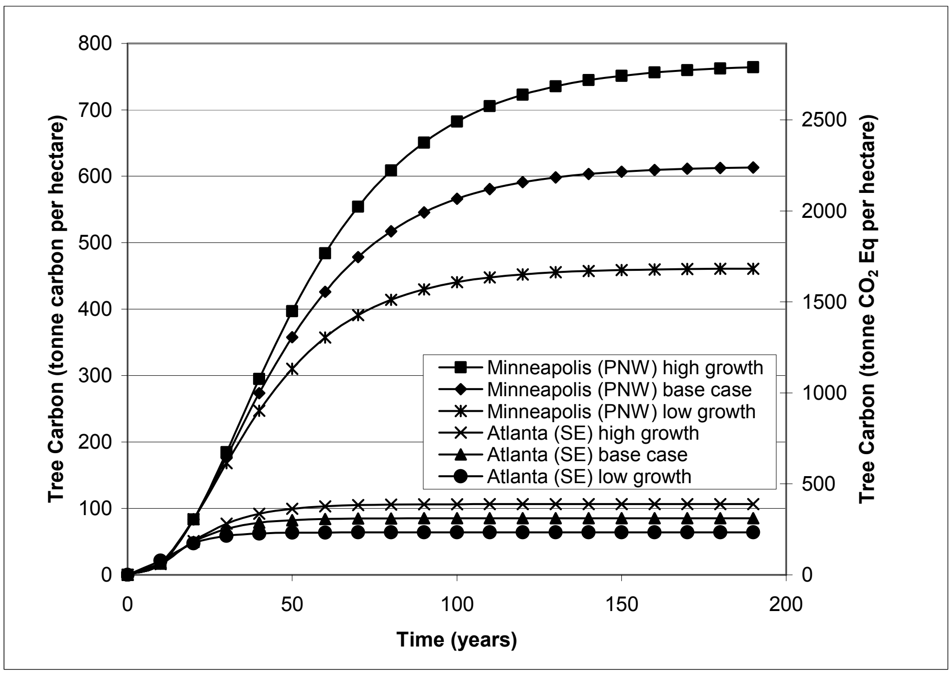

Figure 10.3 Forest Carbon Accumulation Relationships used in the Base Case and Sensitivity Analyses

Decreasing the assumed maximum level of carbon storage in the PNW forest by 25% almost doubled the net GHG benefit of wood-based construction techniques for the Minneapolis case (from 424 to 807 million tonnes CO_2 Eq. over the 100-year analysis period). Increasing the assumed maximum level of carbon storage in the PNW forests by 25% virtually eliminated the net GHG benefit of the Minneapolis case wood-based houses (from the base case result of 424 to 60 million tonne CO_2 Eq. over 100 years), although over time the wood-based house would eventually regain the large advantage due to the saturation of forest carbon benefits. These sensitivity analysis results demonstrate the determining influence that assumptions about carbon storage in forests can impart to LCI results.

Assumptions regarding carbon storage in SE forests were less influential on overall results because both base case and sensitivity analysis carbon storage levels were much lower than those in the PNW forests. Decreasing the maximum SE forest carbon storage level by 25% increased the net GHG benefit of wood-based house construction by 3% for the Atlanta case, while increasing the maximum

SE forest carbon storage by 25% decreased the net GHG benefit of wood-based houses by 3%. In all cases, the wood-based Atlanta houses were associated with a net GHG benefit of over 800 million tonnes CO_2 Eq. over the 100-year analysis period.

Assumptions regarding accumulation rates of carbon in forests have no impact on the energy consumption differences between the building material choices.

10.5 Landfill Decay Parameters

Placement of wood-based construction and demolition debris in landfills serves both as a form of carbon sequestration and as a GHG emission source. A significant fraction of the carbon in wood will be stored essentially permanently when the wood is deposited in a landfill, with the remainder decaying slowly in a manner that can be described by first order kinetics. The fraction of carbon that decays does so anaerobically, typically forming methane and carbon dioxide. A review by NCASI (2004) indicated that although the data are limited, current information suggests that 0.57 is a reasonable value for the fraction of carbon in wood and bark that is permanently stored when the material is placed in landfills, and that a commonly used (albeit probably too high) first order rate constant for decay is 0.03^{-yr}. These are the decay parameters used in the base case. However, review of the published literature indicates that there is uncertainty concerning the most appropriate values of these parameters for cellulosic materials. Therefore, other values were investigated in the sensitivity analysis.

