Life Cycle Biogenic Carbon Accounting

A Primer for Wood Building Products and Construction Systems

August 2024

sustainatree

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For more information about British Columbia wood products and the sustainably managed forests they come from, visit:
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Acronyms and initialisms

CO_2	Carbon dioxide
CSA	Canadian Standards Association
DLCA	Dynamic LCA
EPD	Environmental product declaration(s)
FSC	Forest Stewardship Council
GHG	Greenhouse gas
GWP	Global warming potential
GWP_{100}	Global warming potential over a 100-year period
GWP_{bio}	A plot-level metric that starts the accounting at harvest
HWP	Harvested wood product
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LULUC	Land use and land use change
PCF	Pan-Canadian Framework (on clean growth and climate change)
PCR	Product category rules
PEFC	Programme for the Endorsement of Forest Certification International
SFI	Sustainable Forestry Initiative
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
WBLCA	Whole-building life cycle assessment

Executive summary

Biogenic carbon in wood products refers to carbon removed from the atmosphere by a tree during its growth that continues to be stored in wood products over their lifetime. This report provides an overview of the current state of knowledge on biogenic carbon accounting in the context of life cycle assessment (LCA) studies of long-lived harvested wood products (HWP) and biobased construction systems. There are alternative approaches that attempt to track and quantify the biogenic carbon flows over the life cycle of long-lived HWP, but within the LCA community, there is no consistent and internationally accepted biogenic carbon accounting approach.

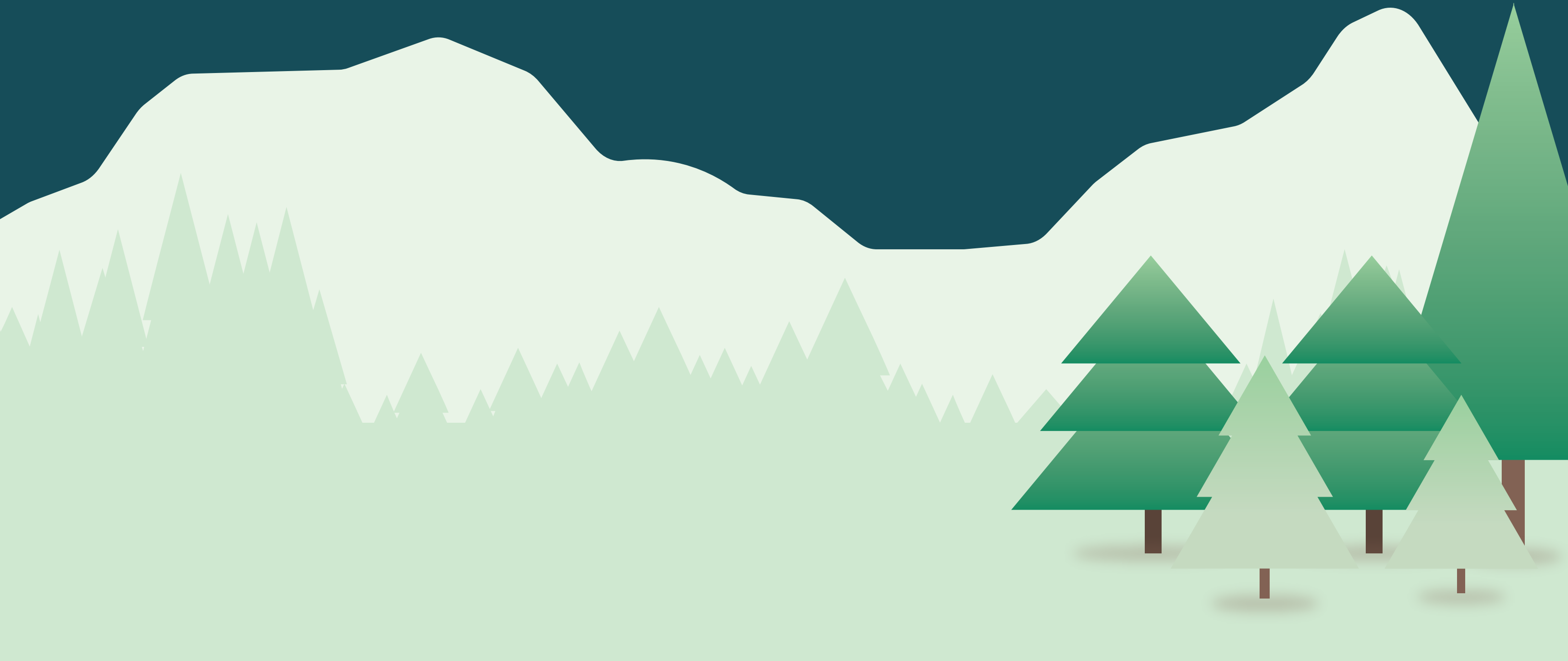
The information in this report is intended to act as a primer for understanding biogenic carbon accounting in the context of the quantitative environmental performance of wood building products and biobased construction systems.

While it is acknowledged that there are tangential aspects and subject areas that are directly and indirectly related to the content of this report — e.g., forest management, forest carbon modelling, national greenhouse (GHG) inventory reporting, emissions trading, GHG offset protocols, additional approaches to model potential climate impacts of GHG removals and emissions over time, substitution/displacement effects, avoided emissions — these are considered out of scope and not discussed explicitly within this document.

