Emission Omissions:

Carbon accounting gaps in the built environment

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Executive Summary

There is a rising interest in Canada about how the choice of building materials may affect future greenhouse gas (GHG) emissions, and whether a preference for a specific building material or combination of materials can help Canada reduce the GHG emissions of the built environment and achieve targeted emission reductions.

Evidence for optimizing the choice of building materials has largely been drawn from life-cycle assessment (LCA) studies that consider the GHG (and other) impacts of products at each phase of their "cradle-to-grave" lifespan (i.e., production, use and end of life). While LCA is the best-available tool for evaluating the GHG performance of alternative building products and designs, policy-makers and building designers should be aware that it also has significant limitations, challenges and uncertainties.

The aim of this research is to identify:

a) Limitations, challenges and uncertainties in existing LCAs and quantify their significance to the current understanding of the relative GHG performance of buildings made alternatively of concrete, steel or wood structural elements.

b) Best practices that could improve the reliability and usefulness of LCA to support effective policies to decarbonize the built environment.

c) Longer-term opportunities to reduce life-cycle emissions in the built environment by supporting decarbonization efforts in the concrete, steel and forestry sectors.

Summary of Key Findings

Existing LCAs produce widely variable results, even for similar buildings, posing challenges for decision-makers.

LCA accounting of the GHG emissions associated with different building materials can vary widely depending on how they handle various assumptions and uncertainties. These assumptions and uncertainties are typically not fully disclosed. Further, sensitivity analyses—or other techniques to identify the importance of assumptions and uncertainties to the results—are rarely conducted. In other words, LCAs rarely assess how their assumptions increase uncertainty around their results and/or how different assumptions could yield significantly different results.

LCAs comparing building materials can exaggerate the importance of embodied impacts when they discount or ignore the contribution of other significant life-cycle emissions.

While many LCA studies focus on the embodied life-cycle GHG emissions associated with different structural elements (typically concrete, steel or wood), they tend to discount or ignore the operational stage emissions as well as the emissions impacts of other building systems (e.g., site preparation, heating and ventilation, supplementary structures, furnishing). This can inflate the relative contribution of the embodied emissions of the structural building elements. Used in isolation, these results can lead to decisions that are too narrow in scope and shift focus away from a more comprehensive picture of emission reduction opportunities in buildings.

Regional variability was found to significantly affect overall life-cycle emissions.

For example, steel production in Canada is mostly split between electric arc furnace (EAF) mills, which use recycled steel feedstock and renewable electricity, and basic oxygen furnace (BOF) mills, which use virgin iron ore. Sourcing steel from EAF mills can decrease embodied emissions by a factor of two to four compared to steel from BOF mills or imported steel from China. Regional markets typically determine the steel that is available. Wood building products' end-of-life emissions are highly dependent on disposal conditions—wood materials that are landfilled at sites that

do not have methane recovery or flaring can have end-of-life emissions up to 10 times higher than wood disposed at landfills with landfill gas recovery. Emissions associated with raw material extraction for both steel and concrete were also identified as having high variability.

Biogenic carbon emissions and sequestration related to the production and end-of-life stages of wood building products hold the most significant uncertainty in existing LCAs.

Whereas emissions from the production of concrete and steel are well understood, accounting for emissions and sinks in the biogenic carbon cycle of wood products is complex and requires sophisticated carbon models that can track exchanges between different carbon pools. LCA studies typically do not track biogenic carbon but simply assume that whatever carbon is harvested is replaced sustainably by new forest growth in the future (i.e., carbon neutrality). Criticisms of this assumption include that it ignores significant and measurable GHG emissions from soil disturbance, carbon losses from the conversion of old-growth primary forest and real-world silvicultural success rates than can be significantly less than 100 per cent. Previous studies have also found that as little as 15 per cent of the carbon stored in a standing tree is sequestered in the final wood product. Few LCAs account for the immediate climate change impacts of these carbon losses relative to the small amount of carbon stored, nor do they account for the time required to recapture that carbon and other biogenic carbon losses in new forest growth.

Sensitivity analyses of assumptions related to biogenic carbon suggest that the life-cycle GHG emissions of wood products can be significantly higher than those presented in LCA literature.

Based on a typical LCA study, it is possible to test the overall LCA impacts of wood building construction against a concrete building, controlling for the GHG impacts of three different forest management scenarios: a silvicultural success rate of 90 per cent, a net permanent loss of soil carbon attributed to a clear-cut harvest and carbon losses from the conversion of primary forest to secondary managed forest.[1] Compared to a baseline that assumes biogenic carbon emissions are zero over the building life cycle, cradle-to-gate life-cycle emissions for wood buildings increased between 5 and 72 per cent depending on the scenario. Aggregating these impacts suggests that a wood building could have greater embodied emissions than a concrete building (see Figures ES1 and ES2).

In an energy-efficient, long-service-life structure, the GHG impacts of building material choice remain negligible, suggesting that embodied emission reductions should not be pursued at the expense of operational efficiency.

While the LCA GHG impacts of materials relative to the overall life cycle of a building vary slightly depending on regional climatic conditions and energy mix as well as the energy efficiency and longevity of the structure, these impacts are small for most buildings in Canada and emphasize the continued importance of prioritizing energy efficiency and designing long-lived low or net-zero-energy buildings. Material choices need to be made on a building-by-building basis, driven by the role they play in enhancing the structure's environmental strategies and performance.

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[1] The three scenarios are supported by forestry research and represent reasonable possible ranges of impacts that reflect identified uncertainties. However, they do not represent probabilistic outcomes or average or specific conditions for any given managed forest in Canada. More research and regional modelling are required to determine the probability of impacts.

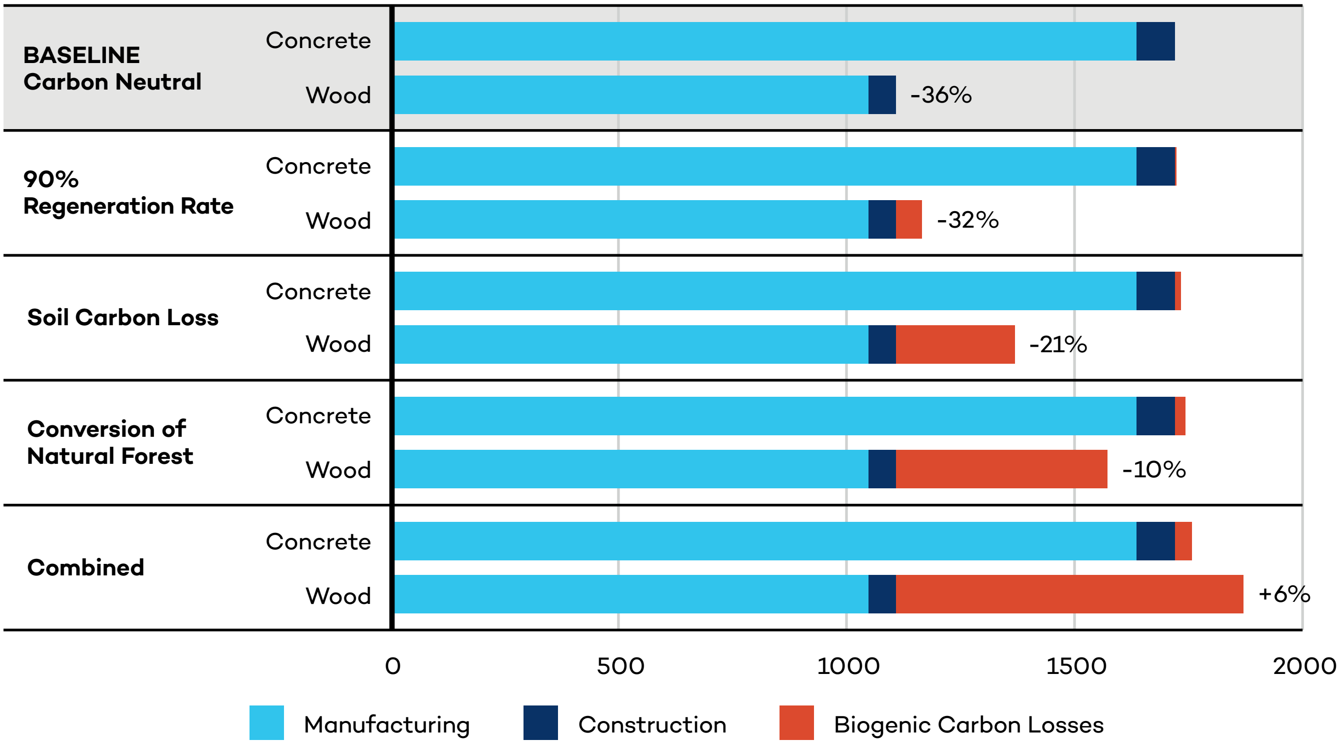

Figure ES1. **Whole-building cradle-to-gate lifecycle greenhouse gas emissions: Alternative wood and concrete building construction considering four different forest management scenarios**

Note:The functional unit is the whole building, based on a concrete and wood building design that has similar operational and service efficiency.

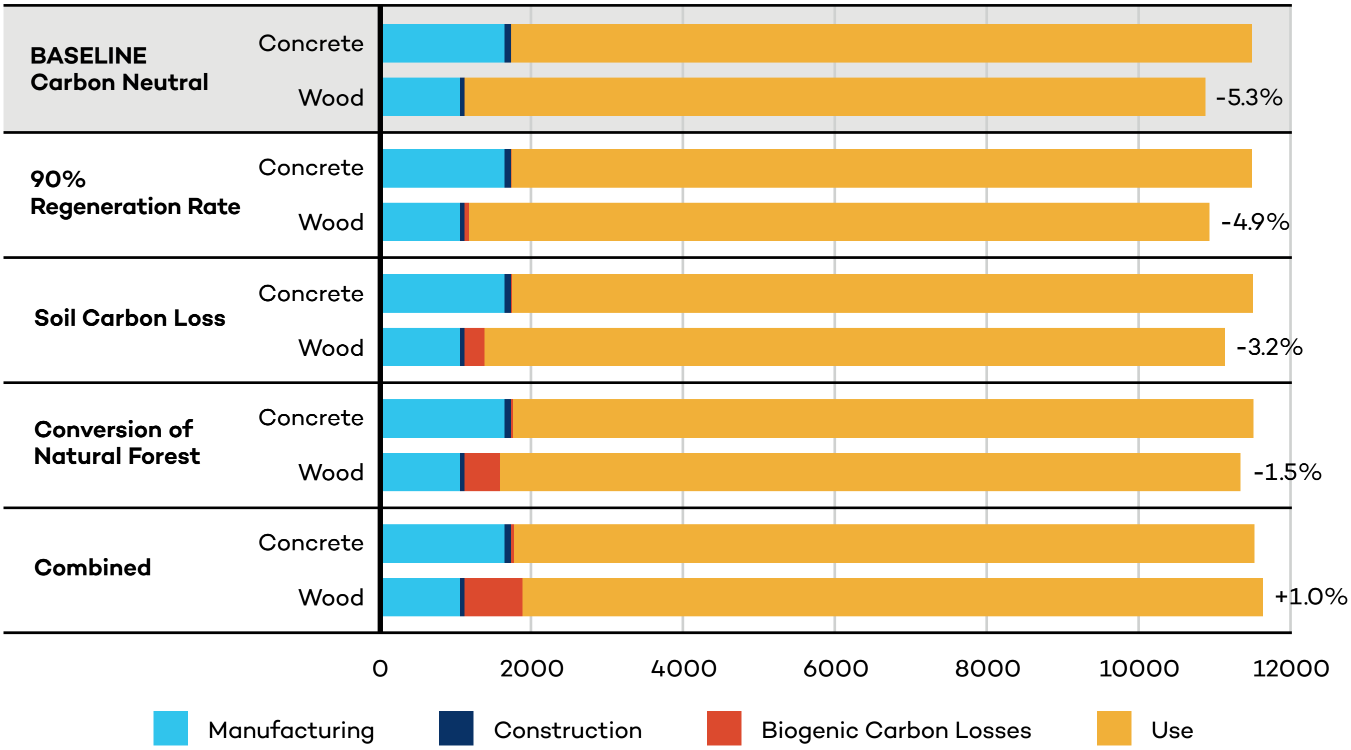

Figure ES2. Building embodied and use emissions (tCO_2e)

Summary of Key Recommendations

Building efficiency and longevity should be the priority for decarbonizing the built environment.

In the short to medium terms, improvements in energy efficiency and developing new low- or net-zero-energy buildings offer the highest mitigation potential from the built environment sector. Effective carbon pricing and complementary policies that cover the manufacturing sector will also work to decarbonize embodied emissions of building materials, albeit likely at a slower rate than the decarbonization of building use. In addition, policies should promote building longevity, durability and service efficiency improvements as well as rehabilitation and remodelling to extend service life, all of which have significant GHG emission reduction benefits.

LCA is the right approach, but more data, transparency and robust standards are needed, especially with respect to biogenic carbon.

Policy-makers and building professionals looking to decarbonize buildings should exercise caution when making decisions that prefer one building material over another. Uncertainties, assumptions and omissions in LCA studies, particularly with respect to the biogenic carbon emission of wood products, suggest that comparisons across building materials are fraught with complexity. Far more transparency, consistency and rigour in LCA data and methodologies are needed to render material comparisons meaningful, especially for policy development. As a start, the federal government should invest in up-to-date regionalized, national life-cycle inventories, including a meaningful carbon accounting for wood products that considers regional biogenic carbon impacts against net carbon sequestered.

To address embodied GHG emissions in buildings, policy-makers and building professionals need to focus equally on material efficiency and incenting decarbonization across all material manufacturing sectors.

Each building is unique in design and, while a given building design may substitute wood, steel or concrete elements to some degree, each of these three materials is typically prominent in varying proportions in all construction. In addition, there are varying strategies, technologies and policy levers that can incent GHG reductions in each material sector, all of which should be identified and equally incentivized as part of a robust built environment decarbonization strategy. When it comes to material selection, climate policy and low-carbon building design are best focused on material efficiency and supporting low-carbon innovation across all material sectors. For concrete and steel, this means rewarding low-carbon producers and driving the adoption of best-available technologies, such as the use of lower-carbon alternative fuels. For wood products, there is evidence that market-ready solutions in forestry management and regeneration can significantly enhance emission sinks in Canadian forests and contribute to reaching Canada's emission reduction targets. Deep emission reductions on the order of 60–80 per cent that are in line with Canada's long-range emission reduction targets will require large-scale investment in new low-carbon technologies, such as carbon capture utilization and storage as well as significant changes to forest management practices (e.g., avoidance of slash burning, enhanced silvicultural practices) focused on optimizing and preserving biogenic carbon pools.

Table of Contents

Acronyms and Abbreviations

AGB	aboveground biomass
BGB	belowground biomass
BOF	basic oxygen furnace
CCS	carbon capture and storage
CSA	Canadian Standards Association
EAF	electric arc furnace
FSC	Forest Stewardship Council
GHG	greenhouse gas
Glulam	glued laminated timber
GWP	global warming potential
GWP_{bio}	global warming potential of biogenic carbon dioxide
HWP	harvested wood product
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	life-cycle assessment
LL HWP	long-lived harvested wood product
OSB	orientated strand board
PCM	phase-change material
PEFC	Programme for the Endorsement of Forest Certification International
SFI	Sustainable Forestry Initiative
SIP	structural insulated panel
SL HWP	short-lived harvested wood product
SOC	soil carbon
UNFCCC	United Nations Framework Convention on Climate Change

1.0 Introduction

Globally, the Intergovernmental Panel on Climate Change indicates that the building sector has the greatest estimated greenhouse gas (GHG) mitigation potential of all sectors investigated (Lucon et al., 2014). The energy associated with the operation and use of buildings in Canada accounts for 12 per cent of GHG emissions (Environment and Climate Change Canada, 2017b), while GHG emissions associated with the built environment are estimated to be at least 26 per cent of domestic emissions (GLOBE Advisors, 2017). In addition, the renovation and occupation of buildings is estimated to contribute one third of global GHG emissions (Ghattas, Gregory, Olivetti, & Greene, 2013). Precise estimates of total life-cycle building emissions (i.e., including both operational energy emissions as well as embodied emissions) in Canada are not available.

If Canada is to meet its climate objectives, it is essential that the design, construction and use of buildings are optimized to achieve GHG emission reductions. To this point, all three levels of government have made buildings a focal point of climate change mitigation policies, largely targeting energy efficiency, but also with a rising interest in how the choice of building materials may affect future GHG emissions.

Evidence for optimizing the choice of building materials has largely been drawn from life-cycle assessments (LCAs). LCA is a widely accepted technique to systematically and quantitatively assess the impact of different materials or products throughout all the processes involved in a product's life (i.e., production, use and end of life—or "cradle to grave"). A considerable number of studies in Canada, the United States and worldwide have been conducted that examine different aspects of life-cycle emissions associated with material choice in construction. Many LCA studies focus on a comparison of residential or commercial buildings that employ structural elements that are alternatively concrete, steel or wood. Increasingly, these types of LCA analyses are being used to quantify and predict GHG emissions and to help develop policies for reducing GHG emissions in the built environment.

The aim of this research is to isolate what the body of available LCA literature can conclusively determine about the GHG impacts of building materials, focusing on alternative uses of concrete, steel or wood in structural building frame elements such as floors, walls and roofs. The goal is to compare life-cycle emissions across these three materials and at different building life-cycle stages and to identify where significant uncertainties exist in LCA analysis. This research also quantitatively assesses the materiality of identified uncertainties from a GHG perspective and highlights specific emission sources that need more careful consideration. Finally, the report discusses which uncertainties must be addressed to provide sufficiently robust and reliable evidence for policy development directed at promoting the construction of low-carbon, climate-resilient buildings.

The report concludes with recommendations on:

- How future LCA studies should be conducted to provide clearer evidence of GHG emission trade-offs, opportunities, benefits and costs for different building construction types.
- The development of policies that maximize the efficiency with which the building sector can be decarbonized over the near, medium and longer terms, recognizing that building materials and related building industry technologies are evolving rapidly in response to the demands of climate change, and that climate change impacts themselves imply that the mid-century built environment likely will be very different from today.
- Additional research, including improvements to LCA analysis and developing policies that maximize the efficiency with which the building sector can be decarbonized over the long term.

While the focus of the study is primarily buildings—and more specifically on concrete, steel and wood building materials—its conclusions and recommendations are relevant to broader built environment decisions to reduce GHG emissions from other types of infrastructure.

The study does not propose to definitively quantify life-cycle emissions associated with any specific building configuration or conduct new primary research, but rather aims to draw on the existing literature to identify the performance of different materials and highlight uncertainties and opportunities to achieve deeper emission reductions in the future.

2.0 Study Methodology

The study was conducted in three main work phases, each corresponding to a main element of this report. It focuses on a relatively narrow subset of LCA building analyses and attempts to compare life-cycle emissions of alternative building material construction related to the substitution of concrete, steel or wood in structural building frame elements such as floors, walls and roofs. These types of studies can assist building design practitioners, including architects and engineers, who may want to understand whether using less of one material and more of another in the building structure could result in net emission reductions over the lifetime of the building.

In the first phase, a review of existing LCA guidelines, methodologies and literature was conducted. This review was then informed by a second analytical phase that considered major documented uncertainties and major variabilities that can be expected in the Canadian context. In some cases, model simulations to quantify the significance of these uncertainties and variabilities were conducted. In the final phase, potential impacts of changes in technology and the built environment and how they fit with longer-term climate objectives were considered. The results of the three phases were analyzed to make recommendations.

To assess the relative GHG performance of one building material (i.e., concrete, steel or wood) over another, it is necessary to carefully account for all GHG emissions and sinks at all important life-cycle stages. It is also important to clearly articulate selected methodologies, system boundaries, data sources, as well as data gaps and potential uncertainties to judge their applicability, suitability and relative importance in decision making.

While a great number of LCA tools and guidelines have been developed for this type of assessment, almost every LCA study published employs a different set of assumptions that can have significant impacts on the relative reported performance of different materials. Before adopting a set of policies that aims to optimize the life-cycle GHG emissions from buildings (by, for example, promoting the substitution of one material for another based on LCA studies), it is critical that both policy-makers and practitioners understand the explicit and implicit assumptions, scope and limitations of each study or set of studies before ascertaining whether they can or should be used to make a valid comparison. In addition, if Canada is to meet its climate objectives, its climate policies will need to consider deep decarbonization of the built environment and drive down GHG emissions from all materials. As such, the study was conducted in three phases, as described below.

2.1 Phase 1: LCA Review of Building Materials

A review of LCA literature related to the GHG performance of alternative building construction was conducted, including: International Organization for Standardization (ISO) standards, LCA and Product Category Rule guidelines, methodology reviews, meta-studies and specific LCA studies. The objective of this first Phase was to provide an overview of how LCA is conducted and the challenges of comparing wood, concrete and steel building materials and to identify the main uncertainties, data gaps and limitations of LCA analysis. The review also aimed to summarize best practices for this type of LCA analysis and identify how following these best practices could improve the reliability and usefulness of results for policy decision making. Major uncertainties documented in the literature and by experts in the field were identified. These uncertainties include those with the largest potential overall impact on life-cycle emissions associated with different building materials. Key variabilities that could be expected in the Canadian context were also identified. Phase 1 analysis included discussion of key model elements, such as model choice, system boundaries, temporal and spatial effects, model equivalency and model data.

2.2 Phase 2: Impact of Uncertainties and Regional Variabilities

The LCA review undertaken in Phase 1 identified key areas of uncertainty associated with the life-cycle emissions from alternative building construction using concrete, steel and wood materials. The review also identified key areas of variability in life-cycle GHG emissions that are a result of the geographic location of buildings within Canada.

In Phase 2, a range of GHG outcomes was determined for each of the uncertainties and variabilities identified in Phase 1. The purpose of Phase 2 was to quantify how assumptions and uncertainties could affect the GHG outcomes at each life-cycle stage. The calculated range, expressed as GHG emissions per unit of production or as a percentage of overall embodied emissions, reflects plausible GHG scenarios described and supported in the literature for baseline conditions in Canada. These results give an indication of the potential variability in embodied emissions (i.e., cradle to gate) as well as overall life-cycle emissions (i.e., cradle to grave) across different materials used in buildings in Canada.

2.3 Phase 3: Impact of Decarbonization and Changes in the Built Environment

The final phase includes a review of longer-term energy-efficiency opportunities in the built environment and technologies that can support decarbonization efforts in the concrete, steel and forestry sectors. It provides a review of advanced production of building materials and construction techniques that could reduce overall building emission intensity in the future, covering technologies that are in the development stage and improvements to operational practices. It also reviews the potential impact of an increase in demand for forest products on the ecological health of forests.

3.0 A Review of LCA for Construction Materials

Although general LCA methodology is well defined in the literature, its application in the building sector has been noted to suffer from a lack of standardization (Rossi, Marique, Glaumann, & Reiter, 2012). The results of this study are consistent with that observation.

Our extensive literature review covered hundreds of journal articles and reports on LCA studies related to life-cycle GHG emissions of buildings and the relative performance of different concrete, steel and wood construction. The aim of the review was to identify best practices for conducting these types of studies, as well as major uncertainties, limitations and data gaps that can affect the reliability of LCA study results. The findings should be useful to both LCA practitioners conducting LCA analyses and policy-makers that seek to fairly judge the GHG performance of alternative building construction and establish policies that can best reduce emissions from the built environment.

The review is organized according to key elements of LCA analysis that were found to affect life-cycle GHG emissions, including: i) LCA model choice, ii) system boundaries, iii) data availability and iv) assumptions and transparency. General results and issues with establishing model equivalency are then presented. Finally, major uncertainties and regional variabilities identified in the literature are described. In the following section, the potential impact of these uncertainties and regional variabilities are estimated.

3.1 LCA Model Choice

LCA analysis is a critical decision-support tool for comparing alternative building materials used in construction, but there are numerous limitations and challenges to ensuring an "apples-to-apples" comparison. The selection of the scope and type of LCA analysis and model is the first step.

LCA analysis specific to GHG emissions must address the sources and sinks of GHGs throughout a product's life. Table 1 identifies typical stages and processes employed in LCA studies of buildings and building materials. These stages and processes are common to most LCA analyses and are based on general principles and standards for LCA of products and services (ISO 14040, 2006; ISO 14044, 2006; ISO 21930, 2017; EN 15978, 2011).

Table 1. Typical stages and processes included in LCA of buildings

Stage	Important Processes (Modules)
Production Stage	Raw material supply/extraction
	Transport to factory
	Manufacturing
Construction Stage	Transport to site
	Construction and installation
Use Stage	Use or occupation
	Maintenance/renovation/repair/replacement/refurbishment
End-of-Life Stage	Deconstruction/demolition
	Transport for disposal
	Waste processing
	Disposal

Three main types of LCA analyses were identified. A general description of each LCA type is provided in Table 2.

Table 2. Description of different LCA analysis types

LCA Type	Description	Advantages	Disadvantages
Process LCA	Most common LCA type, based upon bottom-up data on the energy and material flows for specific processes.	Easy to determine each process that is contributing to emissions.	Impossible to include all processes that emit GHGs, and choices must be made about what to include and how to define the system boundary. While some databases, such as ecoinvent, model infrastructure associated with the transforming activities (e.g., equipment manufacturers that supply cement, steel and wood manufacturing facilities), it is difficult to know precisely what is included in the system boundary, and omissions may create an "apples-to-oranges" comparison.
Input–Output LCA	Based on a top- down approach using national statistical information on monetary transactions between sectors. Economic inputs to a sector, such as the building industry, are then transformed into energy and emission flows using a partitioning and accounting of energy and emissions for the full economy.	Does not suffer from truncation error (i.e., referring to a discrepancy or approximation as a result of excluding some potential sources of emissions such as services like banking, advertisements and legal services) as all emission flows are portioned and included.	Unsuitable for comparing the relative performance of different types of building materials. Associated with monetary transactions that presume an average input emission factor based on all the comprised sectors that may or may not be representative of the structural building element in question. Does not include carbon sequestration that is a critical element in building LCA.
Hybrid LCA	Combination of both process and input–output LCA.	Balances advantages of both process and input–output LCA.	Limited use because of sophistication and complexity.