To simulate decreased landfill carbon sequestration and increased methane emissions, the fraction of carbon permanently stored was changed to 0.5 and the first order rate constant was changed to 0.04^{-yr}. These modifications to the base case resulted in decreased net GHG benefits of wood-based building materials of 16% for the Minneapolis case and 2% for the Atlanta case. For the Minneapolis case, the difference in sequestration of carbon in the landfill decreased from about 256 to about 228 million tonnes of CO_2 Eq. over the 100-year analysis period, while the methane emission difference was predicted to increase from about 129 to about 169 million tonnes of CO_2 Eq. For the Atlanta case, the landfill sequestration difference decreased from about 77 to about 69 million tonnes of CO_2 Eq. over the analysis period and the difference in methane emissions increased from about 39 to about 51 million tonnes of CO_2 Eq.

Increased landfill sequestration and decreased methane emissions were simulated by changing the permanently stored carbon fraction to 0.85 and the first order rate constant to 0.02^{-yr}. These changes resulted in increased net GHG benefits for wood-based building materials of about 36% for the Minneapolis case and about 5% for the Atlanta case. The differences in landfill sequestration between wood and non-wood materials increased from about 256 to about 317 million tonnes of CO_2 Eq. in the Minneapolis case (wood versus steel) and from 77 to 95 million tonnes of CO_2 Eq. in the Atlanta case (wood versus concrete). Differences in landfill methane emissions decreased from about 129 to 36 million tonnes of CO_2 Eq. when comparing wood frame to steel frame construction (Minneapolis case) and from about 39 to 11 million tonnes CO_2 Eq. over the analysis period of 100 years when comparing wood wall to concrete wall houses (Atlanta case).

Rates of cellulosic material decay in landfills have no impact on the energy consumption differences between the building material choices.

10.6 Half-Life of House

The base case assumed a house half-life of 100 years (Skog and Nicholson 1998). House half-life affects the amount of carbon stored in products in use (by determining how long the products remain in use), as well as sequestration of carbon in and emissions of methane from landfills (by influencing the rate of placement of cellulosic materials in landfills). One can imagine reasons why the half-life used in the base case might be either too low or too high. On one hand, the wood used in house construction may have a shorter half-life than the house itself due to maintenance activities. On the other hand, U.S. census data suggest that the half-life for homes in the U.S. may be greater than 100 years (Miner 2006). In the sensitivity analysis, therefore, the house half-life was adjusted by ±50% (to 50 years and to 150 years).

Decreasing the half-life to 50 years decreased the net GHG benefits of using wood-based building materials by 22% for the Minneapolis case and 3% for the Atlanta case. In each case, both carbon sequestration in the landfill and landfill methane emissions increased due to the reduced house half-life. This resulted in a larger increase in net carbon sequestration, corresponding to lower net landfill GHG impacts with shorter house half-life. However, sequestration of carbon in products in use decreased more strongly with decreasing house half-life than landfill-related impacts, resulting in an overall decrease in the GHG benefit of wood-based materials under shorter house half-life scenarios. Increasing the house half-life to 150 years resulted in a 9% increase in the net GHG benefit of using wood-based construction materials over steel (Minneapolis case) and a 1% increase over concrete (Atlanta case).

House half-life assumptions have no impact on the energy consumption differences between the building material choices.

10.7 Recycling Construction and Demolition Debris

This study considered the potential for recovering debris from construction and demolition for recycling rather than disposal. The base case assumed that no recovery takes place and that all debris is landfilled. Landfilling wood-based debris results in both carbon sequestration and methane emissions, so recovery of debris will reduce both these carbon pathways. However, the analysis did not consider the concomitant reduced demand for “virgin” wood-based building materials and associated impacts on land use and forest harvest rates.

Research by McKeever (1999, 2003) indicated that potential recovery rates of construction and demolition debris for recycling may be as high as 50%, while noting that it is typically more difficult to recover and recycle demolition debris than construction debris. Based on these findings, the effect of increasing the rate of recovery and recycling debris on the results was investigated by assigning a rate of 50%.