This report was written to provide an overview and background understanding for architects, engineers, specifiers, developers, policymakers and other stakeholders who are interested in biogenic carbon accounting as it relates to product-level and whole-building LCA studies. The information in this report can help policymakers to be conscious of and take into account the complexities and alternative quantification methodologies associated with biogenic carbon accounting over the life cycle of long-lived HWP when making decisions about policy, research directions, communications, or other actions.

There are many methodological approaches that can be utilized within a LCA study for quantifying the potential climate impacts associated with the timing of biogenic carbon removals and emissions over the life cycle of long-lived HWP, including dynamic life cycle assessment (DLCA) and GWP_{bio}. One of the most complicated aspects of the long-lived HWP supply chain relates to the allocation and linkage of biogenic forest carbon fluxes to the life cycle information of wood building products in the marketplace. This report aims to illuminate that the consideration and analysis of biogenic carbon flows over the life cycle stages of a biobased product (growth, harvest, processing/manufacturing, use, end-of-life) requires numerous assumptions and scenarios in order to define and estimate the spatial and temporal boundaries, reference land use baselines and end-of-life fates for wood building products.

In conclusion, it is suggested that a static analysis approach, viewed as the de facto biogenic carbon accounting methodology in LCA studies and North American environmental product declarations (EPD) for wood products, can be overly conservative. In other words, a static analysis, which does not consider the dynamic aspects and timing of GHG removals and emissions that occur at different points in time throughout the life cycle, can underestimate the potential climate benefits associated with long-lived HWP.



1. Background and relevance

1.1 Biogenic and fossil carbon

The International Organization for Standardization (ISO) defines 'biogenic carbon' as "carbon derived from material of biological origin, excluding material embedded in geological formations or transformed to fossilized material and excluding peat" (ISO 21930, 2017); examples of biogenic carbon are the lignin and cellulose that are contained within wood products. In contrast, 'fossil carbon' is defined as "carbon that is contained in fossilized material" (ISO 14067, 2018).

BIOGENIC CARBON IS DIFFERENT FROM FOSSIL CARBON

Biogenic carbon cycles take place on a human timescale

Biogenic carbon is different from fossil carbon in that it is part of a biophysical cycle that takes place on a human timescale, compared to other geological process that take place over millennia to form fossil carbon. When fossil carbon is removed from beneath the Earth's surface and combusted, carbon that was previously locked underground for millions of years is added to the atmosphere as a net addition of carbon dioxide (CO_2) gas. On a human timescalew), this is a permanent one-way flow of carbon to the atmosphere. In contrast, biogenic carbon is part of a global carbon cycle that is subject to two-way exchanges between carbon pools in the atmosphere, the biosphere and the technosphere (also known as the anthroposphere).

Forest carbon stocks represent the quantity of biogenic carbon stored in different pools, including above- and below-ground biomass (e.g., tree branches, trunks, stumps and roots), soil organic matter and dead organic matter (e.g., fallen leaves and branches, snags and dead roots). The cellulose and lignin within wood products contain biogenic carbon that was removed from the atmosphere during photosynthesis as part of the Earth's carbon cycle. In order to fully understand the biogenic carbon cycle, it is necessary to consider and evaluate all biogenic carbon flows between the biosphere (e.g., forest systems; above- and below-ground carbon pools), the technosphere (e.g., long-lived harvested wood product systems) and atmosphere (e.g., climate systems). See Figure 1.