The process LCA methodology can suffer from systematic truncation error (i.e., a discrepancy or approximation as a result of excluding some potential sources of emissions such as services like banking, advertisements and legal services due to a necessary requirement to define a limited system boundary). However, it is the only type of LCA that can help determine the relative performance of using alternative building materials such as concrete, steel and wood in construction because the method allows the modeller to determine the contribution of emissions related to each individual process and life-cycle stage.

Within process LCA, there is also a distinction between "attributional" LCAs and "consequential" LCAs. Almost all building LCA studies that consider different materials are attributional LCAs that focus on steady-state GHG impacts—that is to say, they assume emission factors do not change in time or in response to demand. While attributional LCAs are suited for individual building assessments at a given moment in time, they ignore the potential macro-scale GHG impacts of, for example, increased demand for one product over another that can be created through different policy interventions. Consequential LCAs seek to quantify the system-level impacts that would occur if the use of a product were to increase. This type of LCA study seeks to understand how change in overall demand affects the supply chain and future levels of emissions.

Consequential LCAs may be particularly important in the context of policies and decisions that favour the use of one material over another. An increase in demand may have surprising effects on production life-cycle emission intensity.

In the case of wood building materials, an increase in wood demand has a direct impact on the ability of forests to achieve sustainable carbon stocks, potentially altering the expected emission performance of the material. In the case of concrete, an increase in demand could result in issues with the local sourcing of raw materials and increase raw material supply and extraction emissions. In the case of steel, an increase in demand may need to be met with imports from countries with more emission-intensive methods of production than steel produced in Canada.

LCA models should also account for emissions when they occur. It is common in LCA analysis to add up emissions that can occur over a very long lifespan. If an emission that occurs at the beginning of a project related to the production stage is treated as having the same weight or global warming potential (GWP) as an emission that occurs 50–100 years later that is related to the end-of-life stage, this can present an inconsistency and lead to scientifically indefensible conclusions. The reason for this is that emissions that occur at different times have very different cumulative radiative forcing impacts. Radiative forcing is a measure of the influence GHG emissions have on altering the balance of incoming and outgoing energy in the Earth atmosphere system and is an index of the importance of the factor as a potential climate change mechanism. If emissions occurring at significantly different times in the life cycle are treated equally, the analysis discounts early emissions that have persisted in the atmosphere over the life of the building compared to end-of-life emissions that will only contribute to global warming much later.

3.2 System Boundaries

Ideally, LCA studies that focus on the relative GHG performance of different building material construction includes all the life-cycle stages identified in Table 1 (i.e., cradle to grave). Without this comprehensive evaluation for the entire life cycle of the building material, from extraction to final end-of-life disposal or reuse, it is difficult to conclude which alternative construction ultimately leads to fewer GHG emissions and contributes to global warming.

Some LCA studies choose to focus on only specific life-cycle stages, depending on their purpose and design. For example, many building LCA studies focus only on the embodied emissions (i.e. the "cradle-to-gate" pathway) of materials that consider only the product and construction process stages. These studies may not be interested in emissions related to building use because the alternative building constructions are assumed to have the same operating energy demand and emissions, or the research question of interest is limited. **Policy-makers should be wary when considering evidence from studies that do not include all life-cycle stages, as ultimately the concern is with absolute overall GHG emission performance as opposed to relative changes at specific LCA stages.**

Other LCA studies neglect to include different sub-processes (e.g., the clearing of land for the development of mines or quarries) at individual LCA stages because of either a lack of data or an assumption that these processes do not contribute significantly to differences in emissions between alternative construction approaches. Other LCA studies may include certain of these sub-processes for completeness, but their treatment is heavily simplified, and results may be misleading. For example, end-of-life emissions and material recycling assumptions are particularly concerning for building LCA studies, as they are rarely comprehensively addressed in LCA studies (Rossi et al., 2012). Non-energy GHG (e.g., biogenic) emissions are also often excluded from LCA studies that exclusively use energy flows to estimate emissions. **Before accepting an LCA study as evidence of the superior GHG performance of a building material, policy-makers should carefully review system boundaries for gaps, limitations and simplifications that may have significant impacts on conclusions.**

Best practice guidance for the inclusion or exclusion of emissions is that, cumulatively, all neglected input flows not exceed 5 per cent for all life-cycle stage modules indicated in Table 1 (ISO 21930, 2017).

LCA studies should be careful not to potentially double count reduced emissions associated with reuse, recycling and energy-recovery activities. Under ISO 21930, "net output flows" of secondary materials or fuels are addressed under Clause 5.2. This clause ensures that double counting of any material, energy and resource flows that occur as a result of reuse, recycling or energy recovery activities (associated with the supply chain of the product system under study and a previous and/or subsequent product system) is prevented and not permitted. **The focus at end of life should be on GHG emissions that occur directly as a result of the different treatment processes at end of life (whether disposal, reuse, recycling and/or energy recovery) and not an assessment of the emissions that could be displaced as a result.**

While structural building frame elements are generally identified as being the highest contributing building element to total embodied GHG emissions, most studies exclude a significant portion of building elements such as:

1. Other building systems (e.g., heating and ventilation, sanitary, sprinklers)
2. Supplementary structures (e.g., ductwork, balconies, stairs, internal walls, windows, final finishes)
3. Furnishings, appliances
4. Site preparation emissions (e.g., excavation, backfilling, piling, ground stabilization)

This is important, as full life-cycle emission analysis has revealed that these building elements can dominate the total embodied building emissions (Ruuska & Häkkinen, 2015); as a result, structural building frame elements made from concrete, steel or wood play a smaller role than many LCAs typically imply.

The key takeaway from systems boundary analysis of existing LCA literature is that meaningful cross comparisons of different building LCA studies are difficult and should be approached with caution due to the many dimensions of LCAs, including different study objectives and different system boundaries.

3.3 Data Availability and Selection

Data collection for LCA involves developing an inventory of all inputs and outputs required for processes within the system boundary. It requires large datasets of embodied energy and emission factors for the construction materials. Most LCA practitioners rely on published commercial datasets rather than developing their own dataset. These published datasets typically employ very broad geographic averages (e.g., North America) that may not be relevant to the supply and production of materials for different regions in Canada. Datasets that can provide regional representation of production, construction, use and end-of-life emissions are preferable, but are often not available. Governments in some jurisdictions aim to address this issue by developing up-to-date, regionalized, national life-cycle inventory. **No such inventory exists in Canada and it is recommended that the federal government invest in one as part of its climate plan.**

The age of an LCA study and underlying data is also a potential concern. Emission and embodied energy factors, as well as recycling rates, have changed significantly over time for many life-cycle stages for concrete, steel and wood products. **It is recommended that data sets used to calculate life-cycle emissions should be within the last 10 years (ISO 21930, 2017). LCA studies published before 2008 have little bearing on current emission trends.**

3.4 Assumptions and Transparency

Journals that reviewed building LCA studies (Rossi et al., 2012; Ghattas et al., 2013), as well as our own review, found that most LCA studies were poor at reporting assumptions and providing background information on how GHG life-cycle emissions at each stage and process are calculated. Given the complexity and sheer volume of calculations that are required, this is not surprising. ISO standards call for open, comprehensive and understandable presentation of LCA information. **A best practice would be to develop a comprehensive list of assumptions employed in an LCA.**

Our review indicates that, in most studies:

- Explicit details of processes at each life-cycle stage are not presented and thus it is unclear if there are any major omissions.
- Emission factors and embodied energy data are not presented, and frequently the source of data is not cited.
- A breakout of emissions, even at the highest level, by life-cycle stage is not always provided. While a provision of a breakout by process is impractical, clear references to the datasets used should be indicated.
- Assumptions regarding recycling and reuse rates of materials are not presented, and it is difficult to know in what context or region they apply (see Section 3.6 Uncertainty and Regional Variability below).

The general lack of transparency found in LCA studies hinders the ability to make general conclusions for policy consideration.

3.5 Typical Findings of LCA and Model Equivalency

Each building is unique in design and often uses all three materials discussed in this paper. In other words, the built environment will likely always require wood, steel and concrete in varying proportions. Most LCA studies identify that use emissions (emissions that arise from the operation and occupation of the building—i.e., heating, cooling, lighting etc.) account for, on average, 80 per cent of emissions, but this estimate varies considerably depending on the building's efficiency, regional climate and system boundaries of the LCA analysis. Regional weather in Canada has a significant influence: in Vancouver, use emissions are typically closer to 60–70 per cent, whereas in less moderate regions like Toronto they can be greater than 90 per cent. It is also highly dependent on the assumed lifetime of the building, exclusion and inclusion of other building elements, and whether renovations and refurbishments are considered. Shorter lifetimes increase the importance of the embodied emissions, whereas, in longer service life structures, operational efficiency remain the dominant GHG consideration.

The ratio of use stage to all other life-cycle emissions is very important because it highlights where efforts to reduce emissions should be focused. If the clear majority of emissions (e.g., greater than 80 per cent) are from the building's use phase (Biswas, 2014; Robertson, Lam, & Cole, 2012; Sathre, 2007), then policies that improve the energy efficiency and renewable energy supply of buildings will clearly have a much greater impact than addressing embodied emissions from the manufacture of a building's structural elements. This is particularly true for less moderate climates with extreme cold and/or hot climates where energy for space heating/cooling and ventilation is a significant source of emissions. Many process LCAs of buildings that compare different building materials simply show a preference for building construction that is more energy efficient (i.e., has a higher insulation value).

However, as building energy efficiency increases and fuels used in the operational-use stage are decarbonized, the embodied emissions of the building materials may become an increasingly important factor (bearing in mind that material choice also plays an important role in energy-efficient design and performance). Even without additional carbon policies, Canada's *3rd Biennial Report* on climate change projects that building operational emission intensity is set to fall nearly 20 per cent by 2030 (Environment and Climate Change Canada, 2017a). Different low-carbon roadmaps for buildings such as the European Commission low-carbon roadmap and pathways to decarbonization in Canada (Bataille, Sawyer, & Melton, 2015) suggest that it is conceivable that operational emissions can fall by more than 80 per cent by 2050. While speculation that operational energy use in buildings can be mostly decarbonized implies that building material emissions from other life-cycle stages will become increasingly important, substantial efforts to decarbonize materials may also achieve deep reductions. **In any case, policies and decisions should simultaneously drive building emission reductions from all life-cycle stages.**

Figure 1 illustrates the relative contribution of different life-cycle stage emissions to total emissions for buildings. The data was compiled from 15 different building LCA studies and reviews that presented life-cycle emissions for a wide assortment of buildings, regions and system boundaries. The ranges are based on fifth and 95th percentile results of the data points (see Annex A for data). As illustrated in the figure, the range of impact is very wide. The relative significance of each stage is affected primarily by operating energy requirements, different regional energy supply mixes, different system boundaries chosen by the LCA studies and, to a lesser extent, by the choice of building materials.

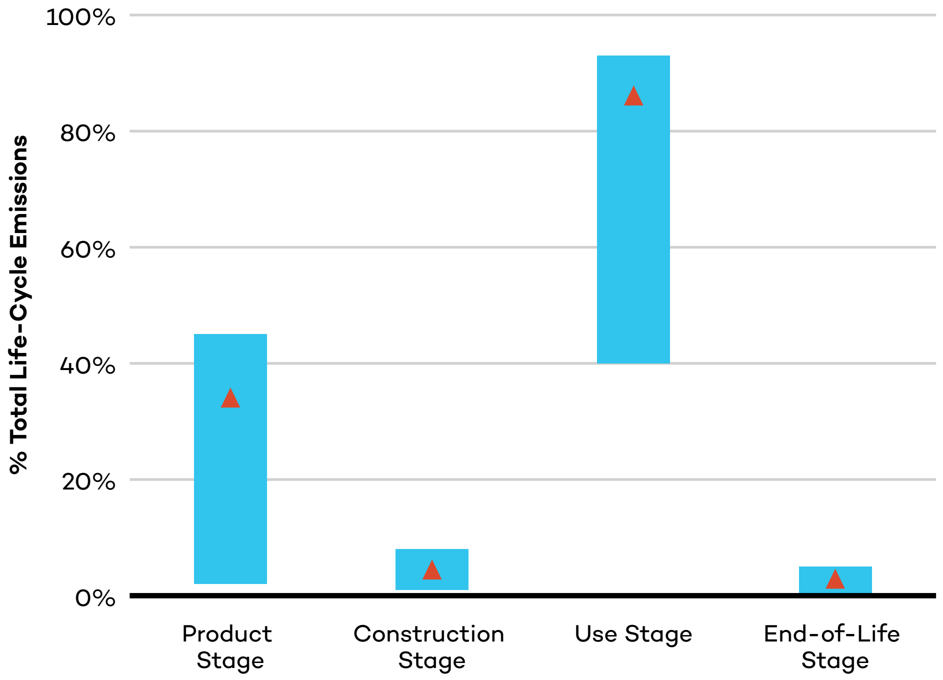

Figure 1. Range and average contribution of life-cycle stage emissions to overall total building emissions reported in the literature[2]

Note: Average contribution for each life-cycle stage is based on the average of values identified in the literature; as a result, the cumulative total is not 100 per cent.

Several general observations can be made from Figure 1:

1. The use life-cycle stage typically dominates. While this stage decreases in importance for energy-efficient buildings and studies that consider shorter building operational lifetimes, *at its lower limit, it is still responsible for over 40 per cent of emissions in all LCAs studied and on average contributes 80 per cent of total life-cycle emissions.*
2. Construction-stage emissions are typically small and not generally significant to overall life-cycle emissions.
3. Product stage emissions may or may not be a major contributor to overall emissions, depending largely on the significance of use-stage emissions.

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[2] The data is not specific to concrete, steel or wood construction, and some small variation would be expected, particularly for end-of-life emissions.

4. End-of-life stage emissions are generally small. (End-of-life studies that include credits for recycling and reuse of building materials were excluded from consideration based on ISO guidelines.)

To make a comparison between building materials, a common functional unit for comparison is required. The purpose of defining a functional unit is to ensure that the services provided by alternative buildings are equivalent, for example in structural performance, energy performance, acoustics, repair and refurbishment. Most process building LCA studies employ usable floor area (m^2) for a whole building as the functional unit. A few studies consider number of occupants, whole buildings or other functional units. The intent of functional units such as floor area is to be able to compare materials with different technical performances within the same study so that there is a benchmark for comparison based on the level of service. GHG units per unit of mass or volume of material are generally inadequate, as equal masses or volumes do not fulfill the same function.

A comprehensive review of building LCA studies on a m^2 basis (Säynäjoki, Heinonen, Junnila, & Horvath, 2017) reports variations in embodied emissions (i.e. cradle to gate) between many studies. In Figure 2, the variation in embodied emissions per m^2 functional unit found in this study is compared for commercial buildings with structural frame elements made primarily of concrete, steel and wood (see Annex A for data). All the studies included in the figure are based on process LCA studies but represent many different climatic regions, building sizes and occupancy uses. The data is not representative of Canada's geography but is indicative of results typically found in the literature.

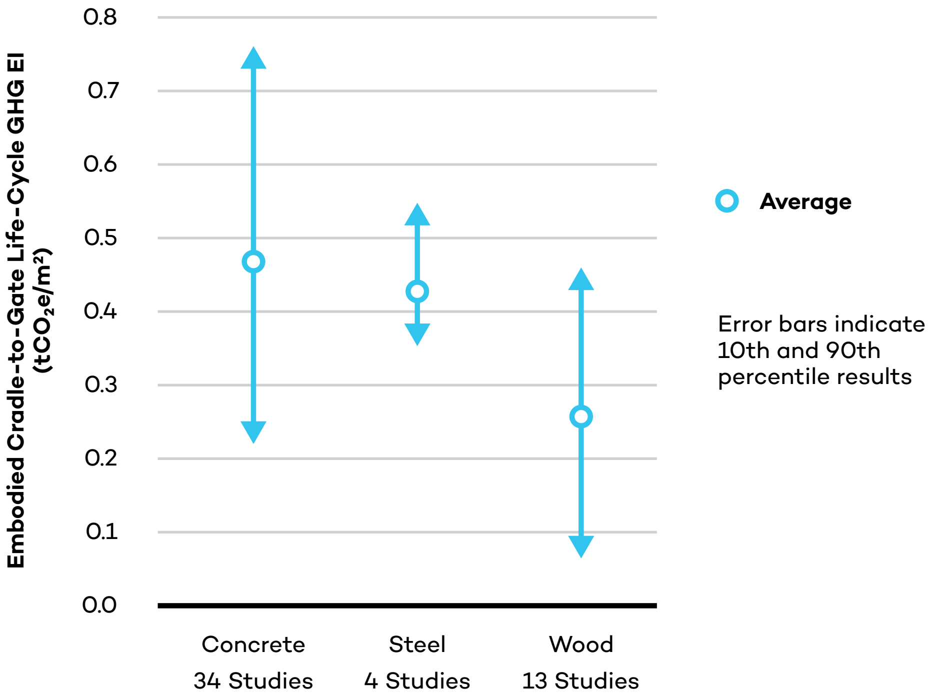

Figure 2. Embodied cradle-to-gate life-cycle GHG emission intensity of commercial buildings (tCO_2e/m^2)

Figure 2 indicates that the emission intensity of wood buildings is lower (i.e., superior performance) than both concrete and steel buildings in the majority of cases. However, variances in emissions are large and Säynäjoki et al. (2017, p. 1) note: "It is the methodological issues and subjective choices of the LCA practitioner that cause the vast majority of the huge variance in the results.… Currently the published building LCAs do not offer solid background information for policy-making without deep understanding of the premises of a certain study and good methodological knowledge."

LCA methodology, climatic zone, regional location, specific inclusions and exclusions of the system boundary, energy supply mix and methods of production all likely have significant roles in contributing to the high variance reported in Figure 2. However, without all of this detail, which is often not reported by individual studies, policy- makers cannot deduce why the results vary significantly and what product choices or related product and built environment policies can actually lead to emission reductions for the built environment.

There are also important interdependencies where the selection of one building material can affect the choice of other buildings materials. For example, structural building elements that are being compared may have different insulation and/or thermal performances and therefore different energy efficiencies and/or different energy systems tailored to different material properties (e.g., thermal mass); they may have different structural characteristics and as a result require more or less structural elements (e.g., foundations and pilings) and materials; or they may require a different maintenance schedule or have different operational lifetimes. This interdependency requires very careful consideration in an LCA analysis. Similarly, the assumptions in the operational phase, in terms of relative performance of primarily wood, concrete or steel buildings, is crucial to the overall performance of different materials.

The longer a building lifespan, the more embodied emissions in building materials are amortized over time, potentially reducing the overall impact, as long as building energy-efficiency performance is not compromised. **This indicates that building durability and longevity coupled with operational efficiency and decarbonized energy sources should be the primary aim of policies and building codes in efforts to reduce GHG emissions.**

In conclusion, the literature on building LCA consists of highly varying results, even when assessing buildings that are very similar (Säynäjoki et al., 2017). **Policy-makers need to understand how different methodological choices and assumptions can affect the life-cycle emissions of building material products in LCA analysis.**

3.6 Uncertainty and Regional Variability

Building LCA studies seldom report uncertainty (Blengini & Di Carlo, 2010; Ghattas et al., 2013) or include a sensitivity analysis of important variables that contribute to uncertainty in the results (Rossi et al., 2012). **The lack of sensitivity analysis is a crucial drawback to the interpretation of results, and LCA best practice would include a sensitivity analysis of key variables.** Many LCA studies published in scientific journals may not include sensitivity analysis simply due to a lack of space or relevance to their goals, whereas LCA studies supporting Environmental Product Declarations almost always include them.

Because of the sheer complexity of LCA analysis, this study was not able to do a rigorous and comprehensive assessment of inputs and assumptions that drive uncertainty in LCA outputs. This review therefore distinguishes between uncertainty related to the choice of LCA model versus data assumptions related to the location of the building (i.e., regional variability). Regional assumptions in LCA studies are typically driven by the individual needs and data availability of each LCA study. Many LCA studies reviewed were not specific to a region in Canada, and therefore do not account for the unique profiles of energy supply and demand, production intensities of building materials and building construction that exist across the country.

Emissions associated with fossil fuel and electricity energy use at every life-cycle stage are well documented in the literature and relatively easy to calculate and track with existing LCA models. Non-energy or industrial process emissions arising from the production of steel and concrete are also well documented. This means that the clear majority of production-stage, construction-stage and use-stage emissions for concrete and steel have relatively low uncertainty. All concrete, steel and wood building materials demonstrate significant uncertainty for end-of-life emissions; however, this stage is much less important than production and use stages to overall emissions.

The most significant uncertainty from a GHG emissions perspective that is often ignored in LCA analysis relates to emissions and sequestration of biogenic carbon linked to the production stage and end-of-life stages for wood.

The indirect emissions from land-use changes associated with clearing land for the mining and quarrying of raw materials are also not well documented and should be further examined. While opening new mines or quarries is likely to result in significant land-use emissions over a short time, amortizing these emissions over the operational life and for all the building products produced from the raw materials extracted is likely to reduce their relative importance in LCA analysis.

Note that regional variability can be high for almost all emission sources at all life-cycle stages, and we focus on the ones that are likely to contribute the most to changes in overall emissions.

Based on the review of the literature, the key uncertainties are identified in Table 3 and the key regional variabilities are identified in Table 4. Recommendations for their treatment in LCA are also provided in the table, and Section 4 investigates the potential impact of these uncertainties and regional variabilities on LCA results.

Table 3. Key uncertainties identified in building LCA emissions for concrete, steel and wood building frame elements

Key Uncertainty	Life-Cycle Stage	Description of Uncertainty	Recommendation for LCA Analysis
The biogenic carbon cycle in wood products	Product and End-of-Life Stages	Almost all LCA studies oversimplify the treatment of wood products and consider them to be carbon neutral (Blengini & Di Carlo, 2010; GLOBE Advisors, 2017; Ochsendorf et al., 2011; Robertson et al., 2012; Salazar, J. & Meil, J., 2009). The assumption may be reasonable if wood building products are made from wood from sustainably managed forests that can reasonably claim carbon neutrality—e.g., biogenic carbon emissions are sequestered in the same growing forests over time. However, broadly making this assumption for all certified forests avoids a very complex accounting of carbon where there is significant debate. Sustainable certification systems are designed around multiple ecological and economic values and are not necessarily targeted to optimize or measure carbon balances. There is considerable uncertainty around whether forest management practices can ensure permanency of sinks, and whether significant risks associated with fire, pests, climate change and land-use pressures are appropriately considered. For example, soil carbon is the largest single carbon pool in the forest. There is evidence that harvesting practices lead to a long-term decline in soil carbon and release of soil organic carbon (as carbon dioxide) to the atmosphere due to harvest disturbance. These releases may significantly affect the balance of emissions (Achat et al., 2015).	LCA studies should transparently state assumptions and should consider sources of emissions and sinks as they occur (indicating flows of biogenic carbon at each life-cycle stage). For wood, current standards allow biogenic carbon to be characterized with a -1 $kgCO_2e/kg\ CO_2$ biogenic carbon flow when entering the product system only when the wood originates from sustainably managed forests (ISO 21930, 2017). However, these standards also assume that current sustainability certifications are sufficient to claim carbon neutrality, which bears further testing. Flows of biogenic CH_4 also need to be included.
Long-term sequestration of carbon related to absorption of carbon dioxide by concrete	End-of-Life Stage	Several studies in the literature indicate that, over the life cycle of its use and disposal, concrete building elements can permanently absorb significant amounts of carbon dioxide from the atmosphere. ISO 21930 provides guidance on what recognized methods can be used to calculate carbonation.	LCA studies should indicate whether long-term sequestration of carbon is related to absorption of carbon dioxide by concrete, and, if so, what recognized methods of calculation are used. More research is required to guide reasonable quantification of the carbonation effect.

Table 4. Key variables that contribute to regional variability in building LCA emission estimates for Canada

Key Variables Contributing to Regional Variability	Life-Cycle Stage	Description	Recommendation
Emission intensity of production	Product Stage	For concrete, steel and wood products, production intensity associated with different manufacturing facilities can vary significantly. For steel, this can be highly variable as there is a main route from iron ore that is significantly more emission-intensive than from scrap steel. Studies do not usually clearly delineate their assumptions or provide sensitivity analysis so that they can be considered in the Canadian context. In many cases, average continent or world data is used whereas Canadian production is often considerably less carbon-intensive than global averages (e.g., our relative clean electricity supply means Canadian steel, for example, can be orders of magnitude less carbon-intensive than that produced in many other economies.)	LCA studies should transparently report production assumptions.
Recycling and reuse rate assumptions for materials at end of life	End-of-Life Stage	Recycling and reuse rates for steel can be very different regionally in Canada than those stated in the literature, which generally consider overall North American or European averages for recycling rates. One also should consider that the rate of recycling also depends on the type of steel product that is being recycled (rebar, beams, plates, wire).	LCA studies should explicitly indicate the rates of recycling or reuse that are assumed in production. Based on best practice for LCA supporting Environmental Product Declarations (ISO 21930), credits for avoided emissions due to recycling and reuse at end of life should not be included in building material product LCAs. As such, we don't consider the variability of this key variable in the analysis section that follows.
Disposal conditions	End-of-Life Stage	Wood materials that are landfilled can have very different levels of emissions depending on operational parameters associated with the receiving landfill (methane oxidation rates, methane gas capture rate, utilization or flaring).	Landfill operation assumptions should be indicated and justified in the LCA study.