This rate of recovery/recycling decreased the net GHG benefit of wood-based houses by 15% from the baseline for the Minneapolis case (from 424 to 360 million tonnes of CO_2 Eq. over the analysis period) and by 2% for the Atlanta case (from 854 to 835 million tonnes of CO_2 Eq.). The net GHG benefit associated with wood-based houses decreases upon reclamation of debris because the higher carbon sequestration in landfills associated with the wood-based building techniques decreases more significantly than the concomitant reductions in landfill methane emissions. For example, in the Minneapolis case, upon increasing recycling of debris from 0 to 50% the landfill sequestration benefit of wood-based houses decreases from about 255 to about 128 million tonnes of CO_2 Eq. (over the 100-year analysis period), whereas the landfill methane emissions penalty associated with wood frame houses only decreases from about 129 to about 64 million tonnes of CO_2 Eq. Similarly, for the Atlanta case, landfill sequestration benefits of wood wall houses decreases from about 77 to

38 million tonnes of CO_2 Eq., whereas the landfill methane emissions penalty decreases from about 39 to about 19 million tonnes of carbon dioxide equivalents over the 100-year analysis period.

The results of the recycling sensitivity studies must be used with caution because they do not include the probable reduced energy and emissions that would result from replacing virgin production with recycled materials, nor do they consider the potential for increased carbon sequestration in the forest due to use of recycled materials.

Rates of recycling of construction and demolition debris have no impact on the energy consumption differences between the building material choices.

10.8 Energy Recovery from Debris

The base case analysis computes GHG impacts of home construction assuming that all construction and demolition debris is landfilled. There is potential, however, for recovery and recycling of this debris, so the GHG impacts of this potential were investigated in the sensitivity analysis. Another possible pathway for the debris would be recovery for energy production (i.e., burning the wood-based construction and demolition debris to produce steam for use by industry or utilities). Energy recovery from construction and demolition debris is a feature of many of the European life cycle studies of building products. These studies have found that energy recovery provides significant life cycle energy benefits (Gustavsson and Sathre 2006; Petersen and Solberg 2005; Gustavsson, Pingoud, and Sathre 2006; Borjesson and Gustavsson 2000). Recovering energy from the debris rather than landfilling it results in decreased landfill methane emissions, decreased sequestration of carbon in the landfill, and decreased "fossil" carbon dioxide emissions as other fuels, presumably fossil fuels, are displaced by the recovered debris.

The impacts of recovering energy from debris were investigated in two scenarios: by assuming 25% and 100% of debris was recovered, and in both cases that steam production from combustion of wood-based debris displaced natural gas combustion.[12] It was assumed that the thermal efficiency of producing steam is 65% from wood fuel[13] and 80% from natural gas. The energy content of wood-based debris was assumed to be the same as that for wood and wood residual fuel published by USDOE (2005), 18.6 GJ HHV/dry tonne. GHG emissions from biomass fuels only include methane and nitrous oxide from combustion, as carbon dioxide from biomass fuels is "carbon neutral" (IPCC 1997a, 1997b). The GHG emission factor used for wood debris combustion was 1.47 kg CO_2 Eq./GJ HHV (USDOE 2005). Natural gas GHG emissions were estimated using the emission factor 50.26 kg CO_2 Eq./GJ HHV (USDOE 2005).

The impacts of assuming 25% debris recovery for energy production on the net GHG benefit of wood-based construction techniques were negligible for both the Minneapolis and Atlanta cases (0.4% and 0% change in the net GHG benefit, respectively). This is because the decreases in landfill carbon sequestration and combustion-related GHG emissions associated with energy recovery from debris (typically benefits for wood-based materials) were offset by decreased landfill methane emissions (landfill methane emissions typically represent a penalty for the wood-based materials). The total net energy benefits associated with wood-based construction materials increased by 6% for the Minneapolis case and by 3.2% for the Atlanta case upon assuming that 25% of debris is recovered for energy production.

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[12] The carbon and greenhouse gas benefits of wood-based building materials would be greater if the displaced fossil fuel was assumed to be oil or coal.