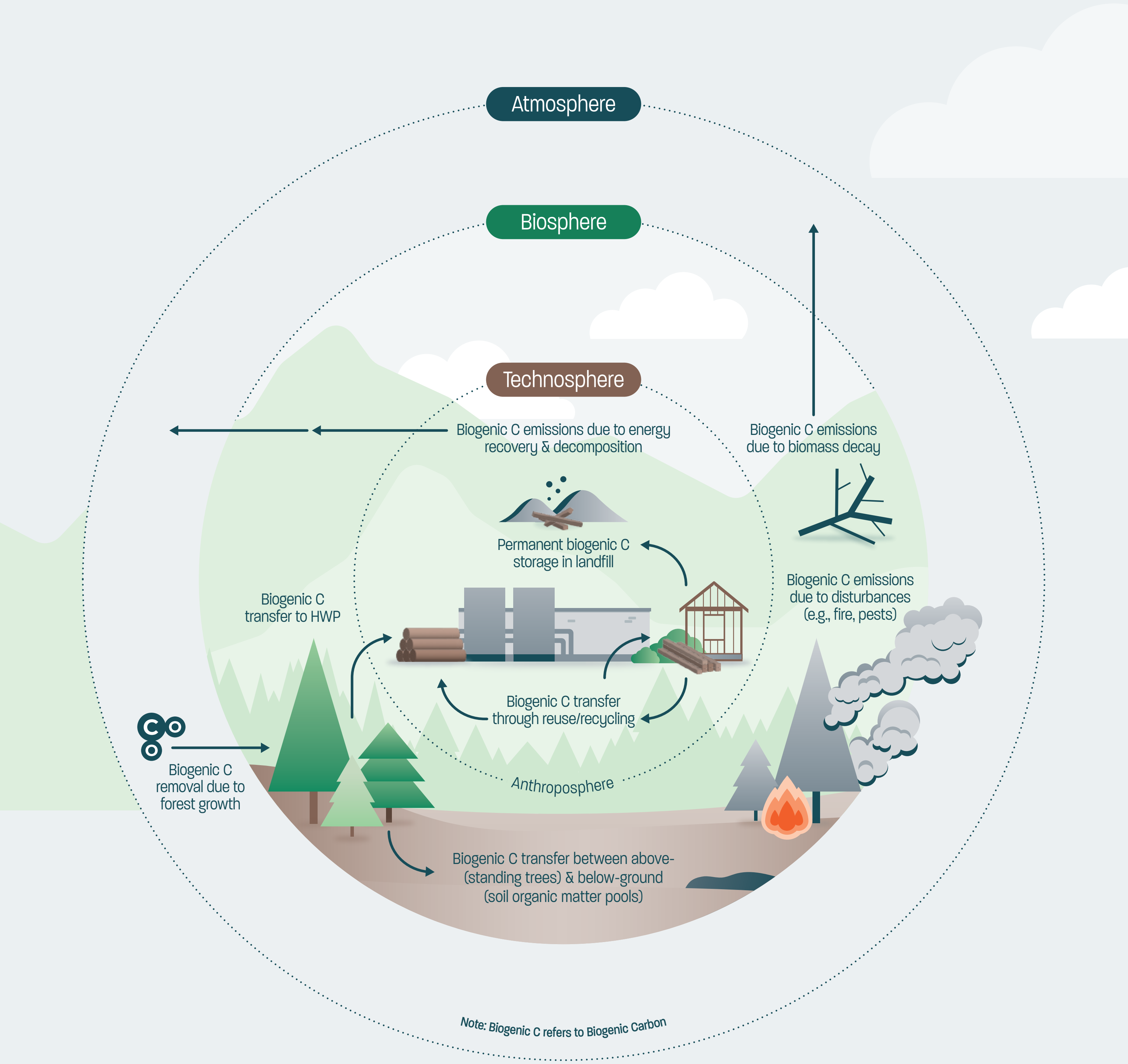


Figure 1 Biogenic carbon flows to/from the biosphere, technosphere and atmosphere

1.2 Policy, regulations, standards and guidelines

The Pan-Canadian Framework (PCF) on Clean Growth and Climate Change recognizes that:

"the use of wood construction products in Canada has environmental, social and economic benefits, such as emissions reductions resulting from carbon storage in long-lived biobased building products and increased domestic demand for local wood fibre, supporting our vibrant forest products industry in their pursuit of innovation, efficiency, sustainable forest management practices and green construction" (Government of Canada, 2019).

The PCF has initiated several actions related to wood products, including activities to help increase stored forest carbon and increasing the use of wood for construction, generating bioenergy and bioproducts, and advancing innovation. These actions outlined in the PCF have led to several policy responses and also helped pave the way for the development of the Government of Canada's Green Construction through Wood Program (Government of Canada, 2021), the Federal Sustainable Development Strategy (Government of Canada, 2019), The Greening Government and Buy Clean Strategies (Government of Canada; Treasury Board of Canada Secretariat, 2024), the Policy on Green Procurement (Government of Canada, 2018), and the Canada Green Buildings Strategy (NRCan, 2022).

Policy actions and funding mechanisms are being undertaken by all levels of government within Canada, illustrating that increasing the use of domestic wood construction is a priority (e.g., BC Wood First Act, 2023). Several jurisdictions in Canada have made provincial- and municipal-level policy changes to facilitate the acceptance and uptake of wood construction, along with the code change that allows for mass timber buildings up to 18 storeys to be constructed under the National Building Code of Canada 2020. The information within this report might also better equip policy makers when considering procurement decisions (i.e., direct purchases) and related procurement policies and programs, market development initiatives, forest management approaches, GHG inventory reporting, GHG offset protocols and climate change accountability reporting. The UN's Intergovernmental Panel on Climate Change (IPCC) indicates that climate mitigation options in the forest sector include (but are not limited to) extending carbon retention in harvested wood products and substituting wood products for alternative products that are more emissions intensive. The IPCC also proclaims that a sustainable forest management strategy aimed at maintaining or increasing forest carbon stocks, while producing timber, fibre or energy, generates the largest sustained benefit to mitigate climate change (Nabuurs et al., 2007).

There are several international standards and GHG accounting frameworks that discuss biogenic carbon accounting as it relates to long-lived HWP. The published approaches are often based on different assumptions and system boundaries and do not yet include all the relevant aspects that are required to comprehensively track the biogenic carbon flows through long-lived HWP that are used in construction.

The following is a non-exhaustive list of the standardized accounting approaches and initiatives that consider (each to a different extent) the flows of biogenic carbon throughout the life cycle of long-lived HWP:

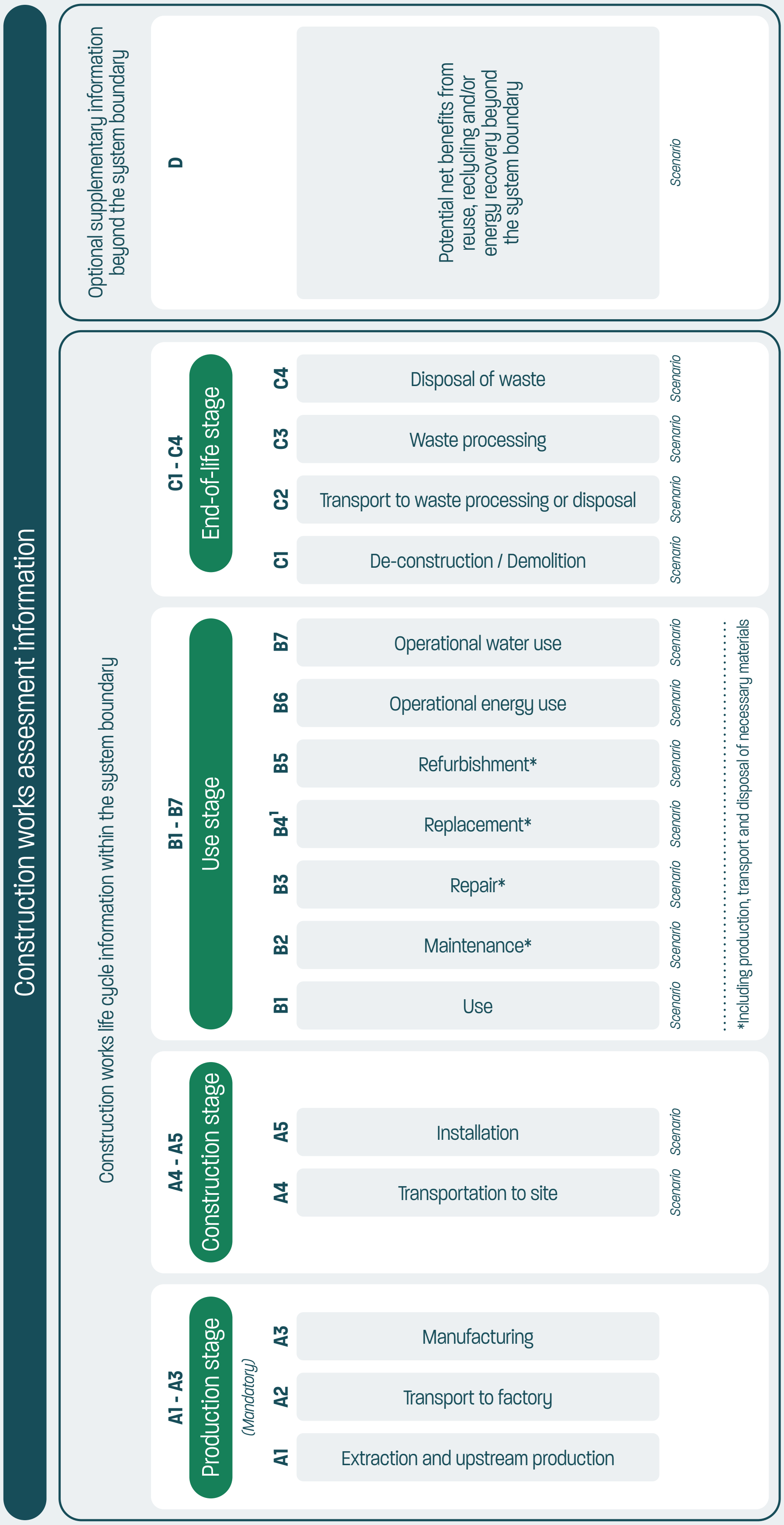
- Greenhouse Gas Protocol Land Sector and Removals Guidance (Draft for Pilot Testing and Review, September 2022);
- Product Category Rules for Part B: Structural and Architectural Wood Products EPD Requirements (2020);
- 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use. Chapter 12 Harvested Wood Products;

- EN 15804:2012+A2:2019 'Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products';
- ISO 14067:2018 'Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification';
- ISO 21930:2017 'Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services';
- ISO 13065:2015 'Sustainability criteria for bioenergy';
- EN 16449:2014 'Wood and wood-based products — Calculation of the biogenic carbon content of wood and conversion to carbon dioxide';
- EN 16485:2014 'Round and sawn timber. Environmental Product Declarations. Product category rules for wood and wood-based products for use in construction';
- PAS 2050:2011 'Specification for the assessment of the life cycle greenhouse gas emissions of goods and services';
- European Commission - Joint Research Centre - Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook – General guide for Life Cycle Assessment - Detailed guidance. First edition March 2010;
- ISO/DIS 13391-1 'Wood and wood-based products — Greenhouse gas dynamics — Part 1: Framework for value chain calculations' (under development);
- ISO/DIS 13391-2 'Wood and wood-based products — Greenhouse gas dynamics — Part 2: Forest carbon balance' (under development);
- ISO/DIS 13391-3 'Wood and wood-based products — Greenhouse gas dynamics — Part 3: Displacement of greenhouse gas emission' (under development); and
- United Nations Environmental Programme – Life Cycle Initiative. White Paper; 'Biogenic Carbon in LCA' (under development).

1.3 Biogenic carbon accounting within environmental product declarations

Product category rules (PCRs) define the requirements for the development of environmental product declarations (EPD). The core rules for the development of EPD for construction products and services are defined in the overarching PCR for construction products, ISO 21930:2017. It is required that all sub-category rules for construction products follow the requirements outlined in ISO 21930:2017; this includes the rules for the development of EPD for wood products. The current version of the North American sub-category PCR for wood products, "Product Category Rules for Part B: Structural and Architectural Wood Products EPD Requirements (2020)," follows the biogenic carbon accounting requirements of ISO 21930:2017. In addition, the PCR for wood products offers guidance on landfill modelling for biogenic carbon.