Key Variables Contributing to Regional Variability	Life-Cycle Stage	Description	Recommendation
Regional variation associated with the extraction of raw materials	Product Stage	Where raw materials are sourced can significantly affect transport emissions, energy requirements and fuel types used for extraction. Wood biogenic carbon emissions and sinks are primarily affected by the combined impact of the length of the harvest rotation period and the biomass growth and carbon sequestration rates of forests from which the wood is harvested (e.g., growth rates are significantly affected by latitude with northern forests regrown considerably slower than southern latitude forests), which in turn affects the validity of the assumption of carbon neutrality that is standard in LCA analysis. If old growth primary forests are harvested, many of these forests can never reasonably recover carbon stocks leading to large emissions. Extraction emissions associated with transporting wood products are primarily related to distances from harvest sites to mills that in some jurisdictions have been increasing significantly over time.	LCA studies should explicitly state whether they are using global averages from energy and LCA databases, or whether they are using regional data. LCA studies should not make an assumption that all wood is carbon neutral and should track biogenic carbon emissions and sinks. Furthermore, they should document whether wood is harvested from forests that have a certified sustainable designation (e.g., CSA) and not assume that this is may be the case.

4.0 Impact of Uncertainties and Regional Variabilities

The LCA review identified key areas of uncertainty and regional variability associated with the life-cycle GHG emissions from alternative building construction using different concrete, steel and wood materials. The most relevant questions are whether LCA studies, as they are currently being conducted, provide an accurate and fair picture of the relative performance of different building materials in Canada and whether policies that promote construction of energy-efficient and low-carbon, climate-resilient buildings can reliably be made based on these studies. There is no question that LCA is a critical tool that provides important information both to those involved in erecting buildings and for policy-makers interested in driving down GHG emissions in the built environment. However, it should be acknowledged that there remains considerable uncertainty in results and that there are many assumptions that affect whether results are appropriate in planning the design of future buildings across Canada.

In this section, we analyze the key uncertainties and regional variabilities that are identified in our review of the literature to try and understand what impacts these uncertainties could potentially have on the existing body of LCA work. The analysis does not definitively quantify life-cycle emissions associated with any specific building or conduct new primary research, but rather draws on existing literature to identify potential ranges in GHG performance.

4.1 The Biogenic Carbon Cycle in Wood Products

The accounting of emissions and sinks in the biogenic carbon cycle of wood products is complex and can only be undertaken using sophisticated carbon models that can track exchanges between different carbon pools such as aboveground biomass, belowground biomass, litter, dead wood, soil, the atmosphere and a range of harvested wood products. Our review identifies four significant issues with existing LCA studies that contribute to uncertainty in life-cycle emissions from wood products used in buildings:

1. Choice of LCA methodology and accounting assumptions
2. Uncertainty related to the regeneration rate after harvest
3. Uncertainty related to transfers of carbon in and out of the soil carbon pool as a result of forest management practices
4. The long-term impact of climate change, potential increased demand for wood products and current forest management practices.

Each of these issues is investigated in different subsections below, followed by a final subsection that presents an estimate of the potential impacts on LCA.

4.1.1 LCA Methodology and Accounting Assumptions

In the 2015 *National Inventory Report* (Environment and Climate Change Canada, 2017b), Canada indicates that there are approximately 226 million hectares of managed forests in Canada that, through forest management activities, have sequestered carbon or contributed to an average sink of 45,400,000 tonnes of carbon dioxide equivalent (tCO_2e) per year over the last 20 years. Carbon sequestration refers to the process whereby carbon dioxide is drawn from the atmosphere by living biomass and stored (or sequestered). The carbon cycle is complex, as the carbon moves between different carbon pools (e.g., aboveground biomass, belowground biomass, dead wood, litter and soil organic matter) and can be released back into the atmosphere when wood is burned or decomposes in a process that can take many years. **The degree of uncertainty in these calculations cannot be understated.**

Uncertainty for emissions related to managed forest lands is estimated and reported in the *National Inventory Report* (Environment and Climate Change Canada, 2017b) as +/-44 per cent and is also the largest single contributor of uncertainty for any emission source/sink included in the inventory.

From a GHG perspective, the 2015 inventory results suggest that the existing level of harvest is sustainable as measured by the fact that the managed forest land emission/sink source category in the inventory has reported carbon sinks for every year since 1990. In principle, this is congruent with the idea behind the common practice in LCA analysis not to track biogenic carbon but to simply assume that whatever carbon is harvested is replaced sustainably (i.e., 1 for 1) by new forest growth in the future (GLOBE Advisors, 2017; Ochsendorf et al., 2011; Robertson et al., 2012; Salazar & Meil, 2009). In fact, for many years LCA was conducted on this principle, supported by carbon accounting guidelines set out by the Intergovernmental Panel on Climate Change (IPCC, 2006). This assumption is based on the total carbon removed by wood harvesting from the living biomass pool eventually being sequestered again in forests that are managed within the same jurisdiction. It also assumes that other biomass pools within the harvested region, such as litter, dead wood and soil carbon, are in net balance.

The recent ISO 21930 guideline indicates that, if wood is from a renewable resource sourced from a sustainably managed forest, a carbon uptake flow of -1 $kgCO_2e/kgCO_2$ of biogenic carbon flow can be assumed when entering the product system. Essentially, this works as a credit until the biogenic carbon is converted in part or as a whole into emissions by combustion or biodegradation. The guideline applies to wood products "responsibly sourced" and certified to the Canadian Standards Association (CSA), Forest Stewardship Council (FSC) and Sustainable Forestry Initiative (SFI) Standards, or other standards globally endorsed by the Programme for the Endorsement of Forest Certification International (PEFC International). ISO 21930 also notes that the concept of sustainably managed forests is not limited to recertification schemes but should include other evidence, such as national reporting under the United Nations Framework Convention on Climate Change (UNFCCC) that can be used to identify forests with stable or increasing forest carbon stocks. In Canada, the assumption around forest product neutrality is supported by the independent certification of 168 million hectares of managed forests by the CSA or other bodies endorsed by PEFC, representing almost three quarters of the country's managed forests.

Over the years, this assumption that all harvested wood can be viewed as carbon neutral if sustainably sourced has been challenged and shown to be flawed (Achat et al., 2015; Agostini, Giuntoli, & Boulamanti, 2014; Holtsmark, 2012). One argument for adopting a carbon-neutral approach in LCA is that forest management is conducted to maximize merchantable timber for harvesting, which equates to maximizing short-term growth in aboveground biomass stocks, limiting losses from natural disturbances and sequestering carbon in long-lived harvested wood products (HWPs). Some studies have shown that management practices favouring lower harvesting frequencies and higher structural retention sequester more carbon than the more common intensive practices (Bell et al., 2017). Other studies suggest that young forests (whether through forestry or natural disturbance) are very often conspicuous sources of carbon dioxide because the creation of new forests frequently follows GHG emissions associated with disturbances to soil and existing vegetation that outpaces net primary production of the regrowth (Bell et al., 2017). In any case, it is unclear whether current practices are aligned with long-term carbon sequestration objectives and, importantly, FSC and other sustainable certification systems should not be assumed to inherently address carbon management in certified forests.

Since forest management can act in many ways to diminish or improve carbon sequestration, it is important to consider different forest management activities that could enhance carbon sinks, including longer rotation logging and decisions not to harvest as a response to climate change, in much the same way that steel and concrete manufacturers are adapting manufacturing practices to reduce product stage emissions.

In response to the challenge that not all biomass should be considered to be carbon neutral, recent LCA methodologies have developed a metric that assesses the global warming potential of biogenic carbon dioxide (GWP_{bio}). Whereas assuming carbon neutrality is essentially the same as assuming a GWP of zero, these studies consider forest growth models and radiative forcing effects over the lifetime of emissions and sinks (Holtsmark, 2015). This is particularly important for wood used for bioenergy that releases carbon dioxide immediately which is not recovered for decades or more, leading to a temporary increase in atmospheric carbon dioxide, and hence increased radiative forcing and global warming. The effect is considerably smaller for wood products used in buildings that store carbon for a long duration (i.e., those that remain in use at least as long as it takes to fully restore carbon losses from harvesting and producing the wood elements); however, note that significant bioenergy is used in the manufacture of these products in Canada and that the amount of wood or carbon stored in long-lasting harvested wood products such as timber generally accounts for a very small percentage (as little as 15 per cent according to GLOBE Advisors [2017]) of the overall wood or carbon that was removed and harvested from the forest.

Studies have also pointed out that, even if forests have sufficient regrowth to replace lost carbon and the replacement rate of carbon is fast enough to ensure that there are no net emissions or contribution to overall radiative forcing and climate warming, it may not be reasonable to assume that wood products have no net embodied biogenic carbon emissions (Ter-Mikaelian, Colombo, & Chen, 2015).

4.1.2 Regeneration Rates of Managed Forests

There is also a growing number of studies that suggest that not all forests in Canada are being sustainably managed from a carbon perspective (GLOBE Advisors, 2017). Current regulatory approaches that oversee provincial and territorial forest management are generally decades old and were not conceived with carbon management in mind. Similarly, the major sustainable forest management certification schemes do not specifically address carbon (National Council for Air and Stream Improvement, Inc., 2013). Forests managed under the PEFC and the CSA Sustainable Forest Management systems have been criticized for inadequate protection of managed forests, and regeneration rates for some forests are below the legally mandated 100 per cent required (Axelrod, 2017). Particularly concerning is the conversion of old-growth primary forests to young-growth forests that occurs under all available regulatory and certification schemes, and the permanent loss of carbon capital that this can entail. Estimates vary, but, depending on the tree species harvested, harvesting methods, forest management rotation and practices, simulations estimate that as little as 40 per cent of the carbon initially harvested from a mature stand may be reabsorbed by growing trees (GLOBE Advisors, 2017). Additionally, these impacts are further exacerbated by temporary and permanent losses to the forest land base as a result of land converted to building access roads and operating areas. This results in a very large release of emissions that are never recuperated under forest management and not currently accounted for in LCAs.

4.1.3 Soil Carbon Pool

Most of the carbon stored in Canada's managed forests is stored in soils. Estimates for boreal forests find that between 65 per cent and 95 per cent of forest carbon is stored in soils (Bell et al., 2017, p. 16; Bradshaw & Warkentin, 2015; Lal, 2005). The long-term impacts of forest management on soil organic carbon is unclear (Achat et al., 2015) and carbon emissions from soils may be underestimated (Buchholz et al., 2014; GLOBE Advisors, 2017). Harvesting practices have been shown to have a significant impact on long-term soil carbon stocks, where net emissions occur under certain conditions. Clearcutting practices, which represent the predominate model of forestry in Canada and globally, expose soil organic carbon to sunlight and construction of logging roads, both of which have a particularly detrimental impact on soil carbon storage. Most LCA analysis of wood products that track biogenic carbon sinks and emissions assume that soil carbon stocks remain constant over time. The extent to which different forest management practices may be deleterious to soil carbon is unclear due to the difficulty in monitoring. Studies suggest that intensive harvesting of tree stems and logging residues can significantly decrease soil carbon. A review of 75 publications conducted by Nave et al. (2010) found that forest harvesting resulted in a significant 8 per cent decrease in total soil carbon on average in temperate forest soils, and a meta-analysis of 945 responses to harvesting collected from 112 publications on carbon dynamics found that soil carbon decreased by an average of 11 per cent after harvest (James & Harrison, 2016). Because of the size of the soil carbon pool, even if harvesting practices led to a small decrease in soil carbon that is reabsorbed by soils in a relatively short time frame, the impacts can be significant, particularly over the large areas implicated.

4.1.4 Long-Term Sustainability of Managed Forests

There is concern over the long-term health of forests and the uncertainty of the long-term effects of harvesting on carbon dynamics. Clearcutting accounts for close to 90 per cent of the forestry activities in Canada (Grant et al., 2010), and this type of practice that removes the majority of above ground biomass can remove substantial nutrients that are needed to rejuvenate the soil and ultimately contribute to long-term carbon loss. Climate change is also a very concerning element that may affect the health of Canadian forests. Higher temperatures, changing stream flows, and increases in pests and disease threaten the ability of both primary forests and managed forests to regenerate. These stresses may result in many forest management areas in Canada being unable to sustain the assumed rate of carbon sequestration or even lead to net emissions from Canadian forests (GLOBE Advisors, 2017). As an example, a recent study that modelled climate-induced vegetation change in Alberta concluded that, over the next century, approximately half of Alberta's boreal forest could be lost to wildfire (Stralberg et al., 2018). These climate change stresses challenge the idea that existing forest management practices are sufficient to ensure a sustainable forest industry.

There are additional climate forcers related to forest management that are rarely included in LCA studies but which may have important effects including landscape albedo, evapotranspiration, aerosols, black carbon and the potential for increased forest growth rates due to the carbon fertilization effect. In many respects, the impact of these climate forcers may be similar in magnitude to biogenic carbon (Agostini, Giuntoli, & Boulamanti, 2014) and a better understanding of how these forcers affect climate is needed.

There is also significant anticipation in Canada for increased competition for wood and demand for wood products for bioenergy use, as a feedstock for biofuels, for short-lived wood products such as paper and cardboard, and for long-lived harvested wood products used in construction. Increased demand will likely mean increased intensity of production in existing areas. This in turn implies increased harvesting of primary old-growth forests (i.e., that have never been harvested before) and the attendant conversion of natural or unmanaged forests to managed forests. As previously noted, many studies have demonstrated that conversion of unmanaged forests results in a loss of carbon that is never recovered; additionally, there are increased risks for species habitat and biodiversity. Many scientists have advocated that significant increases in the area of protected forests are necessary to address these threats and to protect long-term carbon stocks. Consequential LCA studies and modelling should be conducted to determine what effects increased wood demand scenarios have on the sustainable supply of wood and on the balance of emissions and sinks. Consequential LCA provides information about the consequences of changes in the level of output (and consumption and disposal of a product, including effects both inside and outside the life-cycle boundaries of the product).[3] The choice of the baseline case from which to measure net emissions or sinks is fundamental and can lead to dramatically different life-cycle emissions for concrete, steel and wood building products.

Natural Disturbances

Natural disturbances include forest fires, insects, disease and weather damage. These large inter-annual variations in emissions are now separated out in the national inventory from changes in carbon stocks related to forest management to better represent human-controlled emissions and removals in managed forests. Excluding natural disturbances isolates anthropogenic impacts related to forest management practices and natural drivers.

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[3] An example of its application is in the assessment of corn-based ethanol in the United States (Searchinger et al., 2008). In this example, attributional LCA indicated that emission reductions associated with corn-based ethanol would be 20 per cent lower when compared to gasoline, but a consequential LCA that considered the increase in demand predicted a 47 per cent increase in emissions compared to gasoline because of the land use changes induced by higher prices for corn, soybeans and other grains.

There is considerable debate on how natural disturbances and forest management practices should be treated in national inventory accounting (Lee & Sanz, 2017; UNFCCC, 2011). On the one hand, there is a recognition that force majeure events cannot in many cases be controlled and that the burden of these emissions shouldn't necessarily be placed on the forest industry. On the other hand, many experts have identified that exclusion of natural disturbances results in asymmetric accounting that can inflate carbon sinks from forest management (UNFCCC, 2011) and that, ideally, all forest activities should be included to provide appropriate signals to achieve higher levels of carbon sequestration in the land-use sector. Methodologies are still evolving with regards to how best to exclude natural disturbances that are beyond human control that occur on managed lands, but there is some question of whether it is equitable for forests that are under management to accept full credit for carbon sinks that are a natural process of regenerating forests but then fail to acknowledge in the same ledger any emissions that may occur from natural disturbances.

To get a picture of actual changes to carbon stocks in Canada's managed forests, it is necessary to include natural disturbances. Figure 3 identifies the net emissions with natural disturbances, representing actual net changes in carbon stocks from managed forests in Canada.

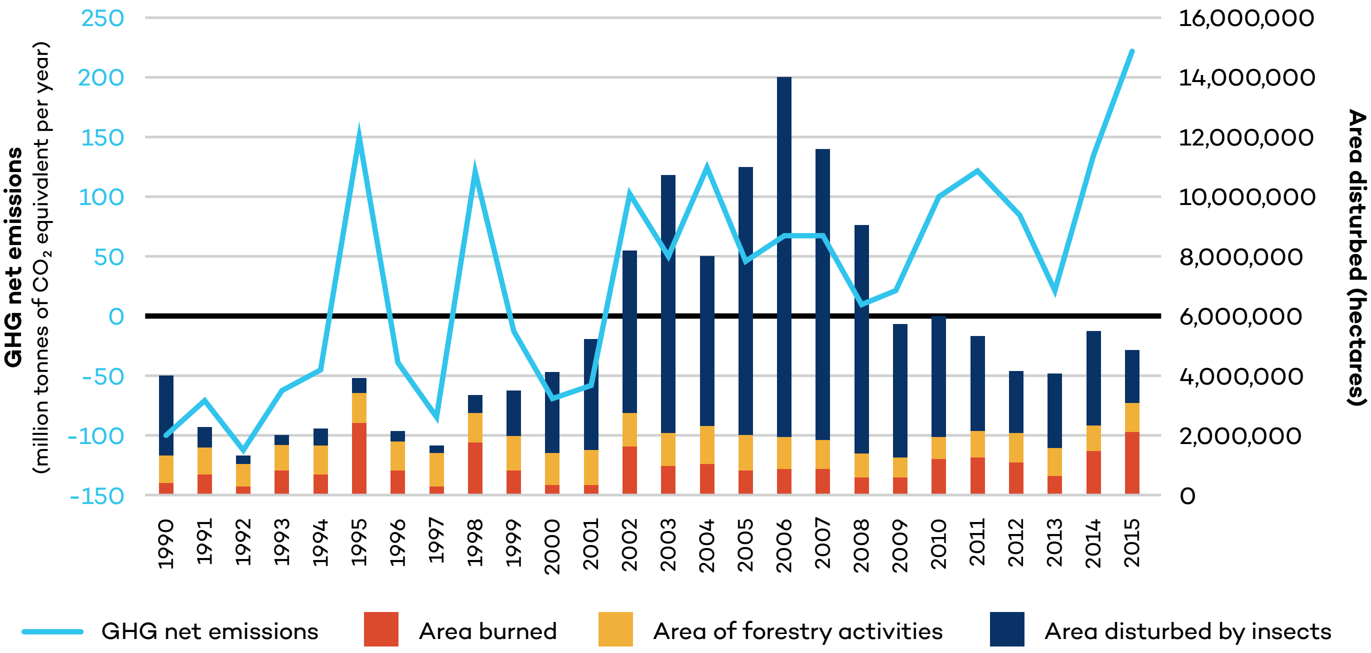

Figure 3. Net emissions from managed forests in Canada (1990–2015)

Source: Environment and Climate Change Canada, 2017b

Net emissions indicated in Figure 3 by the light blue line over the last 20 years are an average of 50,100,000 tCO_2e per year. While future projections of managed forest emissions and sinks are inherently uncertain due to the difficulty in modelling natural disturbances and climate change feedback loops, a comprehensive integrated analysis of the climate change mitigation potential for Canada's managed forests was conducted by Smyth et al. (2014). Net emissions were projected to increase significantly over the next 30 years, with average net emissions close to 100,000,000 tCO_2e per year over this period. These net emissions are driven by an even greater expectation of the extent of natural disturbances. Climate change effects, including changes in temperature, precipitation and season length, are cited as main drivers of increased natural disturbances (Environment and Climate Change Canada, 2017b).

The actual relationship between natural disturbances and forest management practices is complex. Forest management practices influence natural disturbances; for example, the risk of forest fires and their intensity can be exacerbated by certain forest management practices. Conversely, there are also many aspects of forest management that are aimed at reducing stand losses, and thus have the potential to contribute to lower losses from these disturbances, at least given current practices and harvesting rates.

Policy-makers and LCA practitioners need to understand that the use of wood products is not inherently sustainable, and that the accounting of biogenic carbon is extremely complex and has a high degree of uncertainty. Emissions and sinks are driven by a multitude of different forest management practices across a very diverse range of forests and conditions across Canada. This complex system is now threatened by increased disturbances driven by climate change. A meaningful carbon accounting for wood products must include all emissions alongside net carbon sequestered; otherwise, we may develop incongruent policy decisions.

4.2 Sensitivity Analysis

An appropriate study of the overall potential impact of uncertainties associated with biogenic carbon for Canadian forests would be a complex undertaking given that forest management practices are unique to each forest stand and that many complex factors contribute to exchanges of carbon between the atmosphere and different carbon pools. It is incumbent upon national and provincial institutions responsible for forest management and protection to model these uncertainties and identify scenarios that can optimize carbon sequestration in our forests.

The review presented herein takes a simple mass balance approach to testing the sensitivity of different uncertainties related to biogenic carbon emissions and sinks compared to the carbon-neutral baseline that is widely adopted in LCA (National Council for Air and Stream Improvement, Inc., 2013). In this analysis, carbon exchanges between forest pools, harvested wood products and the atmosphere are tracked annually and consider a 60-year harvest rotation within a 100-year assessment period. Selection of a shorter rotation period would increase the estimated net emissions, while a longer harvest rotation period would decrease net emissions. The analysis is not representative of a particular forest or region, but the goal is to test the potential GHG emissions impacts of the following scenarios. Scenarios 1, 2 and 3 are isolated and independent of one another while Scenario 4 combines the impact of all three scenarios (1,2 and 3):

1. Assume that the regeneration rate of a forest that is currently certified by the CSA and currently reported to be 100 per cent or greater is in actual fact overestimated and is at a rate of only 90 per cent due to insufficient forest renewal management practices.
2. Consider an outcome for a boreal forest where there is a net permanent loss of 5 per cent soil carbon attributed to clear-cut harvesting.
3. Consider the conversion of a natural forest with a mature stand of trees to a managed forest with short rotations to maximize yields (40 per cent loss in overall aboveground carbon stock).
4. Combined impacts of Scenarios 1, 2 and 3.

The scenarios were constructed using values derived from the scientific literature described earlier. However, the baseline and the four scenarios are conducted to provide a view of a possible range of impacts due to the identified uncertainties but do not represent probabilistic outcomes or average or specific conditions for Canadian managed forests. More research and regional modelling are required to determine the probability of impacts. Detailed calculations and assumptions related to each of the four scenarios are provided in Annex B.

One-hundred-year GWP_{bio} factors[4] were calculated for LCA analysis and are presented in Table 5. Separate GWP_{bio} factors could be calculated for short-lived HWPs and long-lived HWPs; however, an average is used that can

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[4] GWP_{bio} is a metric that can be used to assess the global warming potential of biogenic carbon dioxide. A factor of zero would indicate that the biogenic carbon would not contribute any net emissions (carbon neutral) nor increase or decrease radiative forcing over a period of time. A factor of 1 would indicate a radiative forcing equivalent to carbon dioxide emissions from fossil fuel combustion sources.

be applied both to the embodied carbon in structural wood building elements and to the bioenergy that is used to manufacture these products. Combining them also reflects the fact that they are often not substitutable, for example, of the merchantable timber transported to the sawmill, only about half is typically converted to long-lived wood products (GLOBE Advisors, 2017).

Table 5. Estimated GWP_{bio} factors for four carbon biogenic scenarios

Scenario	GWP_{bio}
Baseline – Carbon Neutral	0
90% Regeneration Rate (Scenario 1)	0.0625
Soil Carbon Loss (Scenario 2)	0.286
Conversion of Natural Forest (Scenario 3)	0.509
Combined Scenario (Scenario 4)	0.835

GWP_{bio} factors have been calculated using more sophisticated forest growth models and a wide range of results is reported. A GWP_{bio} range of 0.13 to 0.32 was indicated in a recent study that examined the effects of different harvest rotation periods and the percentage of long-lived products versus short-lived products (Liu et al., 2017). The longer the rotation period and the greater the proportion of short-lived HWP, the greater the relative GWP_{bio} factor.

Using published results of embodied life-cycle emissions (cradle to gate) for different wood products including softwood lumber, softwood plywood sheathing, OBS strand board and Glulam of the Athena Sustainable Materials Institute, embodied emissions rise by a factor of from 1.3 to almost 10 times, depending on the assumptions and the product. Figure 4 identifies the changes in embodied emissions estimated for these wood products and the three scenarios outlined above.

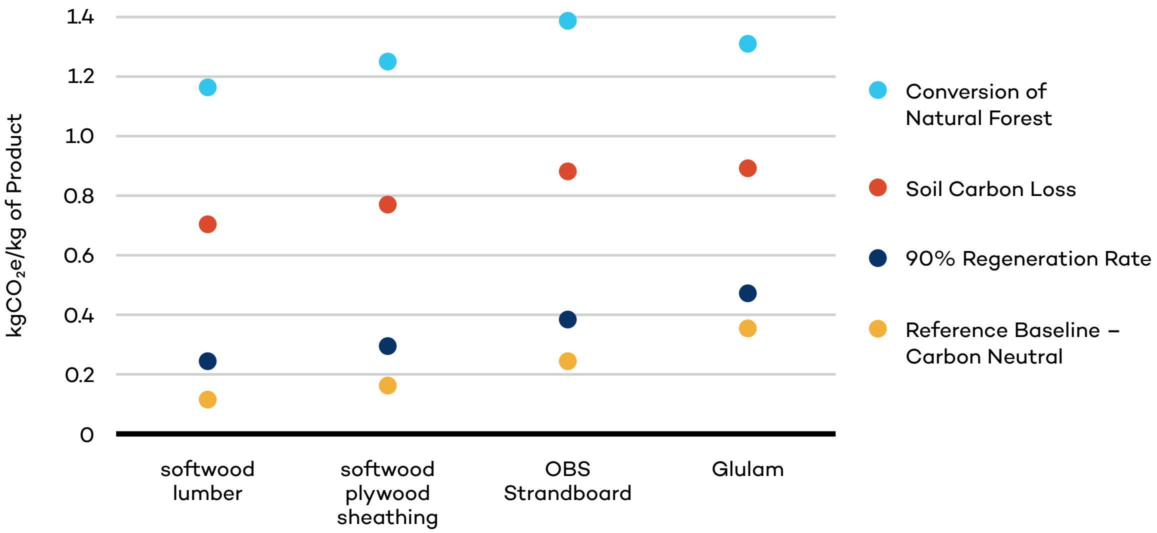

Figure 4. Cradle-to-gate life-cycle greenhouse gas emissions of four wood products under different assumptions

Note: Baseline data from life-cycle assessment studies prepared by the Athena Sustainable Materials Institute.