[13] Modern wood combustion equipment can achieve higher efficiencies. This value reflects the current mix of industrial combustion technologies applied to wood and wood waste in the United States. Higher combustion efficiencies would increase the energy advantages of using wood-based building materials.

When the analysis incorporated the assumption that all debris was recovered for energy generation, the Minneapolis case reflected a 1.4% increase in the net GHG benefit of wood-based materials (net GHG benefit increased from 424 to 430 million tonnes of CO_2 Eq. over the analysis period); however, the impact was still negligible for the Atlanta case (net GHG benefit increased from 853.9 to 855.2 million tonnes of CO_2 Eq.). These results illustrate that energy recovery from construction and demolition debris does not materially influence the GHG impact results of the analysis. Although the GHG impacts are modest, the effects on energy are greater. The total net energy benefits of wood-based house construction increased by 24% for the Minneapolis case and by 13% for the Atlanta case when all construction and demolition debris was assumed to be recovered for energy production.

11.0 EXTRAPOLATION OF RESULTS

One objective of this study was to examine the potential substitution effects on carbon and energy of large-scale shifts in building materials used in residential construction. The analysis described above was performed based on one million single-family housing starts per year. Figure 11.1, which shows single-family housing starts over time, indicates that in recent years, housing starts have equaled or exceeded 1.5 million per year.

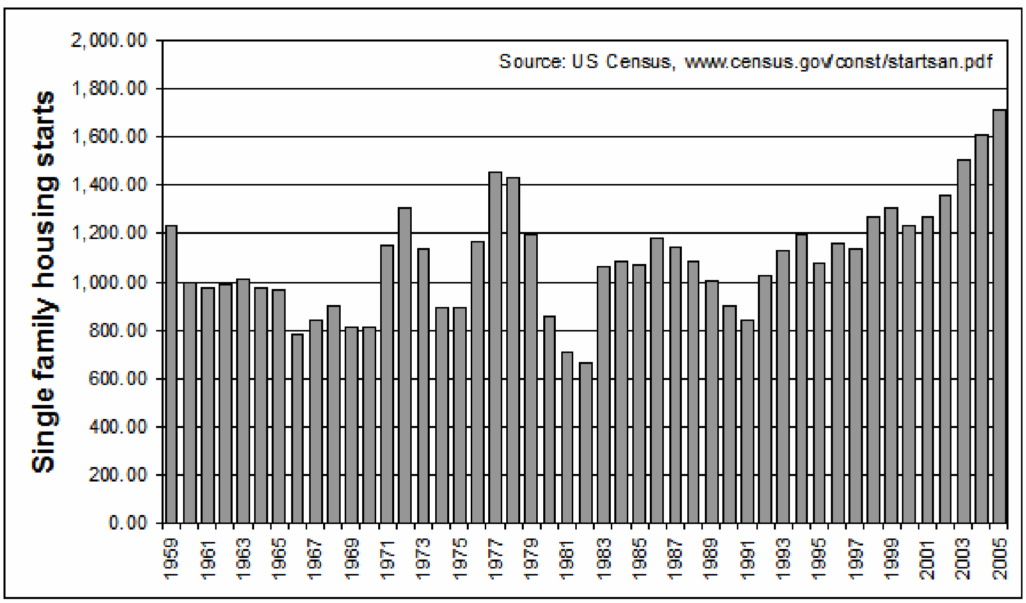

Figure 11.1 Single-Family Housing Starts

For one million housing starts per year over a 100-year period, a cumulative carbon benefit of 233 million tonnes carbon (854 million tonnes CO_2) is estimated for the case where wood walls are used instead of concrete walls. The use of wood framing instead of steel framing is estimated to result in a benefit (i.e., a reduction) of 116 million tonnes carbon (424 million tonnes CO_2). On an annual basis over the 100-year period, the benefits average 8.54 and 4.24 million tonnes of CO_2 per year for the concrete and steel framing substitutions, respectively. At the current rate of 1.5 million housing starts per year, these amount to nationwide differences of 12.8 and 6.4 million tonnes of CO_2 per year, respectively, averaging 9.6 million tonnes CO_2 per year. This represents 11 to 43% (averaging 27%) of the 30 to 60 million tonnes of embodied CO_2 emissions associated with the residential sector.