Within ISO 21930:2017, it is a normative requirement that biogenic carbon flows that enter the product system, (e.g., as a flow from the natural environment, as a secondary reused/recycled material, or secondary fuel), shall be documented and characterized with a factor of −1 kg CO_2e/kg CO_2 within the life cycle information module in which the biogenic carbon flow enters the product system. When biogenic carbon leaves the product system, as either an emission to air or as a biobased material (e.g., a co-product), the biogenic carbon flow shall be documented and characterized with a factor of +1 kg CO_2e/kg CO_2 within the life cycle information module in which the biogenic carbon flow leaves the product system. The requirements of ISO 21930:2017 imply that all biogenic carbon flows into and out of the product system must be quantified and reported in the life cycle information module in which they occur. Within ISO 21930:2017, any biogenic carbon that enters the product system but does not leave the product system (e.g., permanent biogenic carbon storage in landfill) results in a net-negative biogenic carbon balance over the life cycle. All the biogenic carbon that leaves the product system, as a co-product or recovered material, at any point over the life cycle (e.g., bark and chips during manufacture, off cuts during construction, reclaimed timber at end-of-life) for reuse, recycling or energy recovery, is accounted for as an outflow of biogenic carbon from the product system. The life cycle information modules that are defined within ISO 21930:2017 are shown in Figure 2.



[1] Replacement information module (B4) not applicable at the product level.

ISO 21930:2017(E) © ISO®

Common four life cycle stages and their information modules for construction products and construction works and the optional supplementary module D

Figure 2 Life cycle stages per ISO 21930

It is necessary for wood to originate from a sustainably managed forest to utilize the −1 kg CO_2e/kg CO_2 characterization factor. ISO 21930:2017 provides the following examples of sustainable forest management certification systems: Canadian Standards Association (CSA), Forest Stewardship Council (FSC), Sustainable Forestry Initiative (SFI), as well as other standards that are globally endorsed by the Programme for the Endorsement of Forest Certification International (PEFC). It is also appropriate to justify the achievement of sustainable forest management by referencing documentation submitted under annual national GHG inventory reporting to the United Nations Framework Convention on Climate Change (UNFCCC) that identifies forest systems with stable or increasing biogenic carbon stocks.

Other relevant aspects of ISO 21930:2017 that are associated with biogenic carbon accounting include land-use change effects (Clause 7.2.11) and the optional accounting of delayed emissions (Clause 7.2.9). As long as wood fibre is sourced from sustainably managed forests, there is no deforestation and therefore no emissions resulting from land-use change. ISO 21930:2017 allows for the calculation and reporting of the climate benefits associated with delayed emissions resulting from the temporary biogenic carbon storage within long-lived HWP, but this information is not permitted to be included as part of the reported global warming potential (GWP) impact indicator and shall be reported under the "Additional environmental information not derived from LCA" section.

The requirements within ISO 21930:2017 are silent on the quantification and reporting of biogenic GHG removals and emissions associated with the management and use of land to produce biobased products. There are no requirements to allocate the biogenic GHG emissions and removals associated with land use to the product system under study, e.g., fluxes in above- and below-ground biogenic carbon pools resulting from forest management or harvest activities (refer to Section 2.3). The absence of quantification and reporting of these biogenic GHG removals (e.g., replanting and reforestation) and emissions (e.g., long-term decay and combustion of above-ground harvest residues) implicitly assumes that all biogenic carbon fluxes resulting from land use are zero, i.e., biogenic GHG removals are equal to emissions, over the defined period of analysis (e.g., one rotation period or the design life of a long-lived HWP). When applying ISO 21930:2017, it is common practice to consider biogenic carbon emissions resulting from land use to be zero if the average biogenic carbon stocks within all the (living and dead) above- and below-ground carbon pools throughout the landscape do not change over the assumed time horizon (period of analysis of the study), which considers both the pre- and post-harvest biogenic carbon stocks within all the above- and below-ground biogenic carbon pools on the landscape.

1.4 Biogenic carbon accounting within whole building LCA tools

The biogenic carbon accounting approaches within whole building LCA (WBLCA) tools are variable and it is important to understand the differences, as the alternative biogenic carbon accounting assumptions and calculation methodologies have the potential to influence the quantitative environmental performance results for wood building products and construction systems, which can lead to different results across tools when comparing the same building design scenario. The three most prevalent WBLCA tools that are being utilized by architects and engineers in the North American marketplace are TallyLCA, Athena Impact Estimator and One Click LCA. All the WBLCA tools follow the life cycle information modules that are defined within ISO 21930:2017.

In TallyLCA, the user is permitted to either 'include' or 'exclude' biogenic carbon from the analysis. When TallyLCA includes biogenic carbon, the carbon content of wood materials enters the product system during manufacturing as a negative credit against the climate change impact indicator (e.g., GWP_{100}). If the biogenic carbon leaves the product system during the manufacturing or end-of-life stage, the emitted CO_2 equivalent is tracked as an emission and included as part of the GWP. The biogenic carbon content that does not decay in the landfill remains a negative credit against GWP. Following a past recommendation by the US EPA WARM model, TallyLCA assumes that 50% of the biogenic carbon is permanently stored in a landfill scenario. When the user elects to exclude biogenic carbon, TallyLCA ignores the biogenic carbon entering and leaving the product system, thus there is no effect on the GWP as a result of the biogenic carbon stored in wood products within a building system or within a landfill scenario.

For the 'exclude' biogenic carbon option, TallyLCA considers biogenic carbon emissions during manufacturing not to be carbon neutral and these flows are characterized and reported within the GWP impact indicator.

The Athena Impact Estimator tool accounts for the biogenic carbon stored in wood as a negative emission (GWP credit) when it enters the product system. At the end-of-life, biogenic carbon emissions are added to GWP. Biogenic carbon emissions during manufacturing are considered to be carbon neutral and not included in the GWP impact indicator. It is currently not possible to exclude biogenic carbon within the Athena Impact Estimator software. The upcoming version of the software will report biogenic carbon removals and emissions within the life cycle information module in which they occur, which is in alignment with the ISO 21930:2017 requirements.