In order to assess overall building life-cycle impacts, a typical LCA study comparing alternative design construction for a wood and concrete mid-rise residential building conducted by Morrison Hershfield was selected (Morrison Hershfield, n.d.). This LCA estimated whole-building LCA results between two structural frame versions, one of wood and one of concrete, that had equivalent building energy requirements. This example is typical of LCA work found in the literature and estimates that cradle-to-gate life-cycle emissions for a defined wood construction had 36 per cent lower GWP than a concrete alternative. The study assumes that biogenic carbon emissions are carbon neutral and do not contribute to the GWP. The three main wood building components included in the designs are Glulam sections, orientated strand board and softwood lumber. Based on the total mass of these components, the calculated emission intensity and the biogenic carbon emission factors associated with each scenario analyzed above, the additional biogenic carbon emissions for the concrete and wood building can be calculated. The cradle-to-gate emission comparison to the baseline is provided in Figure 5.

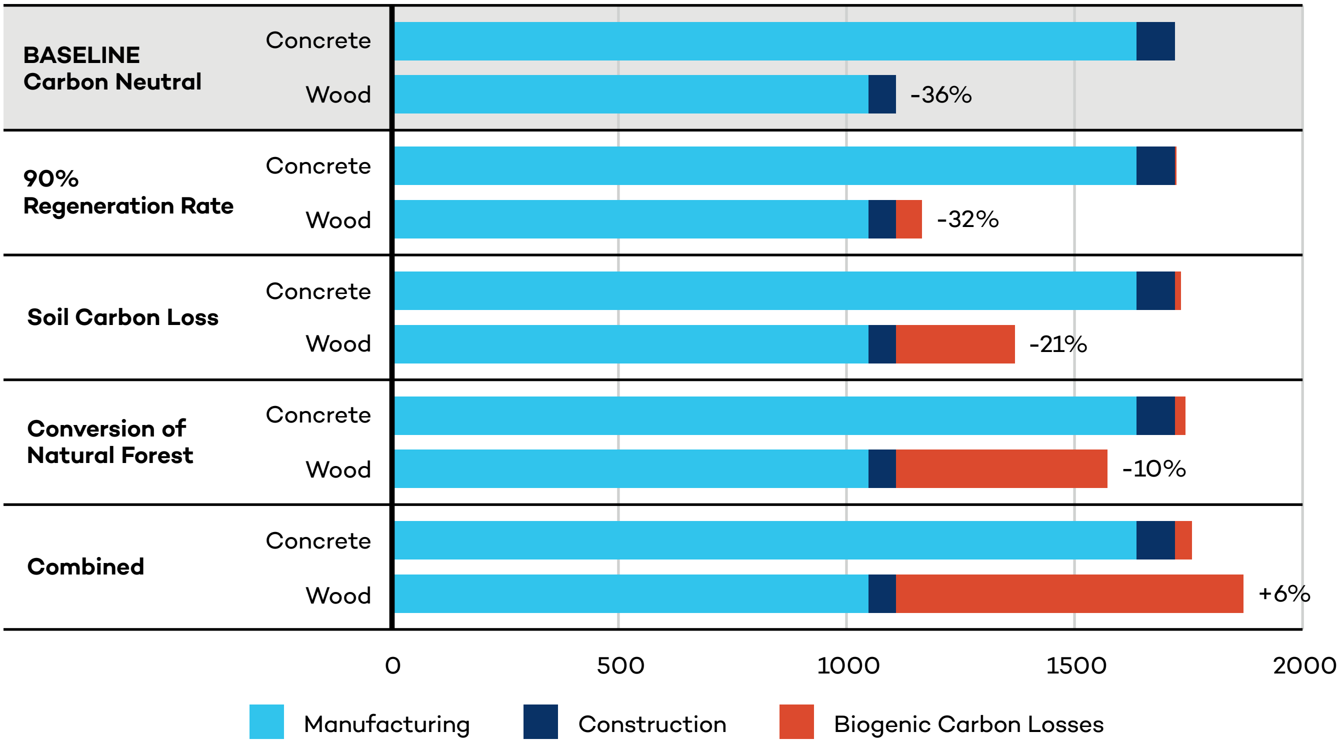

Figure 5. Whole-building cradle-to-gate life-cycle GHG emissions: Alternative wood and concrete building construction considering four different forest management scenarios

Note: The functional unit is the whole building, based on a concrete and wood building design that has similar operational and service efficiency.

Because use-stage life-cycle emissions typically dominate, the relative impacts between baseline and the four different forest management scenarios is typically much smaller than indicated in Figure 5, which only considers cradle-to-gate emissions. Figure 6 presents the relative difference between the wood and concrete building for the scenarios and a range of possible use-stage life-cycle emissions and represent whole-building LCA. The existing construction for a wood and concrete mid-rise residential building in Quebec City conducted by Morrison Hershfield reports very high use emissions (~95 per cent of cradle-to-gate and use-stage emissions) and is represented by the extreme end of the range of overall impacts for typical buildings in Canada identified in the figure. Relative impacts are greater if the fraction of use emissions is higher, as would occur in more moderate climates in Canada in buildings with higher energy efficiency and buildings with lower operational lifetimes. In Figure 1, average building use emissions to total life-cycle emissions is identified in the literature to be around 80 per cent.

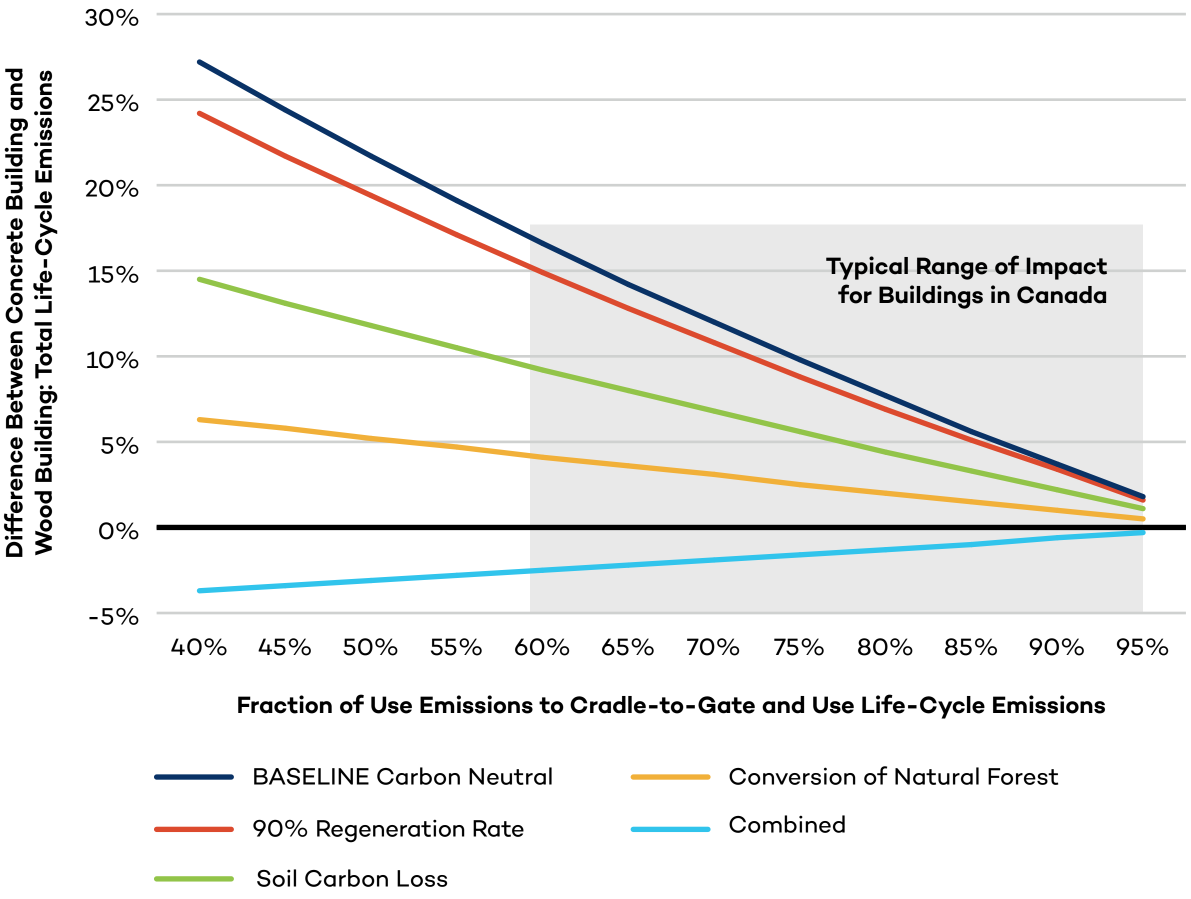

Figure 6. Whole-building, cradle-to-gate and use-stage life-cycle greenhouse gas emissions for a range of use emissions and considering four different forest management scenarios

Note: The functional unit is the whole building, based on a concrete and wood building design that has similar operational and service efficiency.

The discussion and analysis in this section challenges the validity of the typical assertion that building LCA can safely assume that wood products in Canada are carbon neutral. While the review cannot provide insight into the general likelihood of these types of impacts for any specific wood building product certified as sustainably sourced in Canada, it does identify the potential that life-cycle emissions for wood products are significantly higher than presented in the literature. **Detailed study and modelling are required to investigate specific regions and managed forests within Canada and to consider the cumulative radiative forcing impacts of multiple harvest cycles.**

4.2.1 Long-Term Carbonation of Concrete

To make concrete, significant carbon dioxide emissions are released during the production of cement through a chemical reaction referred to as calcination. The calcination process releases approximately 526 kgCO_2/t clinker during the production of cement (Environment and Climate Change Canada, 2017b, Appendix A6.2). Throughout the lifetime of concrete, carbon dioxide is slowly reabsorbed by the concrete through a reverse of the calcination reaction referred to as carbonation. The theoretical limit is that almost all carbon dioxide released in calcination can be reabsorbed eventually; however, in typical applications of concrete in buildings, the fraction that is reabsorbed during the building lifetime is small, and how much is absorbed at the end of life depends significantly on disposal conditions. The practical limit that carbonation of concrete can bind or sequester carbon dioxide varies based on a large number of factors but has been found to be generally in the range of 30–90 per cent of the total calcination emissions released in the manufacture of its cement constituent (Andersson, Fridh, Stripple, & Häglund, 2013). On a global scale, the carbonation of cement materials has been estimated to represent a large and growing sink of carbon dioxide, with one estimate that a cumulative amount of 4.5 GtC has been sequestered in carbonating cement materials from 1930 to 2013, offsetting 43 per cent of the carbon dioxide emissions from the production of cement over the same period (Xi et al., 2016).

Carbonation effects have not been typically considered in LCA studies. Recent guidelines, including ISO 21930 (2017,) support the inclusion and estimation of carbonation at the use and end-of-life life-cycle stages.

The time dimension of carbonation and the treatment of concrete at a building's end of life are extremely important. During a typical building life (60–100 years), carbonation is estimated to be very small, 1 to 2 per cent (Andersson et al., 2013; Collins, 2009). This is driven by the fact that carbonation in existing concrete structures is closely related to exposed surface area to volume ratio of concrete and the associated carbonation depth. In most applications, only the first few millimetres of exposed concrete surface are significantly carbonated, even over a building's lifetime. Most carbonation typically occurs for concrete at end of life, particularly if concrete is crushed and broken into waste fragments with higher surface area available to react with carbon dioxide. The smaller the waste fragments and the more direct exposure to the atmosphere, the significantly higher the rate of carbonation.

Typical concrete at end of life is employed as a fill material, for example as unbound rock or gravel for use as embankment protection or sub-base for pavements. Some concrete of course is still landfilled. While studies indicate that as much as 80 per cent of total calcination emissions could be reabsorbed during the first 20 years with an end-of-life management system that maximizes the degree of fragmentation and exposure of the fragments to the atmosphere, current practice, which focuses the use of concrete as a base material with low air exposure, would have much lower rates of carbonation. Estimates of 11–20 per cent within a 20-year end-of-life time frame based on current practices are more realistic (Andersson et al., 2013; Collins, 2009).

Since calcination emissions account for approximately 25–30 per cent of total embodied life-cycle emissions from concrete for production and construction life-cycle stages (Collins, 2009), including carbonation in LCA analysis for production and construction life-cycle stages could contribute to an overall reduction in concrete-embodied life-cycle emissions of 3 to 6 per cent with current practices. If end-of-life management of concrete were optimized for carbonation, overall reduction could be as high as 20 per cent. Note that these estimates are overstated, as they ignore the considerable time lag between production emissions and of end-of-life removals of carbon dioxide.

Appropriate LCA should consider the radiative forcing climate impact between calcination emissions and carbonation absorption of carbon dioxide.

It is advised to be careful to avoid double counting of end-of-life concrete management that optimizes carbonation where it is considered in LCA. Only carbonation during the use stage and for the standard practice of disposal at end-of-life (e.g., burial of concrete on site) should be considered. In this case, the carbonation effect would not exceed 11–20 per cent of the calcination emissions, or 3–6 per cent of overall embodied life-cycle emissions of concrete products. Due to uncertainties regarding both the potential and long timescale of the absorption of carbon dioxide carbonation, it is recommended that the conservative lower end of this range be considered. From an overall building life-cycle emissions perspective, the impact of including the carbonation effect will be very small. It is unlikely that cradle-to-grave embodied emissions for a building would be reduced by more than 0.5 per cent even where there is a substantial amount of concrete used in an energy-efficient building where use-stage emissions are much lower than average.

4.3 Regional Variability

Table 6 presents a description of key variables that contribute to the potential for regional or project variability in life-cycle emissions and estimates the impact of regional variability in Canada as a percentage of overall life-cycle product emissions.

Table 6. Key variables that contribute to regional variability in building LCA emission estimates for Canada and estimates of overall life-cycle impact of product emissions

Key Variables Contributing to Regional Variability	Life-Cycle Stage	Description	Regional Variability in Canada as a Percentage of Overall Life-Cycle Product Emissions
Emission intensity of production	Product Stage	For concrete, steel and wood products, production intensity associated with different manufacturing facilities can vary significantly. However, only the process of making steel is likely to have a significant impact on overall life-cycle product emissions. For steel, this is highly variable, as there is a BOF route from iron ore and a significantly less emission-intensive route from EAF production using scrap steel. Studies do not usually clearly delineate their assumptions or provide some sensitivity analysis so that they can be considered in the Canadian context. In many cases, average continent or world data is used.	Sourcing steel from the BOF route in Canada would result in approximate emissions of 1.4 to 1.8 tCO_2e/t of crude steel produced. Sourcing steel using the recycled steel EAF route in Canada and assuming renewable electricity would result in approximate emissions of 0.15 to 0.25 tCO_2e/t of crude steel produced (Hasanbeigi, Arens, & Price, 2013). For typical steel products such as primary frames, secondary frames and roof/wall panels, BOF route emissions can account for 60–80 per cent of overall embodied emissions. As a result, alternative sourcing of recycled steel produced using the EAF route would enable overall embodied emission reductions on the order of 50–73 per cent. However, note that some steel products cannot be manufactured from EAF and scrap steel due to impurities and quality issues.

Key Variables Contributing to Regional Variability	Life-Cycle Stage	Description	Regional Variability in Canada as a Percentage of Overall Life-Cycle Product Emissions
Disposal conditions for wood products	End-of-Life Stage	Wood building materials that are landfilled can have very different levels of GHG emissions depending on operational parameters associated with the receiving landfill (methane gas capture rate, utilization or flaring). Most LCA studies that account for end-of-life emissions from wood sent to landfill consider average regional disposal characteristics.	Disposal of wood building products to landfills without emissions capture processes (e.g., no methane recovery, no landfill flaring, wet climate, managed site with greater than 10m depth and frequent surface covering) can lead to end-of-life GHG emissions as high as 3.85 kgCO_2e/kg of wood disposed (IPCC, 2006). However, the time element of decomposition needs to be considered, as these emissions would be distributed over a long time period – e.g. the half-life of decomposition could be greater than 50 years for some wood building products. Actual emissions are typically much lower due to gas recovery, flaring and utilization, as well as lower degradable organic content perhaps as low as 0.39 kgCO_2e/kg wood (IPCC, 2006). Based on the 2017 National Inventory Report (Environment and Climate Change Canada, 2017b), approximately 38 per cent of methane emissions generated at all municipal solid waste disposal sites in 2015 was flared or utilized, or, conversely, 62 per cent of methane generated was released to the atmosphere. However, for wood products disposed of from a specific building site, the actual rate will depend on landfill that receives the waste, where the rate in Canada could vary anywhere from nearly 0 per cent capture to nearly 100 per cent. It is expected that capture rates will increase significantly over the next couple of decades, as the value of landfill methane and stringency of carbon pricing policies increase.

Key Variables Contributing to Regional Variability	Life-Cycle Stage	Description	Regional Variability in Canada as a Percentage of Overall Life-Cycle Product Emissions
Regional variation associated with the extraction of raw materials	Product Stage	Where raw materials are sourced can significantly affect emissions. It impacts transport emissions, energy requirements and fuel types used for extraction, and, in the case of wood, it could mean significant differences in biogenic carbon profiles related to forest type, age, latitude and harvesting practices. Regions where there is substantial conversion of natural forests may have significantly greater emissions. For cement and steel, the main drivers of variability are whether energy used for extraction is from renewable electricity versus fossil fuels and the distance and emission intensity of transport of raw materials to manufacturing sites. Availability of lower-carbon kiln fuels (e.g., waste-derived biomass) for cement manufacturing is also an important regional variable in determining the overall carbon intensity of the final concrete products.	There are many potential contributing factors to regional variation, though reliable estimates could not be derived from the literature

5.0 Longer-Term Climate Objectives

To stay within climate-safe limits, it will be critical for the built environment to reduce the embodied carbon from materials used, including steel, concrete and wood. Steel and concrete, as noted above, currently have significant embodied emissions related to their production, while harvesting of wood products could result in a release of naturally sequestered biogenic carbon and a decline in carbon sinks. There are current best practices and technologies to reduce emissions across all sectors. However, game-changing, innovative technologies and practices will be necessary to achieving mid-century climate objectives for all three products.

In addition, just as the emissions from the products themselves are critical, so too is the performance of buildings with respect to energy. Energy-efficiency performance and building longevity/service life will be influential in building design and product choice going forward, particularly considering increased stringency in building codes and the introduction of carbon pricing across Canada.

In light of mid-century climate objectives and the influence they will have on the building sector, in this section we first look at opportunities to improve the energy efficiency of the built environment. We then examine short- and longer-term opportunities to produce more sustainable construction materials.

5.1 Energy Efficiency and the Built Environment

As noted, structural building decisions are affected by a number of factors, including advancements in energy efficiency. Advancements in building products, as well as in operational or mechanical systems applied and operated in buildings, will increasingly influence how (and how much/what type of) energy is consumed, and therefore have economic and environmental impacts on the sector.

Looking ahead to policies that will increasingly monetize GHG emissions associated with energy (such as the Pan Canadian Framework on Clean Growth and Climate Change), builders will continually look at ways to reduce emissions and therefore reduce their economic exposure. Efficiency is consistently cited as one of the most cost-effective ways to reduce emissions in the building sector (International Energy Agency, 2016; Lucan et al., 2014; McKinsey&Company, 2010; Natural Resources Canada, 2018a).

Energy efficiency is a consideration in material choice, construction options and operations of the buildings, as well as the rules and regulations applied to the building sector. We also look at other potential advancements in building construction (including innovative green building programs) that could influence decisions on building materials in the near future.

5.1.1 Construction

There are many energy-efficiency elements that come into play in building envelope discussions. For example, an exterior blanket for insulation can increase energy efficiency and improve thermal comfort and air tightness in a building (Pearl & Chen, 2017). The Passive House standard encourages exterior blankets, and it is often used where there are no wall cavities as an effective way to manage temperature fluctuations (Bax, Cruxent, & Komornicki, n.d.). Concrete buildings can benefit from external blankets, particularly in regions that experience significant temperature changes through the various seasons of the year.

Another external feature to influence energy efficiency is balconies in mid- to high-rise buildings. Designing and constructing a broken cantilevered balcony system through a rigid insulation and fiberglass rebar can reduce the heat transmittance through the slab by up to 75 per cent; therefore, the interior surface temperature is increased and it improves condensation control (Pearl & Chen, 2017; The Construction Specifier, 2014). As explained by The Construction Specifier, "A typical manufactured structural thermal break replaces the concrete between the exterior balcony and the interior slab with an insulating material such as high-density, graphite-enhanced expanded polystyrene (EPS). Pre-engineered thermal breaks can be used for concrete-to-concrete, steel-to-steel or concrete-to-steel with a thermal break module between an external balcony and an internal structural frame" (The Construction Specifier, 2014).

Roofs are another external element paramount for providing weather protection, and also to reduce heat transfer and maintain a comfortable environment in the building. There are a variety of materials that can be used for roofing. Steel roofing, for example, is gaining momentum as a popular green building material due to its high recycled content and durability. Composite is also used as an alternative material, made from plastic and rubber, designed to look similar to natural materials such as slate and wood. Due to their composition of recyclable materials, they are viewed as an option for green building materials and have lower embodied energy than the natural material alternatives (e.g., stone/slate) (Singh, 2014).

What happens inside walls also plays a role in a building's energy efficiency. For example, steel stud walls are good conductors of heat, thus significantly reducing a wall's effective R-value. By insulating the outside steel stud wall structure between concrete floor slabs, the heat transfer is greatly reduced (Pearl & Chen, 2017). The type of insulation also makes a difference in the R-value of walls, where advanced insulation foam can provide significant energy saving and is moldable to different building configurations, reducing energy costs by 30–80 per cent (Bax, Cruxent, & Komornicki, n.d.). One example is insulated concrete forms that are made out of polystyrene or polyurethane foam, filled with concrete and interlocked with blocks or panels. Through the stacking or interlocking system, a considerable amount of thermal mass and structural support is easily maintained, and it is a durable material with longevity (Pearl & Chen, 2017; Singh, 2014). This has been mostly used under Passive House, LEED and net-zero standards. Insulation can also be made with raw/bio-materials, such as straw. Straw can be mixed with concrete or with mud, which can be fire, vermin and decay resistant as well (McGee, 2013). While energy efficiency can be an advantage to a building constructed of any type of material, the approach will differ with hollow or solid walls, and this may influence material choice. Insulation is also used with wood panels, such as the structural insulated panels (SIPs) that are composed of foam insulation between two sheets of orientated board. SIPs provide superior insulation and air-sealing features that create high R-values in walls (Singh, 2014).

A less-used type of insulation is phase-change material (PCM). PCM can be used with insulation materials inside walls, serving as a passive solar system. Latent heat storage through the use of PCM provides an attractive solution to absorbing, storing and releasing heat in a building through the process of melting and freezing. PCM functions where the thermal inertia of walls and ceilings are absorbed: it stores excessive heat during the day and releases it during the night when air temperatures have gone down (Bax, Cruxent, & Komornicki, n.d.; Kośny, 2015). PCM's ability to store and release heat reduces temperature fluctuations inside the building, reducing the need to use air conditioners to keep temperatures cool, for example, therefore reducing energy use (Bax, Cruxent, & Komornicki, n.d.). As insulation, PCM can be used with wood and steel structures. Studies have been conducted to understand the feasibility of using PCM with concrete walls. However, there is a risk of leakage with this material (Chen, Kessel, & Wolcott, 2012), thus it is not as widely used as other foam materials.

Other design measures can also support energy efficiency in a building, such as minimizing ceiling-to-wall ratio to obtain greater insulation and increase wall thickness (Stevens, 2017). Using cantilevered nail laminated timber roof and upper floor structures can also help to address seasonal sun paths and permit winter solar gains while limiting solar exposure in the summer (Craig & Jahraus, 2017). In addition, reducing the amount of use of glass walls or large windows can also increase energy efficiency in buildings. Some jurisdictions have already restricted all glass towers under the building codes. For example, the City of Toronto has banned all glass towers under the building codes. Ontario has also been moving to stricter exterior requirements for glass buildings (Lorinc, 2016).

Thermal mass also plays a role in efficiency. Thermal mass can reduce peak cooling loads and air temperature peaks and valleys in buildings. Storing heat in the outer envelope and interior of a building in its construction materials allows it to be slowly released to the indoor environment. In winter, stored heat is released when it is needed, and, in summer, heat can be stored to reduce internal temperatures and reduce energy need for cooling. Careful consideration of thermal mass can have a significant energy-efficiency impact (Balaras, 1996).

Table 7 summarizes the different measures discussed above and their applicability to wood, steel and concrete.

Table 7. Exterior and interior measures to boost energy efficiency

Building Feature	Measure	Applicability to Wood, Steel and/or Concrete
Exterior	Exterior blanket	Wood, steel and/or concrete
	Passive solar heating	Wood, steel and/or concrete
	Thermal break for balconies	Wood, steel and/or concrete
	Roofs	Wood, steel and/or concrete
	Nail laminated timber	Wood
	Reduced glazing	Wood, steel and/or concrete
Interior	Insulated concrete forms	Wood, steel and/or concrete
	Insulation with raw materials	Concrete
	Insulation SIPS	Wood

5.1.1.1 Challenges and Opportunities

Through access to information on energy use (data), construction measures and efficiency opportunities, relevant stakeholders in the building construction sector are able to increase their knowledge and understanding of energy efficiency and environmental impact and support the transition into a low-carbon building sector. However, data sources on energy-efficiency technologies are not readily available, and for the most part are scattered throughout various governmental departments, utilities and stakeholders (Équiterre & The Pembina Institute, 2017).