A similar approach can be used to estimate potential national energy savings. Using a basis of one million housing starts per year over a 100-year period, a cumulative energy benefit of 6.3 billion GJ is estimated for using wood walls instead of concrete walls. The corresponding benefit for using wood framing instead of steel framing is estimated to be 11.3 billion GJ. On an annual basis, these average 63 million GJ/yr and 113 million GJ/yr for concrete and steel framing substitution, respectively. At the current rate of 1.5 million housing starts per year, these amount to nationwide differences in total energy consumption of 94.5 and 169.5 million GJ/yr, respectively, averaging 132 million GJ/yr. These figures represent 9 to 34% (averaging 22%) of the 0.5 to 1.0 billion GJ/year of the embodied total energy associated with the residential sector.

This total energy impact is approximately the same as the impact on non-renewable energy because almost all of the total energy benefits are associated with reduced use of non-renewable energy sources (i.e., fossil fuels). In terms of non-renewable energy, the use of wood-based building materials over a 100-year period is estimated to save 97.5 and 189 million GJ/yr, averaging 143.3 million GJ/yr, for 1.5 million housing starts per year.

The substitution effects examined here should be considered in the context of current practices for single-family housing construction. Wood-based materials have a large majority of the current market for structural support elements in exterior walls. In 2001, steel wall framing held only 2% of the wall framing market, while concrete represented about 9% of the market (Garth, Easton, and Edelson 2004). These figures indicate that the U.S. already enjoys about 90% of the carbon and energy benefits associated with using wood-based building materials in exterior wall systems. The impacts estimated in this study, therefore, largely represent emissions that have been avoided as the result of using wood framing. Alternatively, these can be viewed as the projected additional emissions that would be associated with a large-scale shift away from the current practice of using wood frame construction for single-family homes.

In addition to exterior wall systems, there are other opportunities for substituting wood for non-wood materials. Although a number of these opportunities have been investigated (e.g., Knight et al. 2005; Lawson 1996; Scharai-Rad and Welling 2002), they are not considered in these estimates.

It should be noted that the CORRIM research available to date (Phase I) has modeled only two houses. While these are reasonably representative of large regions of the country, the ability to estimate national effects would be enhanced by comparable information on houses representative of parts of the country not addressed in the CORRIM Phase I work.

12.0 SUMMARY AND CONCLUSIONS

The objective of this study was to examine, at the national level, the effects of different building materials on the life cycle energy requirements and greenhouse gas emissions associated with residential structures. Life cycle energy requirements and greenhouse gas emissions were compared for houses constructed of different materials and the differences were examined over time and extrapolated to the national level. Comparisons were based on the annual production of a constant number of thermally comparable homes for the period of analysis, usually 100 years. Results were then extrapolated to the current rate of approximately 1.5 million housing starts per year.

Because this study involved houses with comparable heating and cooling requirements, energy use and greenhouse gas emissions attributable to heating and cooling could be ignored. Instead, the analysis focused on ***non***-heating/cooling energy requirements and greenhouse gas emissions, including a) embodied energy and emissions (i.e., associated with the pre-occupancy phase of the life cycle); b) energy and emissions associated with the post-occupancy phase (i.e., end of life); and c) forest carbon sequestration. Heating and cooling, however, are responsible for a large fraction of the energy and carbon life cycle loads of most residential structures and must be considered in designing homes to have optimal life cycle energy and carbon profiles.

The building systems examined in this study and much of the data used to perform the calculations were developed in research conducted by the Consortium for Research on Renewable Industrial Materials (CORRIM) (Lippke et al. 2004; Perez-Garcia et al. 2005a, 2005b; Puettmann and Wilson 2005). The analysis described in this study differs from the CORRIM research, however, in that a different set of assumptions and a different analytical framework were used to characterize carbon sequestration in forests and forest products. This was necessary to examine national-level impacts over large areas and long periods. In addition, an end-of-life module was developed to address carbon sequestration in and methane emissions from landfills.