See Figure 3 for a graphical depiction of the different assumptions that are used for end-of-life scenarios and the associated emissions and permanent biogenic carbon storage (ASMI, 2019; Kwok et al., 2019 [modified]).

The One Click LCA software implements two optional methods for accounting of biogenic carbon. In the generic method, biogenic carbon storage is only shown as additional information. This means that neither the negative emissions of storing the biogenic carbon nor the releasing of it are included in the GWP results. In the DGNB and Energie Carbon tools (alternative methodological approaches that can be selected by the user), the biogenic carbon storage over the life cycle is reported as part of the GWP results. In this case, the negative emissions from storing the carbon are shown as part of Modules A1–A3 (biogenic carbon storage is deducted from the GWP emissions in Modules A1–A3) and in Module C3, the same amount of carbon is added as it is released back to the atmosphere. In both methods, the total GWP result is the same and assumes a zero accounting result over the life cycle; biogenic carbon removals always equal biogenic carbon emissions in One Click LCA. Unlike TallyLCA and Athena Impact Estimator, the calculation methodology within One Click LCA does not allow the user to consider any permanent biogenic carbon storage within the end-of-life scenario (e.g., permanent storage within landfill) as part of the product system under study.

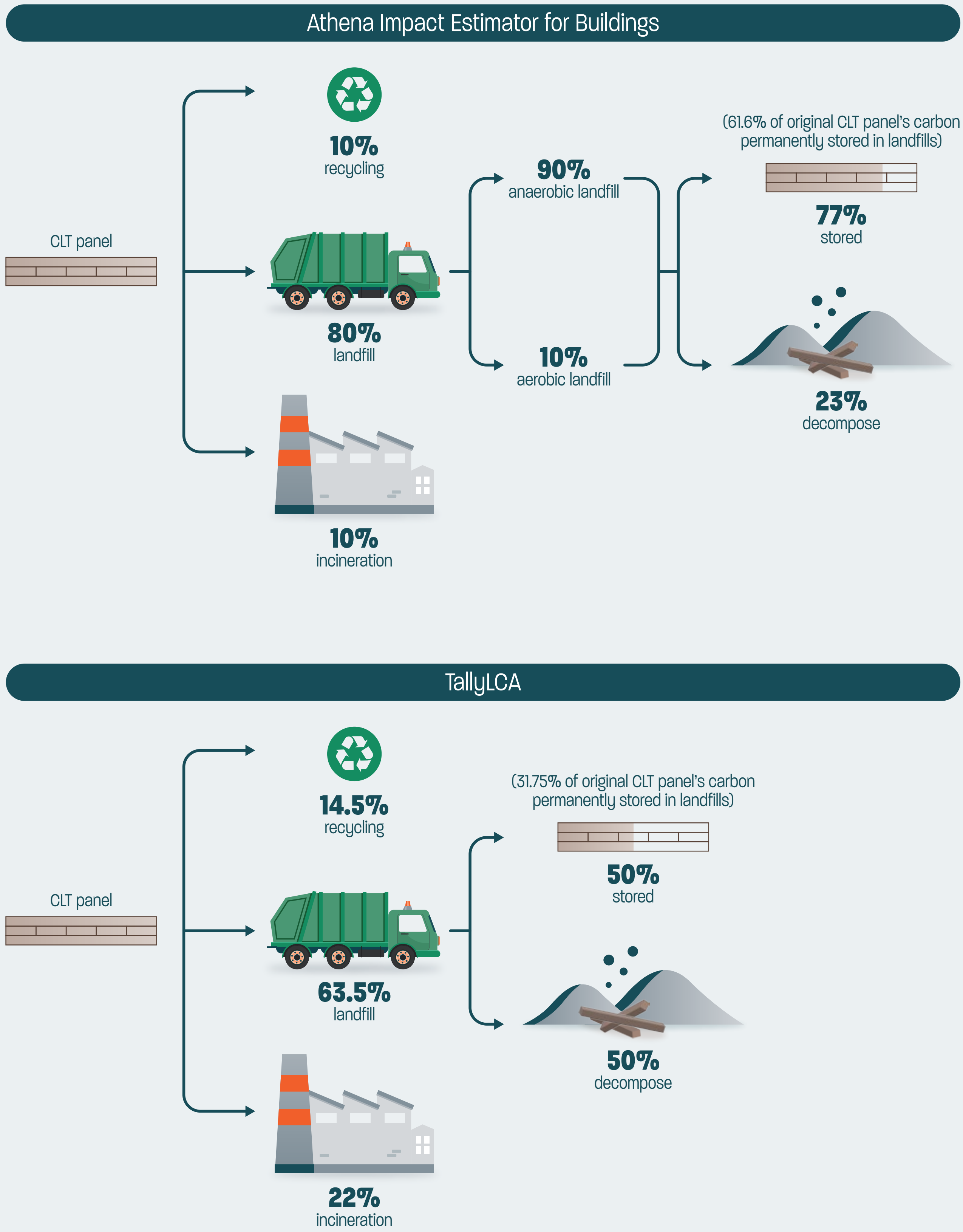


Figure 3 End-of-life assumptions for long-lived HWP in WBLCA tools

2. Methodological choices and boundary conditions

2.1 Scope

There are several methodological aspects related to life cycle biogenic carbon accounting for long-lived HWP that require subjective decision making and can lead to inconsistent results across studies. The system boundaries, including the physical, spatial, and temporal boundaries of the study have elements of subjectivity, which must be addressed by the study practitioner in order to generate biogenic carbon accounting results.