In addition to a lack of data, commercialization of products creates a barrier for the construction industry to adopt alternative materials. For example, there may be a lack of resources needed to effectively market and disseminate product information to stakeholders such as engineers. In addition, some of these products would not make it from prototype to full-scale demonstration projects, limiting their ability to obtain supportive material performance data for their product (Giesekam, Barrett, & Taylor, 2016). In other instances where products do make it to the market and grab the attention of engineers and other construction stakeholders, other priorities, such as cost, may influence material choice.

A way to address some of these challenges is by promoting a wide range of material options, as the material choice will be highly dependent on site- and project-specific factors. Choosing construction materials that have the lowest embodied carbon and increase the energy efficiency of a building will depend on the knowledge, priorities and regulations that guide decision making. Thus, dependent on the project type, policy-makers and advocates for green construction materials and design options can promote the most appropriate option for each particular type of project (commercial, residential, multi-dwelling, etc.). Promotion of material options also includes skills development to design and implement these options and legislation that is sensitive to and supportive of these alternate material options and measures (Giesekam, Barrett, & Taylor, 2016). To support this transition, a crucial step is to inform decision-makers and policy-makers through studies that assess the barriers to adoption of materials as well as identify common leverage points and interventions that can support a variety of solutions to promote energy-efficient and low-emitting buildings (Giesekam, Barrett, & Taylor, 2016).

5.2 Decarbonization and Sustainability

5.2.1 Cement's Role in Concrete

In 2016, global production of cement was 4.2 billion tonnes, with the majority of this production accounted for by China (just under 60 per cent) and followed at some distance by India (almost 7 per cent). In the same year, Canada produced almost 12 million tonnes of cement, less than 1 per cent of the global total. In the mature economies, demand per capita is expected to remain constant in the near future, with growth coming from industrializing markets in Africa and Asia, and to some extent former Soviet states and Latin America.

The cement production process can be divided into two basic stages: production of clinker from raw materials and the subsequent transformation of clinker into cement. In stage one, raw materials—predominantly limestone, but also smaller quantities of clay, shale, sand and industrial waste to ensure the correct balance of chemicals—are ground and heated in kilns to a temperature of 1,450°C. As a result, limestone is decomposed into calcium oxide and carbon dioxide ($CaCO_3 \text{ -> } CaO + CO_2$) in a process called calcination. The resultant calcium oxide then combines with the other raw materials to give calcium silicates and aluminates, the primary components of cement, in the form of cement clinker. In stage two, clinker is ground with other mineral components to produce cement; gypsum is used to control the setting properties while other additives are used to adjust other characteristics such as permeability. Traditional Portland cement—the most widely used cement type—comprises 95 per cent clinker with the remainder being gypsum.

Calcination results in carbon dioxide emissions of approximately 0.45 tonnes per tonne of clinker, and accounts for around 60 per cent of total carbon dioxide emitted during production. The burning of fuel in kilns accounts for a further 35 per cent of total emissions, and electricity use and transport accounts for a final 5 per cent. The average emission intensity is approximately 0.78 tonnes of carbon dioxide per tonne of cement in Canada.

The IPCC *Fifth Assessment Report* estimates that process emissions from the cement industry were 1.352 gigatonnes in 2010, and fuel emissions a further 0.8 gigatonnes (Fischedick et al., 2014). Canada's 2018 *National Inventory Report* estimates that process emissions from cement production reached 6 million tonnes of carbon dioxide equivalent in 2016 (Environment and Climate Change Canada, 2018).

5.2.2 Short-Term Measures to Reduce Emissions

In many jurisdictions, including Canada, there has been a decline in emission intensity over time. This reduction is in part a result of easily implementable short-term measures, in part because of a longer-term shift to best-available technology.

In the short term, there are four main measures that can be implemented in order to reduce emission intensity. First, **clinker substitution** reduces the proportion of clinker that is used in the production of cement and replaces it with ground blast furnace slag, fly ash or natural volcanic materials that can reduce the process-, fuel- and power-related carbon dioxide emissions associated with producing a tonne of cement. However, realization of further reductions may be restricted by the availability and price of substitutes, and by the acceptability of blended cements with respect to building codes.

Second, **Portland limestone cement** is also now available across Canada, which reduces GHG emissions while still allowing for additional GHG mitigation activities to take place. Portland limestone cement is a modified version of cement that includes additional limestone and decreases the amount of energy and calcination emissions in the process through which it is made, reducing the associated GHG emissions (Concrete Producer, 2014) by in excess of 10 per cent.

Third, using **alternative fuels** such as waste and biomass to fire the cement kiln rather than fossil fuels such as petcoke and coal can also lead to a reduction in emissions. Emissions reductions will vary depending upon the mixed fuel used,[5] but estimates have suggested that emission intensity may decline by up to 25 per cent compared to fossil fuels (International Energy Agency, 2009), and this substitution may also lead to a simultaneous reduction in costs. While use of alternative fuels for heating the kiln is widespread in some countries, with some plants being almost fully fired with alternative fuels, in many countries it is not a well-established practice and can be an important lever in securing emissions reductions (Chatziaras, Psomopoulos, & Themelis, 2015). Realizing these reductions is, however, dependent upon supporting legislation to permit co-firing, existence of required infrastructure and availability of fuels at a competitive cost.

Finally, **improving thermal and electrical efficiency** can lead to emission reductions. The thermal efficiency of a plant is largely set by the choice of equipment at the point of installation and is thus a decision that is made once every 40 years. However, once installed, the ongoing maintenance and the operation of the equipment influences its efficiency.

5.2.3 Game-Changing Technologies for Emissions Reductions

Since the majority of emissions from cement production are the result of calcination, the potential for reductions using current production techniques is limited. Nevertheless, there are some technologies that show promise, most notably increasing the use of (decarbonized) electricity, which is already the case in most of Canada.

There have been few dedicated post-combustion carbon capture and storage (CCS) facilities deployed to date, since the technology is still commercially immature. Nevertheless, examples do exist. In 2013, Heidelberg Cement-Norcem launched a CCS project aimed at testing different technologies at their plant in Brevik, Norway. In 2016, the Norwegian government published its plans and budget for full-scale CCS feasibility studies, with Norcem's project being one of three included. Initial estimates suggest an abatement cost range of EUR 100–150 (CAD 150–230) per tonne CO_2 captured, depending on exact design (number of carbon dioxide sources and method of delivery) (Jakobsen, Roussanaly, & Anantharaman, 2017). In Canada, there is currently one operational plant—Boundary Dam—with further development restricted by a combination of high cost and limited prospects for this cost declining in the near term (Leach, 2011).

In addition, there are a number of other technologies incorporating elements of CCS. These include injecting captured carbon dioxide emissions (from both the cement industry and elsewhere) into wet concrete, where it is subsequently trapped, simultaneously reducing emissions to the atmosphere and increasing concrete strength (CarbonCure, 2018). Other technologies include retrofitting a plant with an exhaust stack to capture the carbon dioxide and convert it into carbon nanotubes and oxygen (CarbonCure, 2018) and using carbon dioxide in the production of algae, with this algae subsequently being used as biofuels or as animal feed (Global Cement, 2014). Finally, enhancing the natural capacity of concrete to absorb carbon dioxide as it weathers (mineral carbonation) offers another route to removal of carbon dioxide from the atmosphere (Xi et al., 2016).

Moving beyond the current production technology, recent years have seen the development of new binders that can be used in concrete in the place of cement. Among those explored to date are alkali-activated binders, cements based on the carbonation of calcium silicates and pre-hydrated calcium silicates, and cements based on belite. Among these, for example, a binder developed by Solidia is produced using a lower-carbon process different than Portland cement and is converted into concrete through exposure to carbon dioxide (Lafarge, 2015). These technologies show varying degrees of maturity. For example, Solidia cement has already launched a limited

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[5] For example, substitution with biomass means that biogenic carbon emissions need to be considered. Direct emissions from burning waste (e.g., tire-derived fuel) may be considerable and comparable with burning fossil fuels, but emissions over the life cycle may be lower, or there may be other environmental benefits.

line of commercial products in North America and Europe (European Cement Research Academy & Cement Sustainability Initiative, 2017), while alkali-activated binders are expected to remain very much niche products.

5.2.4 Steel

Iron and steel are globally traded products with energy-intensive manufacturing and one of the largest sources of industrial emissions (Quader et al., 2015). From 2000 to 2013, steel manufacturing has nearly doubled (Quader et al., 2015) and demand is expected to continue to grow at a comparable annual rate of about 5 per cent (Turner, 2012). World Steel (2017) estimates a projected increase of 1.5 times by 2050 and that such demand could result in a comparable rise in carbon dioxide emissions. In comparison to steel produced globally, Canadian, steel has among the lowest carbon emissions; however, there is still progress to be made to further reduce carbon emissions from steel production in the country.

Principle approaches to steel manufacturing include: BOF, which accounts for two thirds of global production; EAF, accounting for as much as a third of production; and open heart furnace, a process used by a small percentage of facilities that is gradually being phased out (Quader et al., 2015). BOF uses a very large quantity of energy and accounts for significant amounts of emissions from use of coke in the process. In the secondary production route of EAF, about a quarter of global production uses recycled material through a direct reduced iron process, which utilizes electricity and can result in emissions reduced by as much as half as compared to BOF (Turner, 2012). It is important to note that recycling steel uses less energy and results in lower emissions versus use of raw materials. European and North American facilities are better positioned in this regard. The use of natural gas instead of coke and coal in steelmaking could also result in significantly lower direct emissions. However, methane emissions from natural gas extraction to distribution could have nearly 100 times the global warming potential upon release compared to carbon dioxide. The various current technologies used and high cost of alternative approaches will have an impact on decarbonization in the sector.

Literature reviewed shows various reductions in energy consumption in the sector by about 50 per cent over a few decades, but this steep reduction has nearly plateaued and additional efforts will be necessary to go deeper. The Canadian Sheet Steel Building Institute (2008) notes that, through voluntary efforts, the Canadian steel industry has reduced its energy intensity by about 9 per cent since the 1990s (Natural Resources Canada, 2018b). It is also important to note that energy demand and emissions in the sector vary significantly from facility and by country, with Japan, OECD member countries in Europe, Korea and the United States having an energy intensity of less than 2 gigajoules per tonne of steel produced while production in China and Ukraine require three times the average energy (Shatokha, 2016).

To reduce emissions in the sector, two approaches can be deployed: short-term state-of-the-art or best-available technologies and practices or game-changing, innovative and disruptive approaches to achieving mid-century decarbonization objectives. Short-term approaches to reducing the emission intensity of steel are feasible and may prove to be cost-effective, especially through policies that would level the playing field and address carbon leakage (e.g., carbon pricing and regulatory measures). At an abatement cost of less than USD 100 per tonne of carbon dioxide, China could reduce its emissions by 230 $MtCO_2$ and India by 110 $MtCO_2$ (Turner, 2012). It is important to note that, given the sector's high-energy demand, improvements in this area will not only have emission reduction benefits but will also improve the internal rate of return of projects.

Improving efficiency of production, use of coproduct, recycling and use of waste heat for other activities can provide immediate benefits. Recovering heat loss presents one of the most important immediate opportunities, which accounts for 20–50 per cent of energy used. Existing technologies include coke dry quenching, top-pressure recovery, continuous casting and furnace gas recovery (Turner, 2012). The largest potential is increased BOF gas recovery (Turner, 2012). Three principal heat-recovery technologies include (Quader et al., 2015, p. 605):

- Coke gas produced in the BOF process could be converted into lighter fuels or used in other processes.
- Using energy produced in the reheating furnaces to produce electricity.
- Recovering the energy from slags through mechanical, air and centrifugal technologies, or use of chemicals.

Transformative technologies are in various stages of research and development across jurisdictions to enable significant decarbonization of the sector, including top gas recycling, electrolysis, smelting reduction and enhancing hydrogen utilization (World Steel Association, 2017). A European project was able to reduce coke consumption by about a quarter through this approach, resulting in comparable carbon dioxide abatement (Shatokha, 2016). Improved use of electricity is also possible, such as alkaline electrolysis to produce other metals and molten oxide electrolysis to support the breakdown of iron oxide without producing any carbon dioxide. The HIsarna process reduces smelting with the use of pure carbon dioxide and allows for its capture at the end of the process; due to the phase-out of coke making and sintering, 20 per cent lower carbon dioxide compared to conventional approaches has been achieved (Shatokha, 2016). Finally, hydrogen can also be used in flash smelting to produce iron from pig iron without emitting carbon dioxide.

We note significant efforts by the sector in a number of jurisdictions and investment on technology innovation. It is also important to note that none of the above technologies, neither near-term improvements to facilities nor transformative technologies, can achieve deep reductions alone. Decarbonization of the energy sector (e.g., electricity sector) will also play a critical role in reducing emissions from the sector, as energy is a key component of steel production and a number of emission reduction technologies rely on a cleaner source of electricity. Realizing decarbonization in the sector will also require radical change in production methods, as carbon remains a key feedstock, and/or the deployment of carbon capture and storage/utilization technologies, which remain a high-cost option with limited commercial scale demonstration. In this regard, we note that three quarters of all emissions from steel production come from the use of coke and coal in BOF process (Turner, 2012). Transformative technologies to reduce reliance on coal and coke and/or improved utilization of carbon dioxide will be critical in achieving decarbonization objectives.

5.2.5 Forestry

Canada has one of the largest forest covers, about one tenth of the global total. Its boreal forest stores 208 billion tonnes of carbon, or one tenth of global stock, over an area of 1.3 billion acres (The Nature Conservancy of Canada, 2017). Below, we discuss a number of high-value opportunities in the short term and efforts needed to meet mid-century decarbonization objectives in the forestry sector. In addition to GHG emissions and their sequestration, we evaluate the potential impact of increased demand for wood products on the ecological goods and services that forests provide. More specifically, this section assesses the potential stress on forests from climate risks, uncertainties regarding future ecological health of forests, and, finally, the role of forests in adaptation efforts and species protection.

5.2.5.1 Mitigation Measures

Potential climate mitigation efforts in Canada's forests fall within two areas: restoration and conservation of forests on the one hand, and enhancement of operational practices and forest management on the other. Disturbance and fragmentation, particularly in Canada's boreal forest, from decades of logging, oil and gas exploration and production are significant to the extent that policies may need to prioritize restoration and conservation efforts (Asadollahi, 2015). When it comes to conservation, retiring leases in areas that have not been disturbed and appropriately designating intact forests can support longer-term mitigation efforts, maintaining healthy forests and contributing to Canada's international conservation commitments. There are also significant opportunities to improve existing forestry practices and enhance forest management in Canada, including: rotation cycles, decay or burning of leftover material, soil disturbance (including carbon release and nutrient loss) and end-of-life product emissions from landfills.

Globally, forests are in a state of decline, and given their high carbon storage value, as well as in light of threats to health of forests, it is critical to conserve and enhance their ecological integrity. Moreover, forests have an important long-term sequestration value and significant initial emissions when harvested, which should not be discounted.

Malcolm (2016) notes, "any positive effects of forest management – for example, carbon sequestration by young forests or long-term storage of carbon in wood products – must be measured against the 'debt' that is incurred during this transition [from a primary forest landscape to a secondary (managed) one]." There are also hundreds of kilometres of seismic lines, steel production mines and access roads from decades-old industrial activity that have not returned to their original state, and some provinces may have requirements in maintaining access roads that result in permanent disturbance and loss of sequestration potential. These disturbances could be undone through public and private partnerships but will require significant investment. Governments could prioritize restoration efforts to concurrently meet other policy objectives, including recovery strategies for species at risk.

Various studies have demonstrated that there is a common misconception about replacement of carbon sequestration under forest management practices (Fargione et al., 2008; Ter-Mikaelian, Colombo & Chen, 2014). That is to say, it is a misconception to believe that, when harvesting trees, the postharvest forest has no net GHG emissions as long as new trees regrow to preharvest carbon levels (Holtsmark, 2012; Ter-Mikaelian, Colombo & Chen, 2014). In reality, there is a carbon debt when mature trees are harvested and replaced by new tree stock, although this debt may be able to be repaid before the end of the rotation period in the boreal forest based on the CMB-CFS3 forest model (Natural Resources Canada, 2017).

When considering forest management efforts to replace harvested tree stock, the amount of carbon absorbed by younger trees can take many centuries to reach the level of sequestration by old-growth forests. The process of carbon cycling is not linear, and it is important to consider the decomposition rates of post-harvested trees (trunks and root systems) as well as the natural disturbances during the growth period of new trees that can either stop or pause growth (e.g., forest fires, floods, droughts).

A recent study found that, by 2030, global conservation, restoration and land management efforts in forests, wetlands, grasslands and agricultural lands can result in 37 per cent of emission reductions needed to keep warming below 2°C, with reforestation providing the highest emission reduction opportunity (Griscom, 2016). It also notes that mitigation measures in the forestry sector are among the most cost-effective globally, under USD 100 per tonne, with one third of the potential under USD 10 per tonne.

In addition to conservation and restoration efforts, operational changes and improvements to forest management can also support the sector's efforts toward deep decarbonization objectives. Improving rotational cycles could provide one of the highest abatement opportunities. In addition to promoting longer rotations, industry could also reduce the use of chemicals and maximize carbon storage (Talberth, DellaSala, & Fernandez, 2015). There are also post-activity mitigation options that can be improved, including decommissioning of roads and lands disturbed.

One comprehensive study referenced notes that, "when a site is logged and the wood converted into long-lived wood products, only 18 per cent of the original carbon stores are preserved, and then only for a few decades at most before those longer lived wood products start to decay" (Talberth, DellaSala, & Fernandez, 2015, p. 4). Furthermore, in the case of boreal forests, 65–95 per cent of the ecosystem carbon is noted to exist in the soil (Bell et al., 2017, p. 16; Bradshaw & Warkentin, 2015; Lal, 2005).

5.2.5.2 Beyond Carbon Sequestration

More frequent extreme weather events (from longer dry periods to flash floods) as well as disease (e.g., spread of pests) could have a significant impact on Canada's carbon sinks. We note uncertainties regarding the full impact of climate change under various emission pathway models. However, with uncertainties in mind, a precautionary approach to protecting and enhancing the ecological health of forests is advisable.

Second, forests provide critical habitat for species, including those that require protection under the federal Species at Risk Act. According to Smith et al. (2016), from 2000 to 2013, about 5 per cent of Canada's large intact forests (an area of over 215,000 km^2) were degraded. Of this, 90 per cent of degradation of intact forests took place in the habitat of species at risk, while 500,000 km^2 of remaining intact forests were within tenures. This rate of deterioration is disquieting, especially in light of the 2017 World Wildlife Fund that found 451 species in rapid population decline of 83 per cent on average, between 1970 and 2017 (World Wildlife Fund, 2017). Boreal caribou, for example, is facing increased predation because of the destruction of mature and old forests by industrial activities in the forestry, oil, gas and mining sectors (Environment Canada, 2014).

Finally, forests play a critical role in climate adaptation efforts, and their degradation increases the risk of wildfires, disease, flooding and landslides (Talberth, DellaSala, & Fernandez, 2015). Harvesting of wood products can transform native forests into brush fields or their replacement with younger trees that may be more prone to fires. Old intact forests also have strong water retention and ensure soil cohesion through their root system, preventing landslides; this ability is reduced when trees are harvested. Access roads, in particular, can channel water runoff from heavy storms and have extensive impacts. Degradation of forest coverage through skid trails and access roads, either from previous activities or new ones, will result in a decrease in net ecosystem productivity or the amount of carbon uptake of forests (Talberth, DellaSala, & Fernandez, 2015, pp. 3–4). Finally, chemicals used the by the forestry sector, such as fertilizers and pest control sprays, can also have local ecological impacts both in the soil and in nearby bodies of water.

6.0 Conclusions

Building LCA studies are complex and highly specific, and despite significant improvements in LCA methods, a huge variance in LCA results can be found in the literature. While LCA is an indispensable tool to evaluate alternative building products such as concrete, steel and wood building frame elements, policy-makers and building designers need to be aware of significant limitations, challenges and uncertainties that persist.

Significant cement and steel production mitigation options to reduce embodied emissions do exist with existing technology (e.g., fuel substitution could reduce emissions from cement by some 20 per cent in Canada). Nonetheless, deeper decarbonization pathways for these products are unlikely in the short and medium terms. For cement, there are options to decarbonize through clinker substitution during the cement production phase, to use alternative fuels (e.g., biomass) to fire the cement kiln, and to improve thermal and electrical efficiency to help reduce emissions. For steel, mitigation options include improving production efficiency, improving use of coproduct, recycling and using waste heat for other activities. For wood products, market-ready solutions in forestry management can significantly enhance emission sinks in Canadian forests going forward and could significantly contribute to Canada's emission reduction targets.

6.1 Uncertainties and Regional Variabilities

The major uncertainties in LCA analysis identified in the study are related to biogenic carbon emissions and, to a lesser extent, carbonation of cement. Regional variability was identified as important in the production of steel, the disposal of wood building materials in landfills and the extraction of raw materials.

Embodied GHG emissions for wood products were found through sensitivity testing to be significantly affected if they included estimates for biogenic carbon emissions. Different forest management scenarios that lead to the permanent losses of soil carbon, harvesting of natural or primary forests and lower regeneration rates were considered, and estimates were made of the potential contribution of biogenic carbon emissions to the overall emissions of wood building products. Based on a number of assumptions, carbon GWP_{bio} potentials in the range of 0.0695 to 0.835 were identified for these scenarios, and, overall, they challenge the common assertion that the biogenic carbon cycle of wood products in Canada is always—or perhaps even ever—truly carbon neutral.

While carbonation in concrete (i.e., absorption of carbon dioxide) should be included in building LCA, current data suggests it is unlikely to make a significant impact on overall life-cycle emissions. Care should be taken when modelling end-of- life treatment of concrete to not include end-of-life management that can optimize carbonation, as this is treated outside the LCA system boundary.

6.2 LCA Best Practices

There are a number of important best practices in LCA that can be highlighted based on the review:

- Building LCA studies need to do a better job of sensitivity analysis for important assumptions and variables to highlight uncertainty in the results as well as to better understand how results might apply to specific jurisdictions with their own unique characteristics.
- Dynamic LCA models should be used to account for emissions as they occur to accurately account for radiative forcing impacts over the study period.
- Do not double count potential net benefits from reuse, recycling and/or energy recovery in LCA.

- Ensure that datasets used are recent and identify how they are regionally appropriate.
- Provide a comprehensive list of assumptions employed in the LCA.

6.3 Policy Development

In the short to medium terms, policies and actions should largely prioritize reducing use-stage emissions that are generally estimated in the range of 60–95 per cent of overall emissions. Improving energy efficiency and developing new low-energy or net-zero-energy buildings offer the highest mitigation potential from the built environment sector. Effective carbon pricing and complementary policies that cover the manufacturing sector will also work to decarbonize embodied emissions of building materials, albeit likely at a slower rate than the decarbonization of building use. In addition, policies and building codes should promote building longevity, durability and service efficiency, as these improvements can have significant GHG emission reduction benefits.

Policy-makers need to be particularly wary of drawing conclusions from studies that are not transparent about assumptions and system boundaries and that cannot demonstrate that they use emission and energy data that are regionally appropriate and current. Without detailed background data and an understanding of LCA methods, policy-makers will have difficulty reliably interpreting results to contribute to good policy.

Ignoring use-stage life-cycle emissions or other building elements can provide a skewed sense of the relative contribution of the embodied emissions of the structural building elements being compared. In a policy context, this can lead to policies that are too narrow in scope and do not consider the comprehensive picture of overall emission reductions from buildings.

Care should also be taken by policy-makers when designing policies that may be preferential to one building material. Each building design is unique, and while a building design may substitute wood, steel or concrete elements to some degree, all materials are typically prominent regardless of a declared material preference in a given structure. Policies should be developed that equally support and drive the decarbonization of life-cycle emissions for all building materials and avoid favouring one material or application without clear evidence that overall life-cycle emissions are effectively reduced.

Since forest management can act in many ways to diminish or improve carbon sequestration, it is important that it considers a broad level of forest management activities that can enhance carbon sinks, including longer harvest rotations and decisions not to harvest certain stands as a response to climate change.

Choosing a combination of construction materials that has the lowest overall embodied carbon and also increases the energy efficiency of a building will be dependent on the knowledge, priorities and regulations that guide decision making. To support this transition, a crucial step will be to inform decision-makers and policy-makers through studies that assess the barriers to selecting the least carbon-intensive combination of materials needed for construction. A second step is to identify common leverage points and interventions that can support a variety of solutions to promote energy-efficient and low-emitting buildings.

6.4 Research Needs

6.4.1 Wood

At a national level in Canada, more work is required to establish a realistic GHG emissions reference baseline to guide forest management, national inventory accounting as well as building LCA analysis. This would include stronger regional data on biogenic carbon releases from soil and forest conversion, as well as more detailed studies of sylvicultural success rates across the country. Detailed study and modelling are required to investigate specific regions and managed forests within Canada and to consider the cumulative radiative forcing impacts of multiple harvest cycles.

6.4.2 Concrete

The indirect emissions from land-use changes associated with clearing land for the mining and quarrying of raw materials are also not well documented and should be further examined. Further study into concrete carbonation rates would also help inform LCA analysis.

6.4.3 Steel

The sourcing of steel by country and process significantly affects the embodied emissions of steel building materials. For example, EAF mills that use recycled steel feedstock can decrease embodied emissions by a factor of 2–4 compared to steel from virgin ore. More data should be made available to help architects and engineers understand the source of the steel products they purchase and their impacts on embodied emissions.