The results indicate that houses built with larger amounts of wood and wood-containing building materials are associated with lower greenhouse gas emissions and energy than thermally comparable houses built with smaller amounts of wood-based materials. Houses with wood-based wall systems required about 15 to 16% less total energy for non-heating/cooling purposes than thermally comparable houses employing alternative steel- or concrete-based building systems.[14] The results for non-renewable energy consumption were essentially the same as those for total energy, reflecting the fact that most of the energy that was displaced was in fossil fuels.

The greenhouse gas benefits of substituting wood for non-wood building materials are generally greater than the energy benefits. This study found that net greenhouse gas emissions associated with wood-based houses were 20 to 50% lower than those associated with thermally comparable houses employing steel- or concrete-based building systems. Only a small fraction of the building materials need to be changed to accomplish these improvements. In the Atlanta example, the additional wood used in the wood-based house represented only 2.3% of the mass of the house, while in the Minneapolis example, the additional wood used in the wood-based house represented 7.7% of the mass.

On an annual basis, assuming the current rate of approximately 1.5 million housing starts a year, the difference between wood and non-wood building systems represents about 9.6 million tonnes of CO_2 equivalents per year. The corresponding energy benefit associated with wood-based building materials is approximately 132 million GJ per year. These figures represent approximately 22% of the embodied energy and 27% of the embodied greenhouse gas emissions in the residential sector of the economy.

The greenhouse gas emissions profiles developed for the Atlanta and Minneapolis comparisons were very different. In the Atlanta case, the most important effects were related to embodied emissions, which are comprised of the emissions from extracting, producing, and transporting building materials. For the Atlanta designs, the embodied emissions represented 65% of the total greenhouse gas impact over 100 years, while for the Minneapolis designs embodied emissions accounted for about 30% of the total greenhouse gas impact.[15] Sequestration of carbon in forests was the most important factor for the Minneapolis designs because they relied on forests that were assumed to be capable of accumulating carbon to very high levels. For the Minneapolis designs, forest carbon sequestration over 100 years accounted for 40% of the total greenhouse gas impact, whereas it accounted for only 4% in the

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[14] The CORRIM studies, from which most of the raw data for this report were drawn, found energy savings in the 16 to 17% range (Lippke et al. 2004). The carbon results from CORRIM cannot be compared with those derived herein because different methods were used to determine carbon sequestration effects.

[15] The "total greenhouse gas impact" is calculated as the sum of the absolute values of the differences between wood and non-wood houses shown in Tables 8.1 and 8.2. It is different than the net impact, which reflects the sum of the actual (not absolute) values.

Atlanta designs. Longer analysis periods diminished the relative importance of forest sequestration. In both designs, carbon sequestration in products in use represented about 20% of the total greenhouse gas impact. Sequestration of carbon by waste materials in landfills had a smaller greenhouse gas emissions impact (8% of the total). Landfill methane emissions (on a CO_2-equivalents basis) were responsible for less than 4% of the total greenhouse gas impact.

A sensitivity analysis revealed that two of the most important sources of uncertainty in this analysis are a) assumptions about carbon accumulation in forests; and b) leakage assumptions which describe carbon losses related to conversion of forests to non-forest uses. The base case assumed that 80% of the surplus forest[16] would be preserved in forests and accumulate carbon at rates based on data from the USDA Forest Service. The carbon on the remaining 20% of the land was assumed to be lost due to land use changes. Another important component of leakage is associated with co-products from building products manufacturing operations. In this study, even if demand for building products was reduced, the demand for co-products was assumed to remain constant. Future studies would benefit from a more refined analysis of a) the leakage of forest carbon sequestration benefits associated with reduced demand for forest products as well as increased risk of fire and other disturbances; and b) the leakage associated with shifting demand for co-products. Future studies might also be improved by examining the benefits of producing biomass energy from surplus forest as an alternative to using surplus forest to sequester carbon.

The sensitivity analysis demonstrated the importance of examining time horizons long enough to distinguish between short-term and long-term effects. This is illustrated by the results for the Minneapolis structures, where steel frame housing was found to have lower net emissions in early years but the advantage switched to wood-based framing over longer periods. This reversal is due to the fact that the benefits associated with leaving trees in the forest saturate (i.e., forests have a maximum carbon storage capacity), whereas many of the carbon benefits associated with using wood in housing do not saturate, but continue to accumulate. This important finding is missed if the analysis is limited to short time horizons.