2.2 System boundaries

In order to analyze biogenic carbon flows in forest product systems, it is necessary to specify the system boundaries that represent the product system under study. The selection of the system boundaries are subjective, but should be relevant to the goal and scope of the study. The selection of the system boundaries can have a significant influence on the results of studies that consider the biogenic carbon flows over the life cycle of a forest product (Peñaloza et al., 2019).

Methods for biogenic carbon accounting differ in terms of the spatial boundaries (scale of the source forest) and temporal boundaries (how far forward or backwards in time one should account for). Different opinions also exist as to whether one should compare the carbon balance of the harvested forest against an alternative scenario in which the forest is not harvested.

The standards and guidance documents that were considered in Section 1.2 provide little instruction on three critical issues:

- **Physical boundaries:** which forest processes to include;
- **Spatial boundaries:** how large of a forest area to include; and
- **Temporal boundaries:** how far forward or backwards in time to consider.

Tillman (1994) states that system boundaries "must be specified in several dimensions: boundaries between the technological system and nature, delimitations of the geographical area and time horizon considered, boundaries between production and production of capital goods and boundaries between the life cycle of the product studied and related life cycles of other products" and that different methods and assumptions need to be compared and evaluated with respect to both relevance and uncertainty, as processes and activities that occur outside the defined system boundaries (e.g., market effects) might have more influence on the results than those that fall within the product system under study.

The most relevant aspects and decisions related to the system boundaries of product systems that consider biogenic carbon flows within long-lived HWP include the physical, spatial and temporal boundaries. The physical, spatial and temporal assumptions within a study are interrelated to one another and changes to one aspect of the system boundaries has implications to other aspects and can also influence the overall results and recommendations of a study.

2.2.1 Physical boundaries

The physical boundaries define the processes and activities (e.g., forest road construction, machinery used for harvest operations, transportation to sawmill, debarking, sawing, planing, drying) that are included in the production of long-lived HWP. Each of these processes and activities has the potential to contribute to the potential climate impacts of the wood product and can be analyzed with respect to GHG removals and emissions over the life cycle of a long-lived HWP. Depending on the normative requirements under which the study is being conducted (e.g., ISO 21930, ISO 14067, GHG Protocol, EN 15804) and the assumptions taken by the practitioner, it is possible to either include or exclude certain physical flows (biogenic GHG removals or emissions) as being considered outside the system boundary, e.g., carbon uptake during photosynthesis, removals or emissions resulting from management of land or land use change effects.

2.2.2 Spatial boundaries

Spatial boundaries define the physical area that is considered as part of the system under study. This is particularly relevant for the biogenic forest carbon considerations within studies of long-lived HWP. Spatial boundaries are related to both physical boundaries and temporal boundaries; i.e., spatial boundaries define the geographical area and can influence the time aspects over which the physical processes and activities are considered. One of the primary considerations when defining the spatial boundaries as they relate to biogenic forest carbon fluxes is the size of the geographic area considered, e.g., should the scale of the forest carbon modeling be conducted at the level of a single tree, a stand/plot, a parcel, a supply region/landscape, a province, a country, a continent or the entire globe? The available options for spatial boundaries in order of increasing area and spatial resolution are stand/parcel/cut block, timber supply area/forest management unit, landscape, province, and nation (refer to Figure 4 for graphical depiction of the aforementioned terms).

Depending on the granularity of the spatial scale and the related temporal considerations, the results of the study can change dramatically. The decision about the spatial boundaries is influenced by the selection of the temporal boundaries and whether or not it is important to understand the timing effects of biogenic carbon removals and emissions over the life cycle of a long-lived HWP. In addition, the choice of the spatial and associated temporal scale can also affect the availability and uncertainty of data, along with the consideration (or lack thereof) of disturbance events within the analysis.

Although biogenic forest carbon fluxes are not explicitly quantified and included in EPD of long-lived HWP, the most recent version of the Product Category Rules for Part B: Structural and Architectural Wood Products EPD Requirements (UL Environment, 2020) suggests that the consideration of landscape level forest management activities can provide a more complete picture of the environmental performance of wood products. National level spatial boundaries are one type of landscape, but this type also includes non-producing forests and are lacking in region-specific trends (e.g., fire and insect disturbance). Stand level spatial boundaries are also possible, but analyses at this scale do not reflect the fact that a given producer sources wood from an entire region that includes forests in various parts of the rotation cycle at any given time.

When considered within LCA studies of long-lived HWP, biogenic forest carbon flows are either modelled at the stand or the landscape level. Modelling biogenic forest carbon flows at the stand level can yield misleading results due to the stark reduction in biogenic forest carbon that occurs after a harvest, as illustrated by the upper graph in Figure 4.

Applying a wider landscape level boundary has the ability to more accurately describe the long-term stability of carbon stocks in a sustainably managed forest system, as illustrated by the lower graph in Figure 4.

A production facility for long-lived HWP does not rely on a single stand for its wood supply, but rather on multiple parcels within a region for a stable annual supply of wood fibre. In the context of product-level studies and the associated forest carbon impacts, it can be considered causal to model the biogenic forest carbon stocks and fluxes over a spatial area that considers, at a minimum, the supply area for the production facility or the provincial forest landscape under which the production facility is regulated. The landscape level boundary provides the ability to consider the biogenic carbon flows (harvest, growth, natural disturbances) that take place over an entire rotation cycle, whereas a stand level approach is viewed as unable to accurately consider these dynamic aspects. Only through consideration of all the forest landscape (spatial boundaries including the entire supply area) over time (temporal boundaries long enough to include effects of forces that act over time, such as shifts in age class distribution), can a realistic dynamic representation of biogenic carbon flows into and out of the system be calculated. Given the complexity of the models, the extensiveness and variability of the input parameters and the multitude of potential scenarios, there is always a balance between utility and comprehensiveness when applying landscape level forest carbon modelling. In addition, there continues to be unresolved methodological debate within the nature-based climate mitigation community around the characterization of climate-related disturbance events (e.g., increased frequency, size and duration of forest fires) as either natural or anthropogenic.