6.4.4 General

Consequential LCA is particularly important in the context of policy development and providing evidence for supporting or promoting the use of one material over another. Increases in demand can have surprising effects on production-stage life-cycle emission intensity. In the case of wood building materials, an increase in wood demand has a direct impact on the ability of forests to achieve sustainable carbon stocks, potentially altering the expected emission performance of the material. In the case of concrete, an increase in demand could result in issues with the local sourcing of raw materials and increase raw material supply and extraction emissions. In the case of steel, an increase in demand may need to be met with imports from countries that have much higher emission-intensive methods of production than domestically. Governments will need to provide support for consequential LCA analysis to develop policies that can consider these nuances.

Datasets that can provide regional representation of production, construction, use and end-of-life emissions for LCA are needed to make informed policy decisions but simply are often not available. The federal government should invest in an up-to-date, regionalized, national life-cycle inventory.

References

Achat, D. L., Fortin, M., Landmann, G., Ringeval, B., & Augusto, L. (2015). Forest soil carbon is threatened by intensive biomass harvesting. *Scientific Reports, 5* (article 15991). Retrieved from https://www.nature.com/articles/srep15991

Agostini, A., Giuntoli, J. & Boulamanti, A. (2014). *Carbon accounting of forest bioenergy*. European Commission. Retrieved from http://publications.jrc.ec.europa.eu/repository/bitstream/JRC70663/eur25354en_online.pdf

Andersson R., Fridh K., Stripple H., Häglund M. (2013). Calculating CO_2 uptake for existing concrete structures during and after service life. *Environmental Science and Technology, 47* (20), 11625–11633. Retrieved from doi:10.1021/es401775w

Athena Sustainable Materials Institute. (2018). Cradle-to-gate lifecycle assessments including: Canadian Glulam Manufacture; Canadian Orientated Strand Board; Canadian Surfaced Dry Softwood Lumber, and Canadian Softwood Plywood Sheathing. Retrieved from http://www.athenasmi.org/resources/publications/

Axelrod, J. (2017, September 21). Forest degradation: Canada's skeleton in the closet. National Resources Defense Council. Retrieved from https://www.nrdc.org/experts/josh-axelrod/forest-degradation-canadas-skeleton-closet

Balaras, C. A., (1996). The role of thermal mass on the cooling load of buildings: An overview of computational methods. *Energy and Buildings, 24*(1996), 1–10.

Bataille, C., Sawyer,D., & Melton, N. (2015). *Pathways to deep decarbonization in Canada*. Retrieved from http://deepdecarbonization.org/wp-content/uploads/2015/09/DDPP_CAN.pdf

Bax, L., Cruxent, J., & Komornicki, J. (n.d.). *Innovative chemistry for energy effieciency of buildings in smart cities*. Retrieved from https://cefic.org/app/uploads/2019/01/Innovative-Chemistry-for-Energy-Efficiency-of-Buildings-in-SmartCities-BROCHURE-iNNOVATION.pdf

Bell, A. Berger, P. Moola, F., Saunders, G… & Legg, D. (2017). *Submission to the Government of Ontario's "Opportunities to Enhance Carbon Storage?" discussion paper*. Submitted by Ontario Nature, Citizens United for a Sustainable Planet, David Suzuki Foundation, Environment North, Green Peace Canada, Plenty Canada, Kingston Field Naturalists, Lennox & Addington Stewardship Council, Quinte Field Naturalists, Sault Naturalists' Club of Ontario & Michigan and Thunder Bay Field Naturalists.

Biswas, W. K. (2014). Carbon footprint and embodied energy consumption assessment of building construction works in Western Australia. *International Journal of Sustainable Built Environment*, *3*, 179–186.

Blengini, G.A. & Di Carlo, T. (2010). Energy-saving policies and low-energy residential buildings: An LCA case study to support decision makers in Piedmont (Italy). *International Journal of Life Cycle Assessment, 15*, 652–665. Retrieved from https://link.springer.com/article/10.1007/s11367-010-0190-5

Bradshaw, C. & Warkentin, I. (2015). Global estimates of boreal forest carbon stocks and flux. *Global and Planetary Change, 128*, 24–30.

Buchholz, T., Friedland, J., Hornig, E., Keeton, S., Zanchi, G., & Nunery, J. (2014). Mineral soil carbon fluxes in forests and implications for carbon balance assessments. *GCB Bioenergy, 6*. Retrieved from https://onlinelibrary.wiley.com/doi/epdf/10.1111/gcbb.12044

Canadian Sheet Steel Building Institute. (2008). *Canadian steel industry: Leading the shift to green. Environmental Fact Sheet*. Cambridge, ON: CSSBI.

CarbonCure. (2018). Technology. Retrieved from http://carboncure.com/technology/

Chatziaras, N., Psomopoulos, C, & Themelis, N. (2015). Use of waste derived fuels in cement industry: A review. *Management of Environmental Quality: An International Journal, 27* (2), 178–193. Retrieved from http://www.emeraldinsight.com/doi/abs/10.1108/MEQ-01-2015-0012

Chen, F., Kessel, A., & Wolcott, M. (2012). *A novel energy saving wood product with phase change materials*. Retrieved from http://www.swst.org/wp/meetings/AM12/pdfs/papers/SP-3.pdf

Chou, J-S. & Yeh, K-C. (2015). Life cycle carbon dioxide emissions simulation and environmental cost analysis for building construction. *Journal of Cleaner Production, 101*, 137–147. Retrieved from https://doi.org/10.1016/j.jclepro.2015.04.001

Collins, F. (2010). Inclusion of carbonation during the life cycle of built and recycled concrete: Influence on their carbon footprint. *International Journal of Life Cycle Assessment, 15*(6), 549–556. Retrieved from https://www.researchgate.net/profile/Frank_Collins/publication/225446969_Inclusion_of_carbonation_during_the_life_cycle_of_built_and_recycled_concrete_Influence_on_their_carbon_footprint/links/0deec5297e9cb76c72000000/Inclusion-of-carbonation-during-the-lifecycle-of-built-and-recycled-concrete-Influence-on-their-carbon-footprint.pdf

Concrete Producer. (2014). The advantages of Portland-Limestone cement. Retrieved from https://www.theconcreteproducer.com/how-to/concrete-production/the-advantages-of-portland-limestone-cement_o

Craig, S., & Jahraus, N. (2017). UBC Engineering Student Centre. Retrieved from https://sabmagazine.com/ubc-engineering-student-centre/

EDGAR. (2016). *Trends in global CO₂ emissions: 2016 report*. Retrieved fro http://edgar.jrc.ec.europa.eu/news_docs/jrc-2016-trends-in-global-co2-emissions-2016-report-103425.pdf

EN 15978. (2011). *Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method*. BSI Standards Publication.

Environment and Climate Change Canada. (2017a). *Canada's 7th National Communication and 3rd biennial report*. Retrieved from http://unfccc.int/files/national_reports/national_communications_and_biennial_reports/application/pdf/82051493_canada-nc7-br3-1-5108_eccc_can7thncomm3rdbi-report_en_04_web.pdf

Environment and Climate Change Canada (2017b). *National inventory report 1990–2015: Greenhouse gas sources and sinks in Canada*. Canada's Submission to the United Nations Framework Convention on Climate Change.

Environment and Climate Change Canada (2018). *National inventory report 1990-2016: Greenhouse gas sources and sinks in Canada*. Retrieved from http://publications.gc.ca/collections/collection_2018/eccc/En81-4-2016-1-eng.pdf

Environment Canada (2014). *Recovery strategy for the woodland caribou, Southern Mountain population (Rangifer tarandus caribou) in Canada* [Proposed] (Species at Risk Act Recovery Strategy Series). Retrieved from https://www.registrelep-sararegistry.gc.ca/virtual_sara/files/plans/rs_woodland_caribou_bois_s_mtn_pop_0114_e.pdf

Équiterre & The Pembina Institute. (2017). *Federal policies for low-carbon buildings: A blueprint to implement the Pan-Canadian Framework buildings strategy*. Retrieved from http://www.pembina.org/reports/federal-policies-for-low-carbon-buildings-2017-en.pdf

European Cement Research Academy & Cement Sustainability Initative. (2017). *Development of state of the art techniques in cement manufacturing: Trying to look ahead.* CSI/ECRA Technology Papers. Geneva: European Cement Research Academy; Cement Sustainability Initiative.

Fargione, J., Hill, J., Tilman, D., Polasky, S. & Hawthrone, P. (2008). Land clearing and the biofuel carbon debt. *Science Magazine, 319*, 1235–1238.

Fischedick, M., Roy, J., Abdel-Aziz, A., Acquaye, A., Allwood,, J. M., Ceron, J.-P. … Tanaka, K. (2014). Industry. In O. Edenhofer et al. (Eds.), *Climate change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press.

Ghattas, R., Gregory, J., Olivetti, E., and Greene, S. (2013). *Life cycle assessment for residential buildings: A literature review and gap analysis.* Concrete Sustainability Hub. Cambridge: Massachusetts Institute of Technology. Retrieved from https://cshub.mit.edu/sites/default/files/documents/LCAforResidentialBuildings.pdf

Giesekam, J., Barrett, J., & Taylor, P. (2016). Construction sector views on low carbon building materials. *Building Research & Information, 44*(4), 423–444.

Global Cement. (2014, July 16). From cement stacks to fish ponds – algae carbon capture. Retrieved from http://www.globalcement.com/news/item/2694-from-cement-stacks-to-fish-ponds-%E2%80%93-algae-carbon-capture

GLOBE Advisors. (2017). *Carbon sequestration in forest-based wood products* (Draft). Pacific Northwest Building Resilience Coalition.

Grant R. F. et al., (2010). Net ecosystem productivity of temperate and boreal forests after clearcutting: A Fluxnet-Canada measurement and modelling synthesis. *Tellus B, 62*(5), 475–496.

Griscom, B. W., Adams, J., Ellias, P. W., Houghton, R. A. … Fargione, J. (2016). Natural climate solutions. *Proceedings of the National Academy of Sciences [PNAS], 144*(44), 11645–11650. Retrieved from doi.org/10.1073/pnas.1710465114

Grann, B. (2013). *A comparative life cycle assessment of two multistory residential buildings: Cross-laminated timber vs. concrete slab and column with light gauge steel walls.* Vancouver, BC: FP Innovations.

Guggemos, A & Horvath, A. (2005). Comparison of environmental effects of steel- and concrete-framed buildings. *Journal of Infrastructure Systems, 11*(2), 93–101. Retrieved from DOI: 10.1061/(ASCE)1076-0342(2005)11:2(93)

Hasanbeigi, A., Arens, M., & Price, L. (2013). Alternative emerging ironmaking technologies for energy-efficiency and carbon dioxide emissions reduction: A technical review. *Renewable and Sustainable Energy Reviews, 33*, 645–658.

Holtsmark, B. (2012). Harvesting in boreal forests and the biofuel carbon debt. *Climate Change, 112*, 415–428.

Holtsmark, B. (2015). Quantifying the global warming potential of CO_2 emissions from wood fuels. *GCB Bioenergy, 7*, 195–206.

International Energy Agency. (2009). *Cement technology roadmap 2009.* Retrieved from https://www.iea.org/publications/freepublications/publication/Cement.pdf

International Energy Agency. (2016). *Energy, climate change and environment.* Retrieved from http://www.iea.org/publications/freepublications/publication/ECCE2016.pdf

Intergovernmental Panel for Climate Change. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Vols. 1–8. Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Japan: IGES.

Intergovernmental Panel for Climate Change. (2014). Industry. In O. Edenhofer, et al. (Eds.), *Climate change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Retrieved from https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_full.pdf

ISO 14040 (2006). Environment management – Life cycle assessment – Principles and framework.

ISO 14044 (2006). Environment management – Life cycle assessment – Requirements and guidelines.

ISO 21930 (2017). Sustainability in buildings and civil engineering works – Core rules for environmental product declarations of construction products and services.

Jakobsen, J., Roussanaly, S., & Anantharaman, R. (2017). A techno-economic case study of CO_2 capture, transport and storage chain from a cement plant in Norway. *Journal of Cleaner Production, 144*, 523–539. Retrieved from https://www.sciencedirect.com/science/article/pii/S0959652616321837?via%3Dihub

James, J. & Harrison, R. (2016). The effect of harvest on forest soil carbon: A meta-analysis. *Forests, 7*(308). Retrieved from http://www.mdpi.com/1999-4907/7/12/308/htm

John, S., Nebel, B., Perez, N., & Buchanan, A. (2008). *Environmental impacts of multi-storey buildings using different construction materials*. Retrieved from https://ir.canterbury.ac.nz/bitstream/handle/10092/8359/12637413_JOHN%20STEPHEN%20ET%20AL%20Environmental%20Impacts%20of%20Multi-Storey%20Buildings%20Using%20Different%20Construction%20Materials%20MAF%20Report%202008.pdf?sequence=1&isAllowed=y

Junnila, S., Horvath, A., & Guggemos, A.A. (2006). Lifecycle assessment of office buildings in Europe and the United States. *Journal of Infrastructure Systems, 12*(1), 1017. Retrieved from: http://ascelibrary.org/doi/abs/10.1061/%28ASCE%291076-0342%282006%2912%3A1%2810%29

Kośny, J. (2015). Short history of PCM applications. In *PCM-Enhanced Building Components: An application of phase change materials in building envelopes and internal structures* (pp. 21–59). Switzerland: Springer International Publishing.

Lafarge. (2015). Lafarge and Solidia commercialize a new low-carbon solution for the construction sector. Retrieved from https://www.businesswire.com/news/home/20150428005153/en/Lafarge-Solidia-Commercialize-New-Low-Carbon-Solution-Construction

Lal, R. (2005). Forest soils and carbon sequestration. *Forest Ecology and Management, 220*, 242–258.

Leach, A. (2011). Time to come clean on CCS. Retrieved from http://andrewleach.ca/canadian-climate-policy/time-to-come-clean-on-ccs

Liu, W., Zhang, Z., Xie., X., Yu, Z., Gadow, K., Xu, J., Zhao., S., & Yang, Y. (2017). Analysis of the global warming potential of biogenic CO_2 emission in life cycle assessments. *Scientific Reports, 7*, 39857. DOI: 10.1038/srep39857

Lorinc, J. (2016). Ontario looks to close loophole on energy standards for buildings. *Globe and Mail*. Retrieved from https://www.theglobeandmail.com/life/home-and-garden/architecture/ontario-looks-to-close-loophole-on-energy-standards-for-buildings/article29261814/

Lucon O., D. Ürge-Vorsatz, A. Zain Ahmed, H. Akbari, P. Bertoldi, L.F. Cabeza, N. …. Vilariño, M.V. (2014). Buildings. In O. Edenhofer, et al. (Eds.), *Climate change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, Cambridge.

Malcolm, J. (2016). *Submission to the Government of Ontario's Discussion Paper* (EBR Registry Number 012-8685).

Marceau, M. L. & VanGeem, M. G. (2006). Comparison of the life cycle assessments of an insulating concrete form house and a wood frame house. *Journal of ASTM International, 3* (9). Retrieved from http://www.polysteel.us/GreenGuide/PDF_files/tab8/06_Life%20Cycle%20Comparison%20ICFs%20vs.%20Wood.pdf

McGee, C. (2013). Materials: Your home. Retrieved from http://www.yourhome.gov.au/sites/prod.yourhome.gov.au/files/pdf/YOURHOME-Materials.pdf

McKinsey&Company. (2010). *Energy efficiency: A compelling global resource*. Retrieved from https://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/sustainability/pdfs/a_compelling_global_resource.ashx

Morisson Hershfield (n.d.). *LCA and energy analysis on a mid-rise residential building*. Report Presented to FP Innovations.

Nässen, J., Holmberg, J., Wadeskog, A., & Nyman, M. (2007). Direct and indirect energy use and carbon emissions in the production phase of buildings: An input-output analysis. *Energy, 32*, 1593–1602. Retrieved from http://www.sciencedirect.com/science/article/pii/S0360544207000163

Nave, L.E., et al. (2010). Harvest impacts on soil carbon storage in temperate forests. *Forest Ecology and Management, 259*(5), 857–866. Retrieved from doi:10.1016/j.foreco.2009.12.009

National Council for Air and Stream Improvement, Inc. (2013). A review of biomass carbon accounting methods and implications. *Technical Bulletin No. 1015*. Research Triangle Park, N.C.: National Council for Air and Stream Improvement, Inc. Retrived from http://www.ncasi.org/Downloads/Download.ashx?id=8832

Natural Resources Canada. (2018a). Energy and greenhouse gas emissions (GHGs). Retrieved from http://www.nrcan.gc.ca/energy/facts/energy-ghgs/20063

Natural Resources Canada. (2018b). Industrial sector – Disaggregated industries Canada. Retrieved from http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=CP&sector=id&juris=ca&rn=47&page=0

Ochsendorf, J., Norford, K., Brown, D., Durschlag, H., Hsu, S., … Wildnauer, M. (2011). *Methods, impacts, and opportunities in the concrete building life cycle*. Massachusets Institute of Technology & Concrete Sustainability Hub. Retrieved from http://www.advantageicf.com/downloads/sustainability/MIT%20Buildings%20LCA%20Report.pdf

Pearl, D. & Chen, C. (2017). Bois Ellen Housing Co-op. *SABMag, 58*, 14–17.

Quader, M., Ahmed, S., Ghazilla, R., Ahmed, S., & Dahari, M. (2015). A comprehensive review on energy efficient CO_2 breakthrough technologies for sustainable green iron and steel manufacturing. *Renewable and Sustainable Energy Reviews, 50*, 594–614.

Robertson, A. Lam, F., & Cole, R. (2012). A comparative cradle-to-gate life cycle assessment of mid-rise office building construction alternatives: Laminated timber or reinforced concrete. *Buildings, 2*, 245–270. Retrieved from https://www.mdpi.com/2075-5309/2/3/245/htm

Rossi, B., Marique, A.-F., Glaumann, M., & Reiter, S. (2012). Lifecycle assessment of residential buildings in three different European locations, basic tool. *Building and Environment, 51*, 395–401. Retrieved from https://doi.org/10.1016/j.buildenv.2011.11.017

Ruuska, A. P. & Häkkinen, T. M. (2015). The significance of various factors for GHG emissions of buildings. *International Journal of Sustainable Engineering, 8*, 317–330. Retrieved from http://dx.doi.org/10.1080/19397038.2014.934931

Salazar, J. & Meil, J. (2009). Prospects for carbon-neutral housing: The influence of greater wood use on the carbon foot print of a single-family residence. *Journal of Cleaner Production, 17*(17), 1563–1571. Retrieved from https://doi.org/10.1016/j.jclepro.2009.06.006

Sathre, R. (2007). *Life cycle energy and carbon implications of wood-based materials and construction*. Retrieved from http://miun.diva-portal.org/smash/get/diva2:2032/FULLTEXT01.pdf

Säynäjoki, A., Heinonen, J., Junnila, S. & Horvath, A. (2017). Can lifecycle assessment produce reliable policy guidelines in the building sector? *Environmental Research Letters, 12*. Retrieved from http://iopscience.iop.org/article/10.1088/1748-9326/aa54ee/pdf

Searchinger, T., Heimlich, R., Houghton, R., Dong, F., Elobeid, A., Fabiosa, J., …Yu, T. (2008). Use of US croplands for biofuels increases greenhouse gases through emissions from land use change. *Science, 319*(5867), 1238–1240. Retrieved from http://www.sciencemag.org/cgi/content/abstract/1151861

Sharma, A., Saxena A., Sethi, M., Shree, V., & Varun. (2011). Life cycle assessment of buildings: A review. *Renewable and Sustainable Energy Reviews, 15*(1), 871-875. Retrieved from https://doi.org/10.1016/j.rser.2010.09.008

Shatokha, V. (2016). Environmental sustainability of the iron and steel industry: Towards reaching the climate goals. *European Journal of Sustainable Development, 5*(4), 289–300.

Singh, V. (2014). Green building materials. Retrieved from https://www.coa.gov.in/show_img.php?fid=137

Smith, W., Cheng, R., Potapov, P. & Minnemeyer, S. (2016, August). A fresh look at Canada's virgin forests. *Global Forest Watch*. Retrieved from https://blog.globalforestwatch.org/people/partner-post-a-fresh-look-at-canadas-virgin-forests

Smyth, C. E., Stinson. G., Neilson, E., Lemprière, T.C., Hafer, M., Rampley, G. J., & Kurz, W. A. (2014). Quantifying the biophysical climate change mitigation potential of Canada's forest sector. *Biogeosciences, 11*, 3515–3529. Retrived from https://www.biogeosciences.net/11/3515/2014/bg-11-3515-2014.pdf

Stevens, P. (2017). Bergeron Centre for Engineering Excellence. *SABMag, 58*, 8–16.

Stralberg, D., Wang, X., Parisien, M.-A., Robinne, F.-N., Solymos, P., Mahon, C. L. … Bayne, E. M. (2018). Wildfire-mediated vegetation change in boreal forests of Alberta, Canada. *Ecosphere, 9*(3), e02156. Retrieved from https://doi.org/10.1002/ecs2.2156

Talberth, J, DellaSala, D. & Fernandez, E. (2015). *Clearcutting our carbon accounts*. Ashland: GEOS Institute. Retrieved from https://sustainable-economy.org/wp-content/uploads/2015/11/Clearcutting-our-Carbon-Accounts-Final-11-16.pdf

Ter-Mikaelian, M., Colombo, S. & Chen, J. (2015). The burning question: Does forest bioenergy reduce carbon emissions? A review of common misconceptions about forest carbon accounting. *Journal of Forestry, 113*(1), 57–68. Retrieved from http://ucanr.edu/sites/forestry/files/212529.pdf

The Construction Specifier. (2014, July 30). Enhancing energy performance with balcony thermal breaks. Retrieved from https://www.constructionspecifier.com/enhancing-energy-performance-with-balcony-thermal-breaks/

The Nature Conservancy of Canada. (2017). *Impact report 2017*. Retrieved from https://www.natureunited.ca/content/dam/tnc/nature/en/documents/canada/TNC%20Canada%20Impact%20Report%20(web).pdf

Turner, M. (2012). *Mitigating iron and steel emissions*. Columbia Climate Centre. Earth Institute, Columbia University. Retrieved from http://climate.columbia.edu/files/2012/04/GNCS-Iron-Steel.pdf

United Nations Framework Convention on Climate Change. (2011, November 22). *Synthesis report of the technical assessments of the forest management reference level submissions, Ad Hoc Working Group on Further Commitments for Annex I Parties under the Kyoto Protocol*. Note by the Secretariat.

World Steel Association. (2017). *Steel's contribution to a low carbon future and climate resilient societies*. Retrieved from https://www.steel.org.au/resources/elibrary/resource-items/steel-s-contribution-to-a-low-carbon-future-and-cl/download-pdf.pdf/

World Wildlife Fund. (2017). *Living planet report Canada: A national look at wildlife loss*. Retrieved from http://assets.wwf.ca/downloads/WEB_WWF_REPORT.pdf

Xi, F., Davis, S., Ciais, P. Crawford-Brown, D., Guan, D. & Zhang, Y. (2016). Substantial global carbon uptake by cement carbonation. *Nature Geoscience, 9*, 880–883. Retrieved from https://www.nature.com/articles/ngeo2840

Annex A

Data from Säynäjoki et al. (2017) used in Table 2.