The sensitivity analysis indicated that assumptions regarding the lifetime of houses and the fate of construction and demolition debris, including assumptions about the fate of carbon in landfills, had relatively little influence on greenhouse gas results. In contrast, the energy benefits of using wood-based building materials could be increased significantly (by 13 to 24% or more) by burning construction and demolition debris for energy instead of landfilling it. The impacts of recycling construction and demolition debris also warrant additional investigation.

The national estimates developed in this study made extensive use of data from studies of houses representative of large regions of the Southeast and Midwest U.S. The estimates would be improved if comparable information was developed for houses representative of regions not included in the CORRIM Phase I work.

A review of the literature revealed results generally consistent with this study. In particular, the literature indicated that for houses with comparable heating and cooling requirements, wood-based building systems require less energy and produce fewer greenhouse gas emissions during the pre-occupancy phase of the life cycle (i.e., less embodied energy and emissions) than building systems based on steel, concrete, and brick. None of the studies in the literature, however, examined large-scale and long-term forest carbon impacts, end-of-life issues, and national-level outcomes in a manner that allowed direct comparison to the results of this study.

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[16] Surplus forest is forest that is no longer needed for wood production due to decreased consumption of wood when non-wood alternatives are used (Gustavsson and Sathre 2006).

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APPENDIX A

CARBON SEQUESTRATION IN AND METHANE EMISSIONS FROM LANDFILLS

This appendix provides a description of how carbon sequestration associated with placement of forest products debris in landfills was characterized. The approach used to estimate methane emissions associated with these landfilled materials is also presented.

There are two sources of forest products debris relevant to the current study: construction debris and demolition debris. Construction debris refers to the portion of raw materials used to build new houses which is discarded (e.g., debris such as end pieces of lumber and panels). Demolition debris consists of materials leaving the products in use pool as houses age and are maintained or retired. The base case scenario assumed that all construction and demolition debris is landfilled. Other fates of debris (e.g., recycling or recovery for energy production) were investigated in the sensitivity analysis.

Information on construction debris generation during house construction was drawn from the CORRIM assessment and represents a constant rate of annual debris addition to landfills (different rates for each construction technique in each region studied).

Demolition debris generation and deposition rates were estimated corresponding to a first order decay equation applied to the quantity of wood used in home construction each year. The relation, drawn from the Intergovernmental Panel on Climate Change (IPCC 2003), relates the fraction of products that goes out of use each year, f_D, to the half-life of the product, HL (assumed to be 100 years for houses in the base case), as follows:

$$f_D = \ln(2)/(HL) = 0.693/(HL)$$

The amount of demolition debris generated each year was calculated based on the sum of all debris generation (calculated from the relation above) corresponding to the houses constructed in prior years.

Once the annual debris deposition rates were calculated (including both construction and demolition debris), the total annual deposition was divided into "permanently" stored carbon and decomposable carbon based on information presented by NCASI (2004) (57% of carbon permanently stored, the remainder decomposable). Only a portion of the decomposable carbon, however, will decay over the analysis period, with the rest remaining in the landfill through the end of the analysis period.

Methane generation from the decomposable carbon was estimated using a first order decay relationship with a rate constant of 0.03/yr (NCASI 2004 presents a summary of published rate constants from which 0.03/yr was selected). Methane generation for each year's deposit over the remainder of the analysis period was calculated using the following relation:

$$Methane = Decomposable\ Carbon \times \left(\frac{16kg\ CH_4}{12kg\ C}\right)\left[1 - e^{0.03\times(analysis\ period - placement\ year)}\right]$$

Total sequestration of carbon in landfills over the analysis period was determined by summing each year's permanently stored carbon with the fraction of each year's decomposable carbon that did not decompose to methane (difference between total decomposable carbon and that converted to methane as predicted by the relation above).

The above relation was used to estimate methane generation from each year's deposition of debris over the analysis period. However, only a portion of the methane generated by decay of debris is emitted to the atmosphere. Information from EPA (USEPA 2002) was used to adjust total generation to account for oxidation of methane to CO_2 in the landfill cover (10% oxidation) and for methane recovery and destruction systems. EPA estimated that the average recovery rate of landfill gas at facilities where this is practiced is 75% (i.e., facilities recovering landfill gas only collect 75% of the gas; 25% is emitted to the atmosphere). Furthermore, EPA estimated that 49% of all landfill methane is generated at landfills with recovery systems. To extend the analysis to likely practices of the future, the current study assumed that the percentage of methane generated at landfills with recovery systems will increase linearly to 75% over the next 100 years.

To summarize annual methane emission estimations, generation over the analysis period (corresponding to each year's deposit) was computed based on first order decay of decomposable carbon, adjusted for 10% oxidation to carbon dioxide in the landfill cover, and adjusted to account for current and likely future implementation of landfill gas collection/destruction systems (where 25% of non-oxidized methane escapes the collection system). The resulting annual methane emission estimates for each year were then summed over the analysis period to arrive at total methane emissions from landfilled construction and demolition debris.

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APPENDIX B

CHARACTERIZATION OF ACCUMULATION OF CARBON IN FORESTS

BASE CASE ANALYSIS

The analysis includes a characterization of carbon accumulation in the forest which is based on Forest Inventory and Analysis (FIA) data compiled and summarized by the USDA Forest Service Carbon On-Line Estimator (COLE) (Proctor et al. 2005)[17] for the two regions included in the CORRIM study (Perez-Garcia et al. 2005a, 2005b; Lippke et al. 2004). The data in COLE are based on augmented FIA data and are therefore a representative sample from forest land in the U.S. The COLE data were used to develop Von Bertalanffy growth equations of the form

$$y = a * \left(1 - e^{-b*time}\right)^3$$

where the a-coefficient gives the asymptote, and the b-coefficient controls the rate of approach to the asymptote. Carbon versus time curves developed from these equations relate standing carbon pools in trees (includes roots, stem, and crown of live and standing dead trees) to age of stand.

The two regions included in the CORRIM study were emulated by filtering the COLE data. The Pacific Northwest (PNW) case was modeled by Douglas fir and hemlock in publicly owned forests west of the Cascade Mountain Range in Oregon and Washington. The Southeast (SE) case was modeled by loblolly and slash pine in privately owned forests in Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Texas, and Virginia.

The resulting equations are

$$PNW : Carbon = 615.18 \times \left(1 - e^{-0.036*time}\right)^3$$

$$SE : Carbon = 85.136 \times \left(1 - e^{-0.09*time}\right)^3$$

where carbon accumulation is expressed in units of metric tonnes of carbon per hectare.

The carbon sequestered in forests not needed for wood (because non-wood building materials were used) was modeled by starting at the average carbon content of a stand over a rotation (as reported in the CORRIM research), determining the corresponding stand age based on the growth curves described above, then "growing" the forest using those same curves.

SENSITIVITY ANALYSIS

Although these relationships were based on data representative of the regions of the CORRIM study, it is possible that these relationships do not accurately predict the density of carbon that can accumulate in live trees in these regions under scenarios where the forests are allowed to grow to "climax" stage. There is a relative lack of data on carbon contained in very old forest stands simply because there is not an abundance of very old forest stands from which to collect it, particularly in the southeastern U.S.

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[17] Data were extracted from COLE on December 9, 2005. The database is updated periodically.

To characterize the potential impacts of carbon accumulation in forests on the results of the analysis, a sensitivity analysis was performed. The analysis evaluated a set of carbon accumulation curves developed in a manner that emulates the initial shapes of the curves based on the COLE data but approaches an asymptote either 25% greater or 25% less than the base case carbon accumulation curves. The resulting curves were

$$\text{PNW high growth}: Carbon = 768.98 \times \left(1 - e^{-0.0324*time}\right)^3$$

$$\text{PNW low growth}: Carbon = 461.39 \times \left(1 - e^{-0.0418*time}\right)^3$$

$$\text{SE high growth}: Carbon = 106.42 \times \left(1 - e^{-0.076*time}\right)^3$$

$$\text{SE low growth}: Carbon = 63.85 \times \left(1 - e^{-0.118*time}\right)^3$$

where carbon accumulation is expressed in units of metric tonnes of carbon per hectare.

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