Cradle-to-Gate Life-Cycle GHG (tCO_2e/m^2)	LCA Method	Building Type	Location	Climatic Zone*	Area (gross m^2)	Material
0.33	Process	Office	CA	Dfc	4620	Concrete
0.35	Process	Office	CA	Dfc	4620	Concrete
0.08	Process	Apartment	SE	Dfc	1679	Concrete
0.22	Process	Apartment	FI	Dfc	2447	Concrete
0.2	Process	Apartment	FI	Dfc	1346	Concrete
0.36	Process	Office	FI	Dfc	15600	Concrete
0.41	Process	Office	FI	Dfc	24000	Concrete
0.55	Hybrid	Office	US	Dfb	4400	Concrete
0.26	Process	Apartment	FI	Dfc	1679	Concrete
0.26	Process	Apartment	FI	Dfc	1700	Concrete
0.34	Hybrid	Office	US	Dfc	4400	Concrete
0.55	Hybrid	Office	FI	Dfb	4400	Concrete
0.38	Process	Office	FI	Dfc	9000	Concrete
0.84	Hybrid	Office	TH	Aw	60000	Concrete
0.27	Process	Apartment	FI	Dfc	2065	Concrete
0.19	Process	Apartment	CH	Dwa	3913	Concrete
0.55	Process	Apartment	CA	Dwa	3913	Concrete
0.22	Process	Office	UK	Cfb	87109	Concrete
0.22	Process	Office	UK	Cfb	87109	Concrete
0.22	Process	Office	UK	Cfb	87109	Concrete
0.42	Process	Office	CA	Dfb	14233	Concrete
0.54	Process	Apartment	AT	Cfb	1980	Concrete
0.67	Process	Apartment	AT	Cfb	970	Concrete
0.77	Process	Apartment	AT	Cfb	1150	Concrete
0.36	Process	Office	IT	Cfb	4790	Concrete
0.44	Process	Apartment	IT	Cfb	2610	Concrete

Cradle-to-Gate Life-Cycle GHG (tCO_2e/m^2)	LCA Method	Building Type	Location	Climatic Zone*	Area (gross m^2)	Material
1.1	Input–output	Apartment	FI	Dfc	21546	Concrete
0.52	Process	Public	AU	Csa	4020	Concrete
1.39	Hybrid	Apartment	LE	Csa	1232	Concrete
0.42	Hybrid	Apartment	TU	Csa	471	Concrete
0.74	Hybrid	Apartment	TU	Csa	4829	Concrete
0.58	Process	Public	CA	Dfb	2100	Concrete
0.52	Process	Apartment	KO	Dwa	208392	Concrete
0.64	Process	Public	CH	Cfa	16873	Concrete
0.36	Process	Office	CA	Dfc	4620	Steel
0.38	Process	Office	CA	Dfc	4620	Steel
0.62	Hybrid	Office	US	Dfb	4400	Steel
0.35	Process	Public	CA	Dfb	2100	Steel
0.32	Process	Office	CA	Dfc	4620	Wood
0.34	Process	Office	CA	Dfc	4620	Wood
0.05	Process	Apartment	SE	Dfc	1679	Wood
0.22	Process	Apartment	SE	Dfc	1700	Wood
0.3	Process	Apartment	SE	Dfc	1679	Wood
0.19	Process	Apartment	FI	Dfc	2065	Wood
0.13	Process	Office	CA	Dfb	14233	Wood
0.19	Process	Apartment	CH	Dwa	3913	Wood
0.49	Process	Apartment	AT	Cfb	1609	Wood
0.66	Process	Apartment	AT	Cfb	1381	Wood
0.03	Process	Apartment	DE	Cfb	726	Wood
0.32	Process	Apartment	NO	Dfb	160	Wood
0.12	Process	Public	CA	Dfb	2100	Wood

**Key to climate zones*

Type	Abbreviation	Identification
Climatic Zone	Dfc	snow, fully humid, cool summers—for example, Scandinavia and other northern parts of Europe
	Cfb	warm, fully humid, warm summers—for example, central Europe and some parts of Australia
	Dfb	snow, fully humid, warm summers—for example, the Midwest of the United States and some eastern parts of Europe
	Aw	equatorial, dry winters—for example, the outer margins of the tropical zones, occasionally an inner-tropical zone
	Csb	warm, steppes, warm summers—for example, north-western Italy
	Dwa	snow, dry winters, hot summers—for example, some parts of China
	Csa	warm, steppes, hot summers—for example, the Mediterranean area and some parts of Australia
	Cfa	snow, fully humid, hot summers—for example, some parts of Canada and northern central Asia

Data used in Figure 1 (15 different sources)

Life-Cycle Stage	Reference	Value
Use Stage	Sharma et al., 2011	80%
Use Stage	Blengini & Di Carlo, 2010	54%
Use Stage	Ruuska & Häkkinen, 2015	45%
Use Stage	Ochsendorf et al., 2011	88.5%
Use Stage	Rossi et al., 2012	62%
Use Stage	Chou & Yeh, 2015	89.0%
Use Stage	John, S., et al. 2008	74.2%
Use Stage	Ruuska & Häkkinen, 2015	85%
Use Stage	Ruuska & Häkkinen, 2015	61%
Use Stage	Ochsendorf et al., 2011	91%
Use Stage	Ghattas et al., 2013	90%
Use Stage	Ghattas et al., 2013	50%
Use Stage	Säynäjoki et al., 2017	85%
Use Stage	Chou & Yeh, 2015	89.5%
Use Stage	Marceau et al., 2012	61.6%
Use Stage	John, S., et al. 2008	79.1%
Use Stage	Biswas, 2014	85%
Use Stage	Junnila et al., 2006	88%

Life-Cycle Stage	Reference	Value
Use Stage	Sharma et al., 2011	85%
Use Stage	Blengini & Di Carlo, 2010	80%
Use Stage	Ruuska & Häkkinen, 2015	76%
Use Stage	Ochsendorf et al., 2011	93.0%
Use Stage	Rossi et al., 2012	98%
Use Stage	Chou & Yeh, 2015	90.1%
Use Stage	John, S., et al. 2008	84.0%
Construction Stage	Sharma et al., 2011	0.4%
Construction Stage	Blengini & Di Carlo, 2010	1.00%
Construction Stage	Rossi et al., 2012	1.00%
Construction Stage	Guggemos & Horvath, 2005	0.40%
Construction Stage	Chou & Yeh, 2015	1.3%
Construction Stage	Grann, 2013	1.8%
Construction Stage	Ruuska & Häkkinen, 2015	1%

Life-Cycle Stage	Reference	Value
Construction Stage	Nässen et al., 2007	0.8%
Construction Stage	Chou & Yeh, 2015	3.2%
Construction Stage	Marceau et al., 2012	0.4%
Construction Stage	Biswas, 2014	2.2%
Construction Stage	Junnila et al., 2006	2%
Construction Stage	Grann, 2013	1.9%
Construction Stage	Sharma et al., 2011	11%
Construction Stage	Blengini & Di Carlo, 2010	2%
Construction Stage	Rossi et al., 2012	20%
Construction Stage	Guggemos & Horvath, 2005	11%
Construction Stage	Chou & Yeh, 2015	5.0%
Construction Stage	Grann, 2013	2.0%
Product Stage	Blengini & Di Carlo, 2010	20%
Product Stage	Ruuska & Häkkinen, 2015	24%
Product Stage	Ochsendorf et al., 2011	6.9%
Product Stage	Chou & Yeh, 2015	3.6%
Product Stage	John, S., et al. 2008	15.8%
Product Stage	Grann, 2013	13.7%
Product Stage	Ruuska & Häkkinen, 2015	15%
Product Stage	Ruuska & Häkkinen, 2015	40%
Product Stage	Ochsendorf et al., 2011	9%
Product Stage	Nässen et al., 2007	11%
Product Stage	Ghattas et al., 2013	10%
Product Stage	Ghattas et al., 2013	50%
Product Stage	Chou & Yeh, 2015	6.0%
Product Stage	Marceau et al., 2012	38.0%
Product Stage	John, S., et al. 2008	19.8%
Product Stage	Biswas, 2014	12%
Product Stage	Junnila et al., 2006	10%
Product Stage	Grann, 2013	18.1%
Product Stage	Blengini & Di Carlo, 2010	46%
Product Stage	Ruuska & Häkkinen, 2015	55%
Product Stage	Ochsendorf et al., 2011	11.2%
Product Stage	Chou & Yeh, 2015	8.4%
Product Stage	John, S., et al. 2008	23.8%
Product Stage	Grann, 2013	22.4%
End-of-Life Stage	Ochsendorf et al., 2011	0.1%
End-of-Life Stage	Rossi et al., 2012	0.20%
End-of-Life Stage	Chou & Yeh, 2015	1.3%
End-of-Life Stage	John, S., et al. 2008	0.2%
End-of-Life Stage	Grann, 2013	1.4%
End-of-Life Stage	Ochsendorf et al., 2011	0.2%
End-of-Life Stage	Chou & Yeh, 2015	1.3%
End-of-Life Stage	John, S., et al. 2008	1.1%
End-of-Life Stage	Junnila et al., 2006	0.5%
End-of-Life Stage	Grann, 2013	1.4%
End-of-Life Stage	Ochsendorf et al., 2011	0.2%
End-of-Life Stage	Rossi et al., 2012	5%
End-of-Life Stage	Chou & Yeh, 2015	1.3%
End-of-Life Stage	John, S., et al. 2008	2.0%
End-of-Life Stage	Grann, 2013	1.5%

Annex B

In this Annex, calculations and assumptions are presented for four forest harvesting scenarios that consider different potential uncertainties related to biogenic carbon emissions and sinks. The scenarios are compared to a carbon-neutral baseline similar to what is widely adopted in LCA and that reflects a net transfer of biogenic carbon to the atmosphere and cumulative radiative forcing over the lifetime of the harvested wood product of zero.

Carbon exchanges between forest carbon pools and the atmosphere are tracked annually in each scenario. Scenarios 1, 2 and 3 are isolated and independent of one another while Scenario 4 combines the impact of all three scenarios (1, 2 and 3):

1. Assume that the regeneration rate of a forest that is currently certified to the Canadian Standards Association (CSA) and currently reported to be 100 per cent or greater is in fact overestimated and is at a rate of only 90 per cent due to insufficient forest renewal management practices.
2. Consider an outcome for a boreal forest where there is a net permanent loss of 5 per cent soil carbon attributed to clear-cut harvesting.
3. Consider the conversion of a natural forest with a mature stand of trees to a managed forest with short rotations to maximize yields (40 per cent loss in overall aboveground carbon stock).
4. Combined impacts of scenarios 1, 2 and 3.

Common assumptions for the baseline and all three scenarios outlined above include the following:

- No particular forest or region of Canada is modelled, instead an archetype forest meant to be representative is defined.
- A 60-year harvest rotation is assumed (while most forests in Canada may be under a lower or higher harvest rotation period, boreal forests, which account for the majority of wood products, typically have harvest rotation periods that are equal to or greater than 60 years. Selecting a longer harvest rotation period would have the impact of decreasing net biogenic emissions for all scenarios considered and selecting a shorter harvest rotation period would increase net biogenic emissions).
- The lifetime of the biogenic carbon LCA assessment period selected was 100 years. This is longer than the typical building lifetime and sufficient time to capture forest carbon dynamics between different carbon pools. It also corresponds to the length of time that global warming potential coefficients are typically compared in mitigation assessments.
- Transfers of carbon are modelled between aboveground carbon pools, harvested wood product (HWP) carbon pools and the atmosphere for each scenario. The soil carbon scenario also considers exchanges from the soil organic carbon pool to the atmosphere.
- Biogenic carbon transferred to the long-lived harvested wood product pool (LL HWP) is assumed to have a half-life of 60 years, meaning that about half of the carbon would be expected to be released to the atmosphere after 60 years. Biogenic carbon transferred to the short-lived harvested wood products pool (SL HWP) is assumed to have a half-life of five years, meaning that about half of the carbon would be expected to be released to the atmosphere after five years. Selection of longer half-lives would decrease the net biogenic emissions, while shorter half-lives would increase the net biogenic emissions.

Model Simulation of the Baseline Includes:

- The following initial distribution of total biogenic forest carbon into different carbon pools before harvest (i.e., year 0): 14.9 per cent in aboveground biomass (AGB) pools, 67.6 per cent in soil carbon (SOC) pools, 5.1 per cent in HWP pools and the remaining 12.4 per cent in belowground biomass (BGB), dead wood and litter carbon pools. Transfers of carbon pools are not simulated for these remaining carbon pools as they are assumed to be in steady state over the lifetime of the forest (i.e., the cumulative radiative forcing effects of emissions and sinks are assumed to be zero over the 100-year assessment period).

- Harvesting results in 72 per cent of the total AGB forest carbon being transferred to SL HWP and LL HWP pools. 50 per cent of the harvested forest carbon is assumed to be converted to SL HWP pools, and 50 per cent of the harvested forest carbon is assumed to be converted to LL HWP pools. This ratio is conservative in the sense that the proportion sent to LL HWP is considerably above the national average, and that the larger proportion sent to LL HWP increases the overall carbon sink potential of the harvested wood products category. Forests with a higher proportion of LL HWP would decrease the net biogenic emissions or increase sinks, while forests with a lower proportion of LL HWP would increase the net biogenic emissions or decrease sinks.
- The growth rate in AGB is set so that after the 60-year harvest rotation period, the AGB accumulated is equal to the value before harvest (i.e., year 0). This assumption corresponds to the forest reaching an equivalent merchantable timber level after 60 years as before harvest. An assumption of a higher growth rate would decrease net carbon biogenic emissions, while a lower growth rate assumption would increase net carbon biogenic emissions.

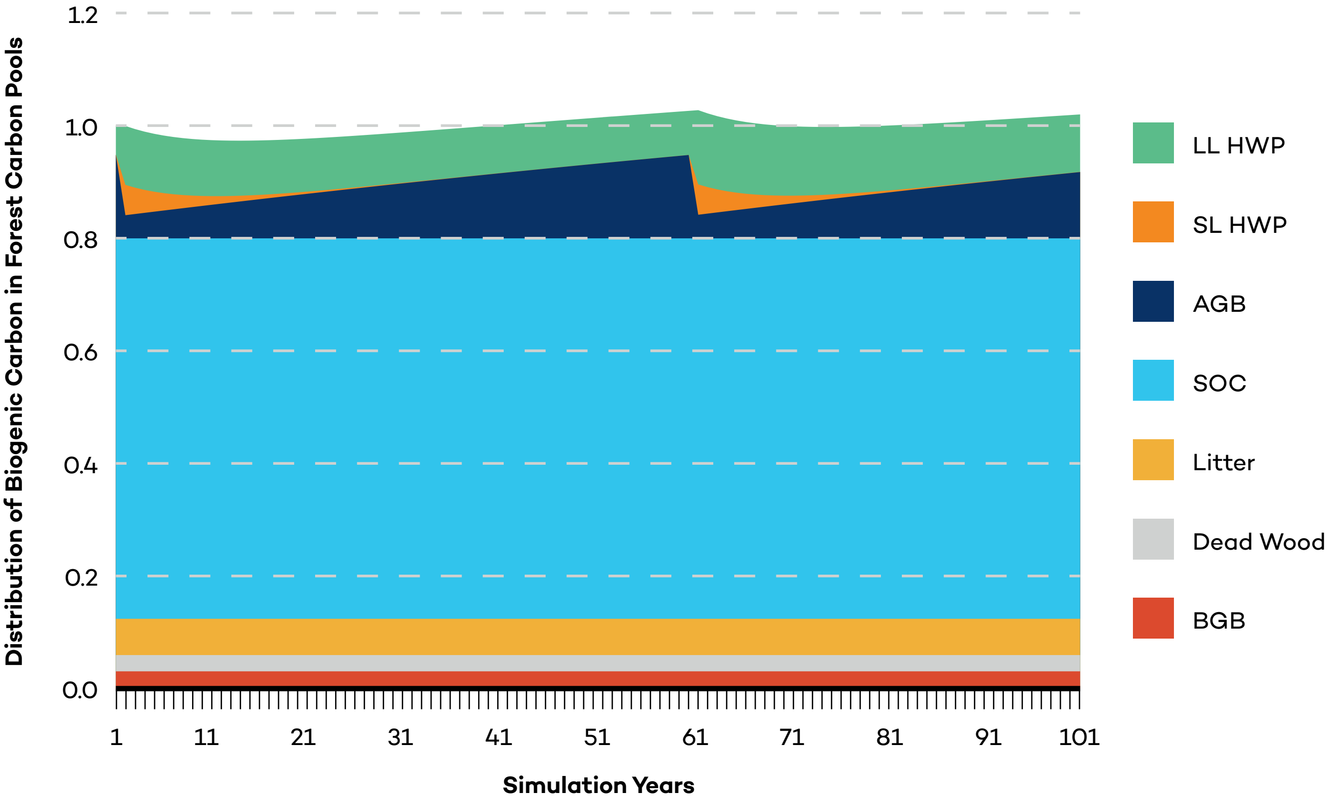

Figure B.1. Baseline biogenic carbon pools for a 100-year simulation period

Note that where cumulative biogenic carbon for all forest carbon pools is below 1 in Figure B.1, this indicates net emissions to the atmosphere, while where cumulative biogenic carbon for all forest carbon pools is above 1, this indicates a relative net sink in forest carbon pools. While over the 60-year rotation period net emissions and net sinks vary, the overall radiative forcing as represented by the GWP of emissions and sinks through the entire 100-year assessment period lifetime is zero (i.e., the area of white space below 1 representing emissions to the atmosphere is roughly equal to the area occupied by the forest carbon pools that is above 1).

Model Simulation of a **90 per cent Regeneration Rate Scenario** includes:

- The same initial distribution of total biogenic forest carbon as the baseline. 14.9 per cent in AGB pools, 67.6 per cent in SOC pools, 5.1 percent in HWP pools, and the remaining 12.4 per cent in BGB, dead wood and litter carbon pools.
- The same AGB carbon pool harvesting assumptions as the baseline. Harvesting results in 72 per cent of the total AGB forest carbon being transferred to SL HWP and LL HWP pools. 60 per cent of the harvested forest carbon is assumed to be converted to SL HWP, and 40 per cent of the harvested forest carbon is assumed to be converted to LL HWP.
- A lower growth rate in AGB as the baseline, at 90 per cent of the baseline value. Set so that after the 60-year harvest rotation period, the AGB accumulated is 90 per cent of the value before harvest (i.e., year 0). This assumption is based on evidence that some harvested land areas have permanent losses to the forest land base as a result of land converted to building access roads and operating areas, as well as a lower merchantable volume of timber compared to previous harvests (GLOBE Advisors, 2017).

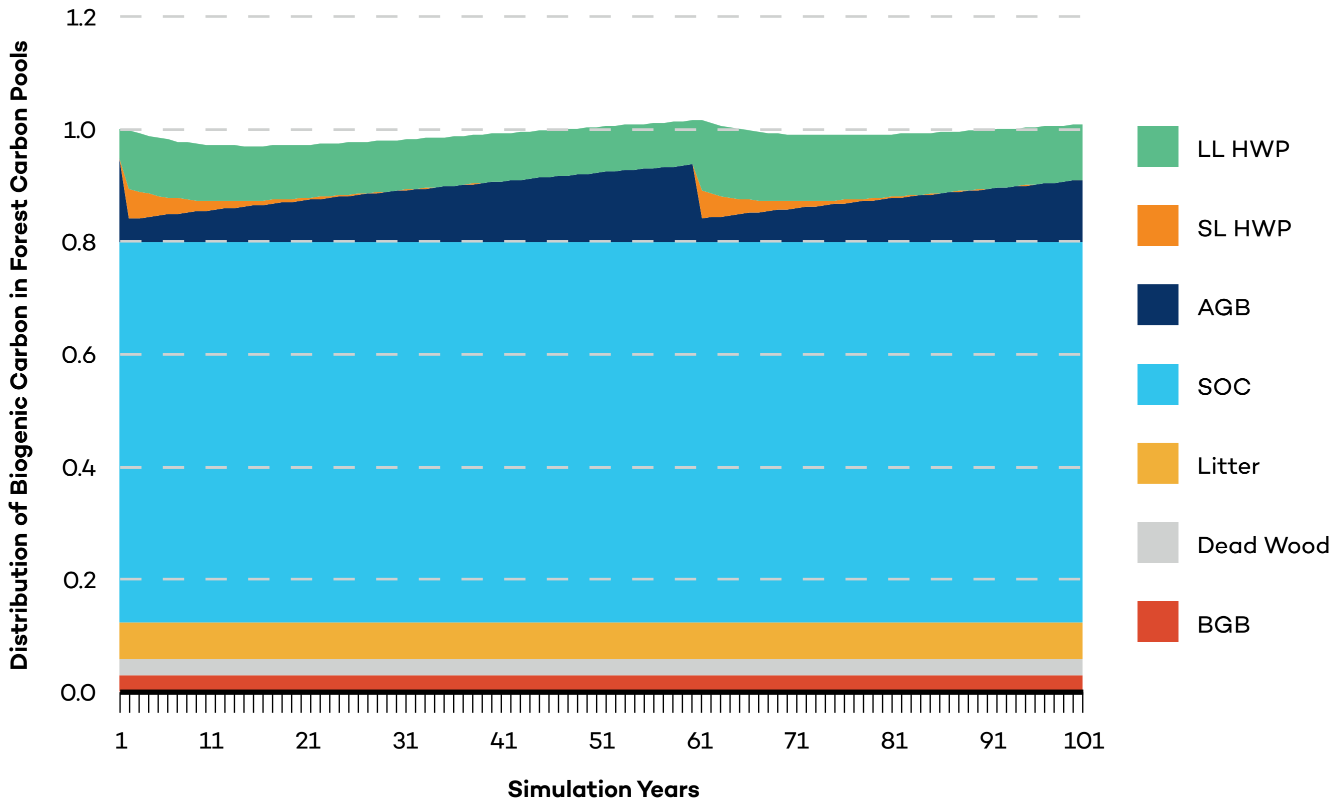

Figure B.2. **90 per cent regeneration rate: Biogenic carbon pools for a 100-year simulation period**

Model Simulation of the **Loss of Soil Organic Carbon Scenario** Includes:

- The same initial distribution of total biogenic forest carbon as the baseline: 14.9 percent in AGB pools, 67.6 percent in SOC pools, 5.1 percent in HWP pools, and the remaining 12.4 per cent in BGB, dead wood and litter carbon pools.

- The same AGB pool harvesting assumptions as the baseline. Harvesting results in 72 per cent of the total AGB forest carbon being transferred to SL HWP and LL HWP pools. 60 per cent of the harvested forest carbon is assumed to be converted to SL HWP, and 40 per cent of the harvested forest carbon is assumed to be converted to LL HWP.
- The same growth rate in AGB as the baseline—set so that after the 60-year harvest rotation period, the AGB accumulated is equal to the value before harvest (i.e., year 0).
- An assumption that 5 per cent of the total soil organic carbon pool is permanently lost in the first five years after harvest. This assumption is based on estimates from studies that forest harvesting can significantly decrease total soil carbon in temperate forest soils (James & Harrison, 2016; Nave et al., 2010).

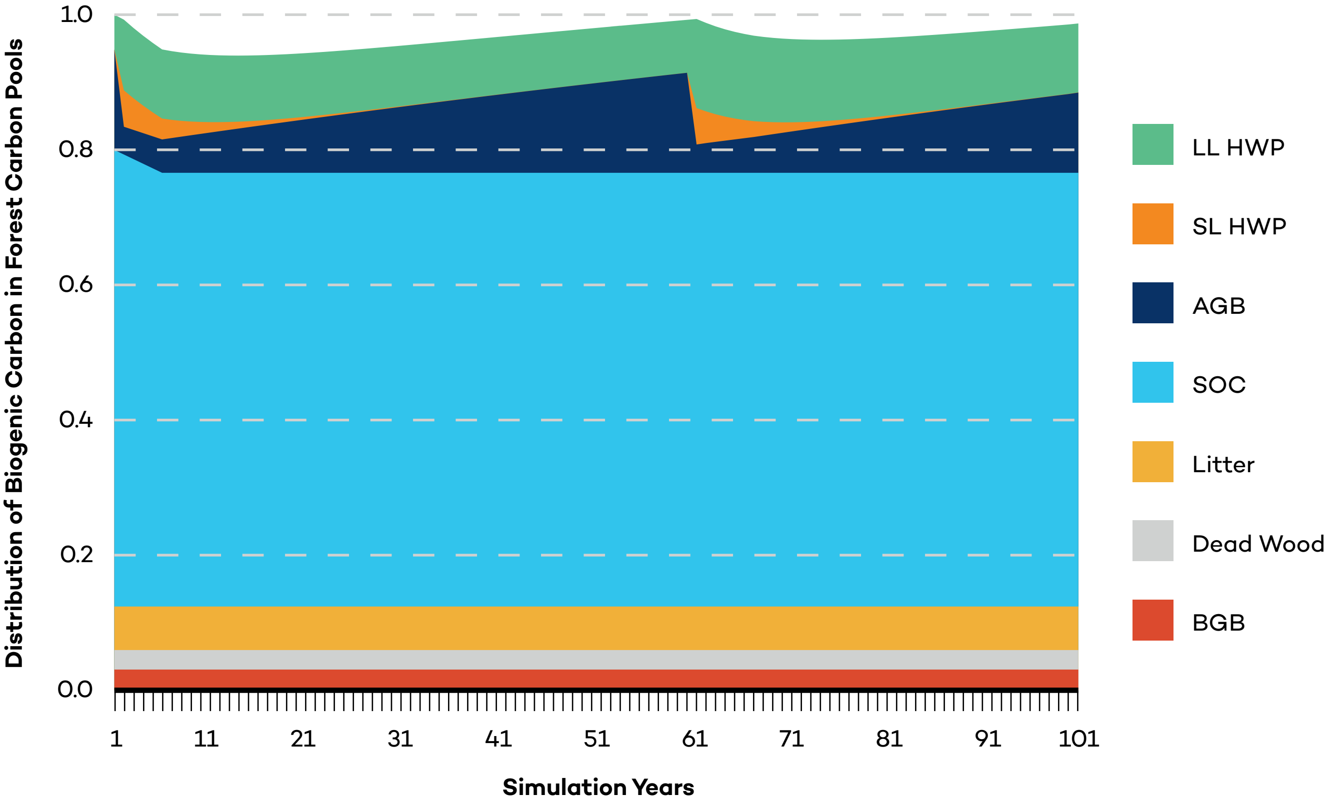

Figure B.3. Soil organic carbon loss: Biogenic carbon pools for a 100-year simulation period

Note that cumulative biogenic carbon for all forest carbon pools is always below 1, indicating net emissions to the atmosphere. In fact, total forest carbon including in HWPs never recovers to initial levels and is at 98 per cent at the end of the 100-year assessment period. This leads to a net global warming potential over the period.

Model Simulation of the **Conversion of a Natural Forest Scenario** Includes:

- The following initial distribution of total biogenic forest carbon into different carbon pools before harvest (i.e., year 0): 23.4 per cent in AGB pools, 63.8 per cent in SOC pools and the remaining 12.9 per cent in BGB, dead wood and litter carbon pools. Transfers of carbon pools are not simulated for these remaining carbon pools as they are assumed to be in a steady state over the lifetime of the forest (i.e., the cumulative radiative forcing effects of emissions and sinks is assumed to be zero over the 100-year assessment period).

- Initial harvesting results in 82 per cent of the total AGB forest carbon being transferred to SL HWP and LL HWP pools. 50 per cent of the harvested forest carbon is assumed to be converted to the SL HWP and 50 per cent of the harvested forest carbon is assumed to be converted to LL HWP. This ratio is conservative in the sense that the proportion sent to LL HWP is considerably above the national average, and that the larger proportion sent to LL HWP increases the carbon sink potential of the harvested wood products category. Subsequent harvesting rates result in 72 per cent of the total AGB forest carbon being transferred to HWP. Forests with a higher proportion of LL HWP would decrease the net biogenic emissions, while forests with a lower proportion of LL HWP would increase the net biogenic emissions.
- The growth rate in AGB is equal to the baseline growth rate where, after the 60-year harvest rotation period, the AGB accumulated is equal to 60 per cent of the value before harvest. This assumption is based on estimates of carbon being reabsorbed by growing trees after the harvest of a mature stand (GLOBE Advisors, 2017). An assumption of a higher growth rate would decrease net carbon biogenic emissions, while a lower growth rate assumption would increase net carbon biogenic emissions.

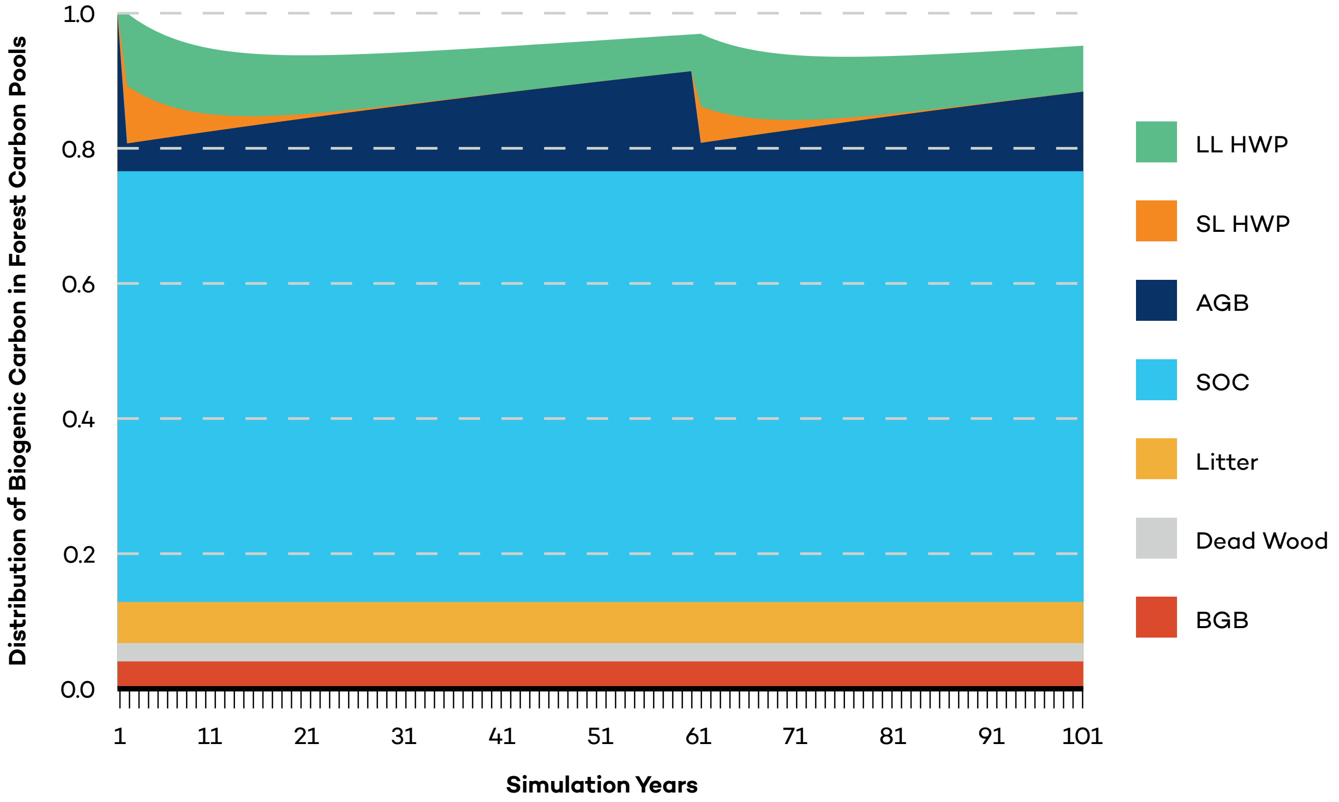

Figure B.4. Natural forest conversion: Biogenic carbon pools for a 100-year simulation period

Note that cumulative biogenic carbon for all forest carbon pools is always below 1, indicating net emissions to the atmosphere. In fact, total forest carbon including in HWPs never recovers to initial levels and is at 94 per cent at the end of the 100-year assessment period. This leads to a net global warming potential over the period.

Model Simulation of the Combined Scenario Includes:

Combined assumptions of the **90 per cent Regeneration Rate, Loss of Soil Organic Carbon** and the **Natural Forest Conversion** scenarios:

- The following initial distribution of total biogenic forest carbon into different carbon pools before harvest (i.e., year 0): 23.4 per cent in AGB pools, 63.8 per cent in SOC pools and the remaining 12.9 per cent in BGB, dead wood and litter carbon pools. Transfers of carbon pools are not simulated for these remaining carbon pools as they are assumed to be in a steady state over the lifetime of the forest (i.e., the cumulative radiative forcing effects of emissions and sinks is assumed to be zero over the 100-year assessment period).
- Initial harvesting results in 82 per cent of the total AGB forest carbon being transferred to SL HWP and LL HWP pools. 50 per cent of the harvested forest carbon is assumed to be converted to SL HWP, and 50 per cent of the harvested forest carbon is assumed to be converted to LL HWP. This ratio is conservative in the sense that the proportion sent to LL HWP is considerably above the national average, and that the larger proportion sent to LL HWP increases the carbon sink potential of the harvested wood products category. Subsequent harvesting rates result in 72 per cent of the total AGB forest carbon being transferred to HWP. Forests with a higher proportion of LL HWP would decrease the net biogenic emissions, while forests with a lower proportion of LL HWP would increase the net biogenic emissions.
- The growth rate in AGB is equal to the baseline growth rate where after the 60-year harvest rotation period, the AGB accumulated is equal to 60 per cent of the value before harvest. For subsequent harvest after 60 years, the growth rate is 90 per cent of the growth rate in the baseline.
- An assumption that 5 per cent of the total soil organic carbon pool is permanently lost in the first five years after harvest.

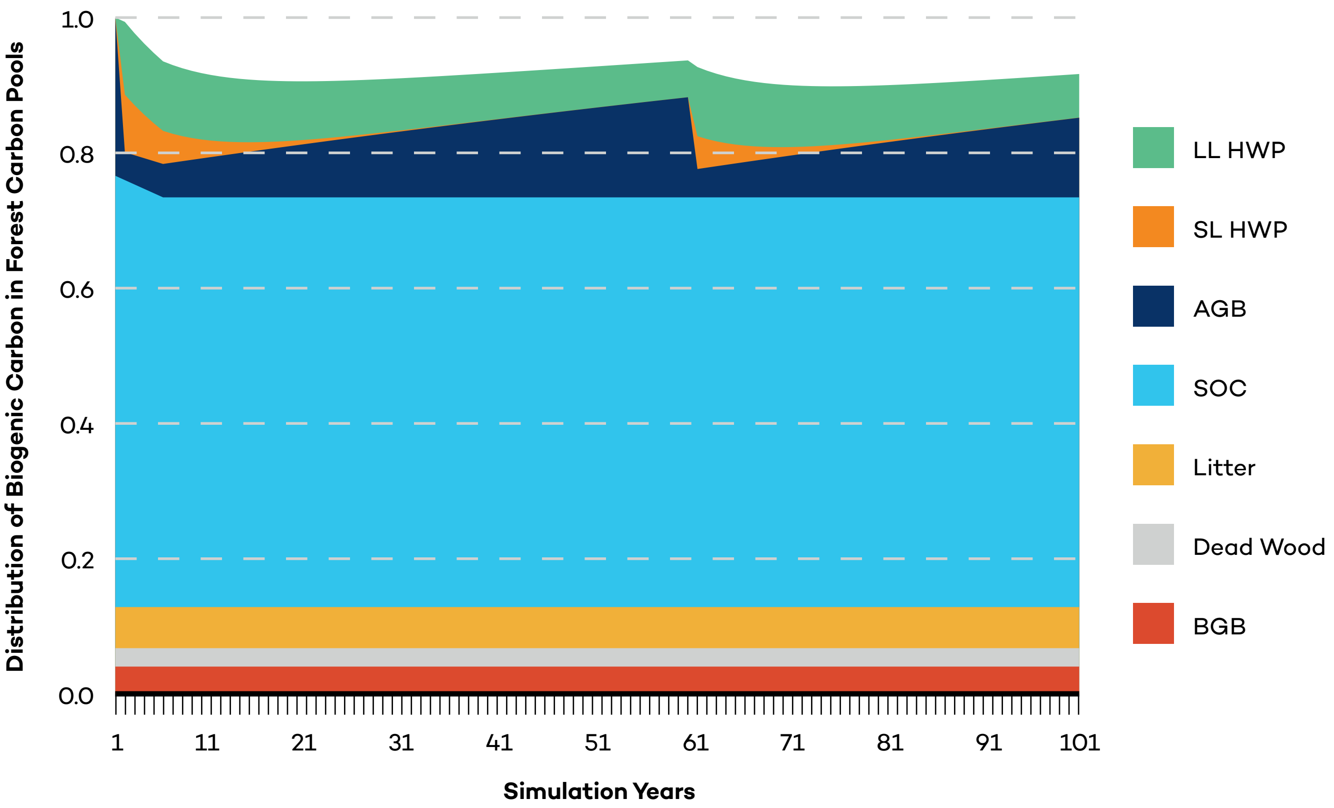

Figure B.5. Combined scenario (scenarios 1, 2 and 3 together): Biogenic carbon pools for a 100-year simulation period

Note that where cumulative biogenic carbon for all forest carbon pools is below 1, this indicates net emissions to the atmosphere, while where cumulative biogenic carbon for all forest carbon pools is above 1, this indicates a relative net sink in forest carbon pools. While over the 100-year simulation period net emissions and net sinks vary, the overall radiative forcing as represented by the GWP potential of emissions and sinks through the entire 100-year assessment period lifetime is negative.

The baseline and four scenarios provide only a view of a possible range of impacts due to identified uncertainties and are not representative of probabilistic outcomes, or average or specific conditions for Canadian managed forests. For each scenario, it is possible to estimate yearly carbon flows associated with all harvested wood products by attributing the net annual change in biogenic carbon emissions projected on an equal weighted basis for all HWPs.

In this study, we calculate the GWP_{bio} factors using the simulations identified above and accounting for the radiative forcing effects within a period of 100 years. Other GHGs that can possibly arise from the combustion or anaerobic degradation of the biogenic carbon, including nitrogen dioxide and methane are not included in the simulation, but these are typically accounted for in LCA analysis.

The GWP_{bio} factor is calculated by averaging the net emissions (positive) or sinks (negative) of biogenic carbon in the atmosphere (i.e., not in any of the forest carbon pools indicated in each figure) over the entire 100-year simulation period. Separate GWP_{bio} factors could be calculated for SL HWP and LL HWP; however, an average is used that can be applied both to the embodied carbon in structural wood building elements and the bioenergy that is used to manufacture these products. In addition, the scenarios all consider a split between SL HWP of 60 per cent and LL HWP of 40 per cent, which means that LL HWP is significantly higher than the national average. Combining them also reflects the fact that they are often not substitutable; for example, of the merchantable timber transported to the sawmill, only about half is typically converted to LL HWP (Global Advisors, 2017).

The GWP_{bio} factors presented in Table B.1 are calculated by summing the net emissions to the atmosphere and dividing by the net carbon sequestered in HWP over the 100-year time frame. This can be visualized as the area in white below 1 in each figure divided by the area for both SL and LL HWP.

Table B.1. Estimated GWP_{bio} factors for four carbon biogenic harvesting scenarios

Scenario	GWP_{bio}
Baseline – Carbon Neutral	0
90% Regeneration Rate (Scenario 1)	0.0696
Soil Carbon Loss (Scenario 2)	0.293
Conversion of Natural Forest (Scenario 3)	0.509
Combined (Scenarios 1, 2 and 3)	0.835

The GWP_{bio} factors can be used to estimate biogenic carbon emissions and adjust embodied life-cycle emissions (cradle to gate) associated with any wood product that has not included them. Adjustments can be made to life-cycle emissions associated with the embodied carbon in the product itself, but also related to the wood biomass combusted for energy in production. The necessary data for three products is summarized in Table B.2 below. The product information was gathered from cradle-to-gate life-cycle assessment reports from the Athena Sustainable Materials Institute (2018) for each wood product including softwood lumber, softwood plywood sheathing, Orientated Strand Board (OSB) and glued laminated timber (Glulam).

Table B.2. Product mass and carbon mass associated with product and wood biomass consumed for energy production

	A	B (A*0.5)	C
Product	Product Mass (kg)	Product Wood Carbon Mass (kg C)	Production Wood Biomass Requirement (kg C)[1] (assuming 20kg / MJ and carbon density of 0.5 kg C/kg wood)
1 m^3 of Glulam sections	417	209	5.4
1 m^3 OSB	562	281	62.8
1 m^3 of small dimension lumber	417	209	25.4
1 m^3 softwood plywood sheathing	428	214	35.8

Calculated total embodied emission intensity for each product is provided in Table B.4 for the Conversion of Natural Forest Scenario where GWP_{bio} is equal to 0.509.

Table B.3. Adjusted emission intensities that include embodied biogenic emissions (GWP=0.509) for four wood products

	D	E (B + C) * (44/12) * 0.509	F (E/A)	G ((D+E)/A)
Product	Cradle-to-Gate Emissions (kgCO_2e)	Embodied Biogenic Emissions where GWP_{bio} = 0.509 (kgCO_2e)	Embodied Biogenic Emission Intensity (kgCO_2e)	Total Combined Emission Intensity per kg of Product (kgCO_2/kg product)
1 m^3 of Glulam Sections	148	399	0.957	1.31
1 m^3 OSB	137	641	1.14	1.39
1 m^3 of small dimension lumber	48.7	436	1.05	1.16
1 m^3 softwood plywood sheathing	69.4	466	1.09	1.25

The calculation in Table B.3 can be repeated for each product to produce Figure B.6 below.

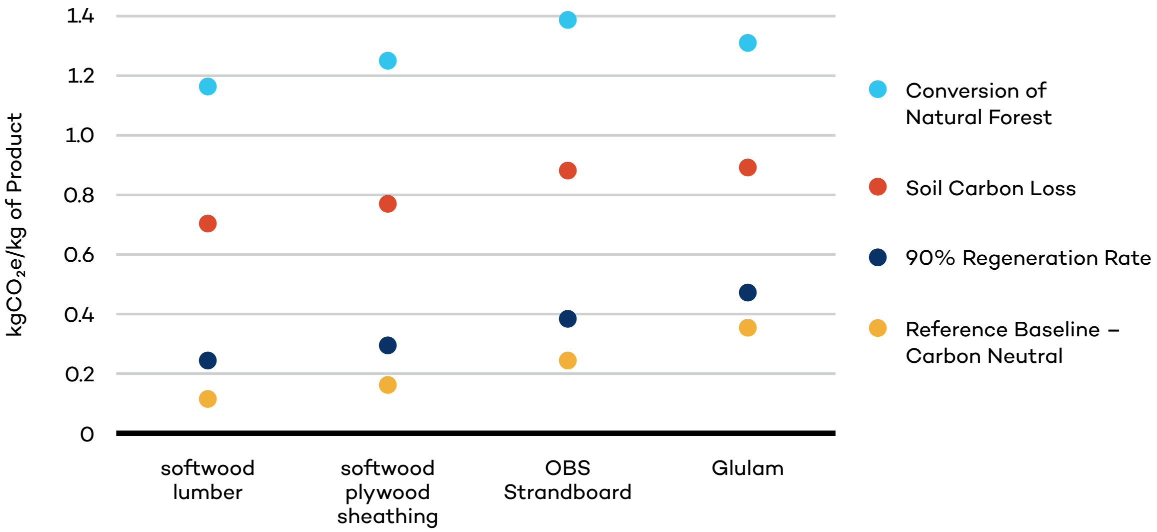

Figure B.6. Cradle-to-gate life-cycle GHG emissions of four wood products under different scenario assumptions

Figure B.6 identifies that embodied (cradle to gate) emissions can rise by a factor of 1.3 to nearly 10 times when including biogenic carbon emissions depending on the scenario and the product.

In order to assess overall building life-cycle impacts, a typical LCA study comparing alternative design construction for a wood and concrete mid-rise residential building conducted by Morrison Hershfield was selected (Morrison Hershfield, n.d.). This LCA estimated whole-building LCA results between two structural frame versions one of wood and one of concrete that had equivalent building energy requirements. This example is typical of LCA work found in the literature and estimates that cradle-to-gate life-cycle emissions for a defined wood construction has 36 per cent lower GWP then the concrete alternative. This LCA makes the assumption that biogenic carbon emissions are carbon neutral and do not contribute to the GWP. The three main wood building components included in the designs are Glulam sections, OSB and softwood lumber. Based on the total mass of these components, the calculated emission intensity and the biogenic carbon emission factors associated with each scenario, the additional biogenic carbon emissions for the concrete and wood building can be calculated.

Table B.4. Calculation of embodied biogenic emissions for example concrete and wood building for natural forest conversion (GWP_{bio}=0.509)

Product	H		I (H *A)/1000		J (I * F) / 1000	
	Number of Components		Mass of Product		Embodied Biogenic Emissions (tonnes) Where GWP_{bio} = 0.509	
	Concrete Bldg	Wood Bldg	Concrete Bldg	Wood Bldg	Concrete Bldg	Wood Bldg
Glulam sections (m^3)	0	214	0	89	0	85.4
OSB (9mm)	3047	39,558	15.4	200	17.6	229
Small dimension softwood lumber (m^3)	12	344	5.0	143	5.2	150
TOTAL for all wood products	-	-	20.4	433	22.8	464

Embodied biogenic emissions can then be compared to overall emissions calculated for the LCA life-cycle stages and processes. Table B.5 below identifies the LCA life-cycle emissions reported in the LCA study compared to the biogenic emissions calculated for each of the four scenarios.

Table B.5. LCA emissions for alternative concrete and wood constructions

LCA Embodied Emissions	BASELINE Carbon Neutral		90% Regeneration Rate		Soil Carbon Loss		Conversion of Natural Forest		Combined	
	Concrete	Wood	Concrete	Wood	Concrete	Wood	Concrete	Wood	Concrete	Wood
Biogenic	0	0	3	57	13	261	23	464	37	762
Manufacturing	1,635	1,048	1,635	1,048	1,635	1,048	1,635	1,048	1,635	1,048
Construction	85	60	85	60	85	60	85	60	85	60
Use	38,900	38,900	38,900	38,900	38,900	38,900	38,900	38,900	38,900	38,900

Figure B.7 presents cradle-to-gate embodied emissions for each of the four scenarios compared to the baseline (carbon-neutral assumption). The results indicate that different conditions within managed forests can significantly affect the overall embodied emissions, reducing the difference between the concrete and wood buildings from 36 per cent in the baseline case to as low as 10 per cent in the conversion of natural forests scenario. The combined scenario, which considers a 90 per cent regeneration rate, soil carbon loss and conversion of a natural forest together, actually flips the performance of the alternative building so that the wood building has 6 per cent higher cradle-to-gate embodied emissions than the concrete building.

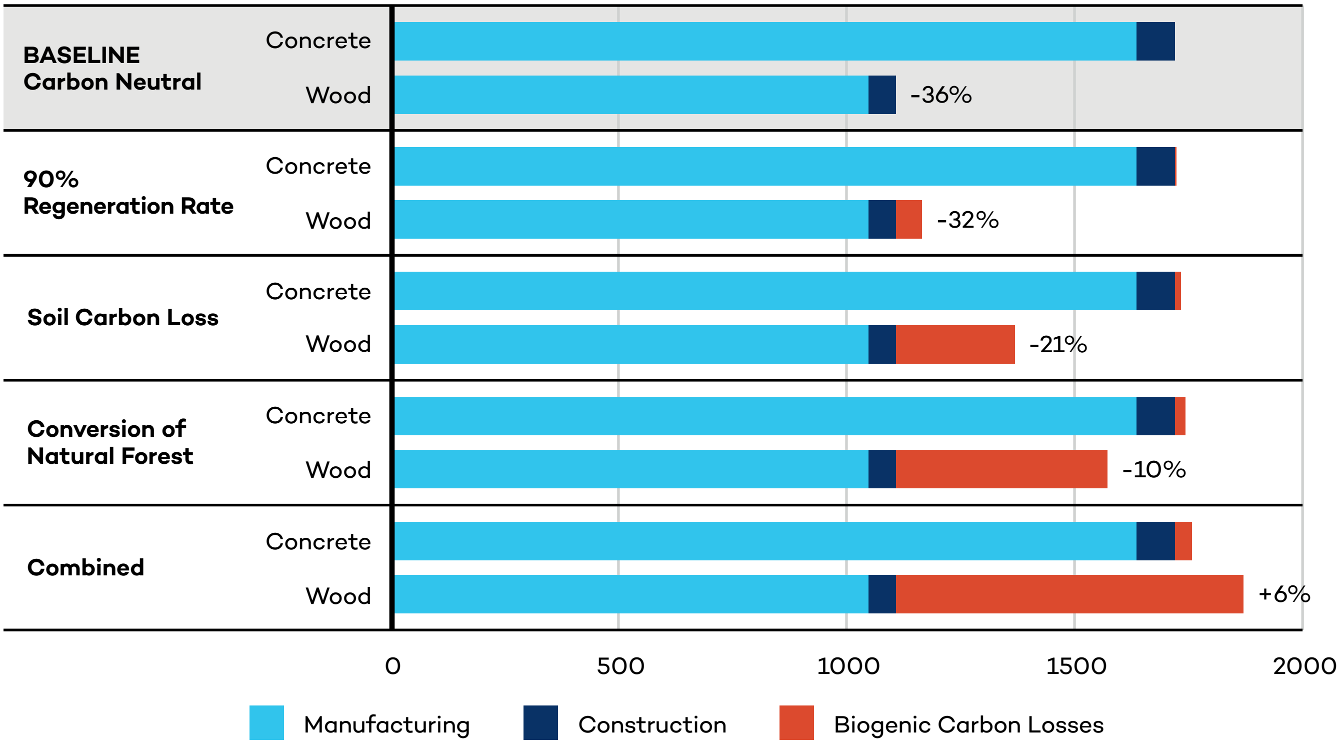

Figure B.7. Consideration of cradle-to-gate building embodied emissions for several biogenic carbon cycle assumptions relative to a carbon-neutral baseline

Figure B.8 identifies that, when the use stage is considered, the difference between building alternatives can vary significantly. In the case of the study building that is located in Quebec City, the fraction of use emissions to cradle-to-gate and use-stage emissions is very high (nearly 95 per cent) and the impact is negligible, but for buildings that are in more moderate climates or that have higher operating efficiencies, the impact can be significant when use-stage emissions become a greater fraction of overall emissions.

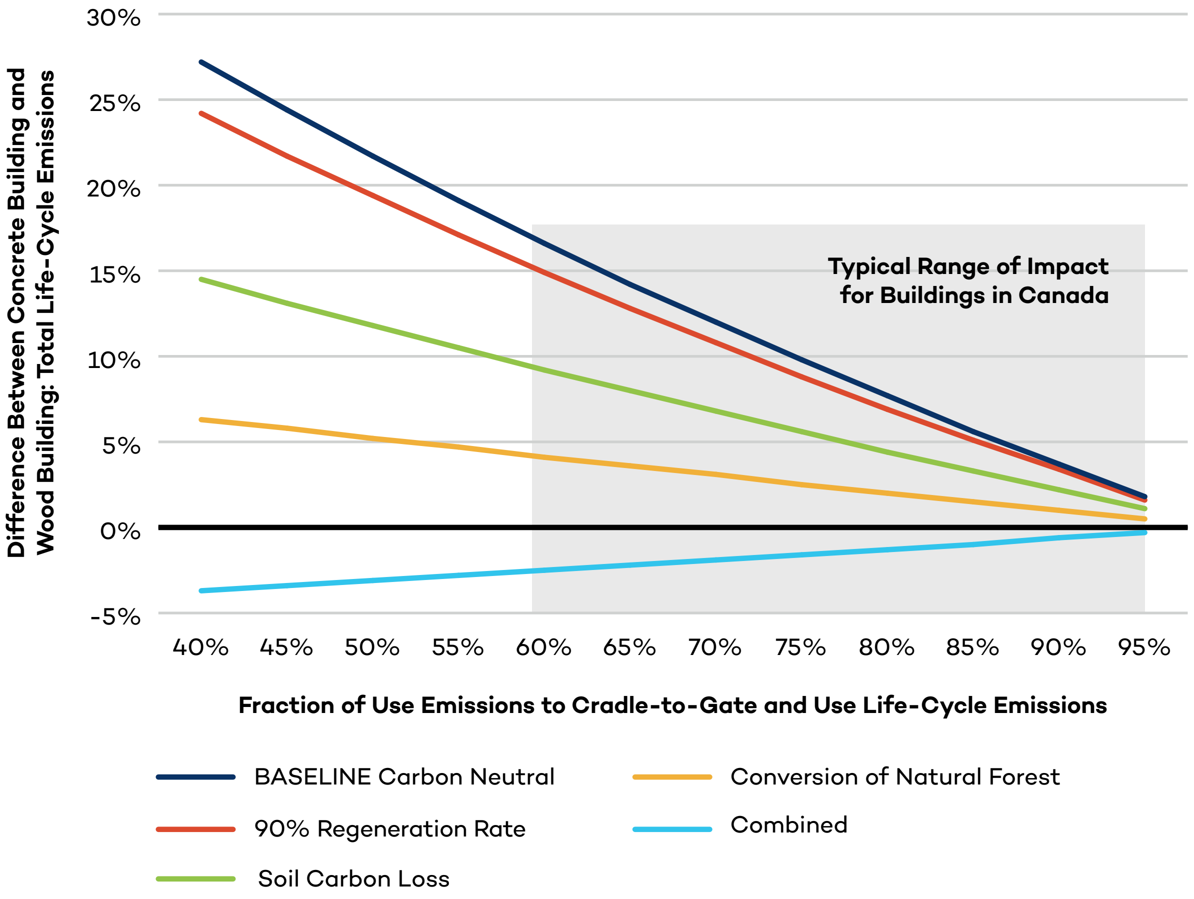

Figure B.8. Consideration of cradle-to-gate and use-stage building embodied emissions for several biogenic carbon cycle assumptions relative to a carbon-neutral baseline

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