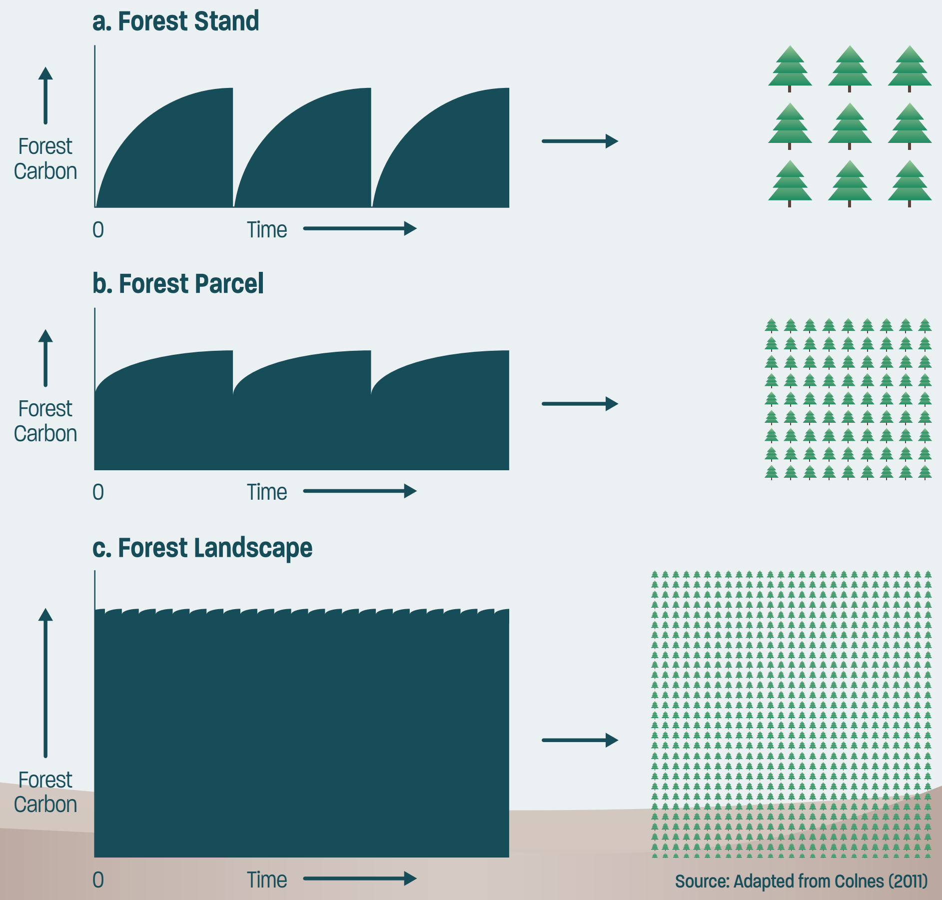


Figure 4 Forest carbon stocks and fluxes over time for three different spatial boundaries

2.2.3 Temporal boundaries

The last significant aspect of biogenic carbon flows within long-lived HWP relates to the temporal boundary, i.e., the time period or time horizon that is defined when conducting a study. The selection of temporal boundaries has the ability to include or exclude certain processes and activities within the study. In addition, the temporal boundary can influence the perceived changes in biogenic forest carbon stocks over time, potentially affecting the conclusions that are drawn about the potential climate impacts related to the production and use of long-lived HWP.

The timing of removals and emissions has received considerable attention in the debate on approaches for biogenic carbon accounting. The long service lives of buildings mean that GHG emissions and removals over the life cycle of wood building products can occur 25, 50, or even 100 years after resource extraction (harvest); see Figure 5. Static carbon accounting is typically applied to consolidate the various flows into a single metric that is simple to communicate but misses the distinction of timing. The temporal dimension is critical in biogenic carbon accounting because forest growth is not instantaneous, and most climate change mitigation policies are time sensitive.

TEMPORAL DIMENSION IS CRITICAL IN BIOGENIC CARBON ACCOUNTING

because removals of CO_2 during growth are not instantaneous, and emissions occur at different points throughout the life cycle.

A further explanation of the important relationship between the temporal boundaries of a study and carbon accounting within a forest product system is provided by NCASI (2013):

> Even in regions where long-term average forest carbon stocks are stable, there are periods during which stocks may increase or decrease for a variety of reasons including market dynamics and natural disturbances. The time used to judge the stability of forest carbon stocks, therefore, must be long enough so as to avoid being misled by transient conditions that may not be important in the longer term…In general, for studies focusing on the attributes of specific forest products, temporal boundaries are extended back in time to include processes, including photosynthesis, that are part of the system producing the biomass…To capture the full impacts of using biomass, the temporal boundaries should extend forward in time as long as needed to characterize the total ultimate releases of greenhouse gases from product use and end of life management.

2.2.4 Unresolved and subjective decisions around system boundaries

When considering long-lived HWP within a LCA study, there are certain aspects associated with system boundaries that are discretionary, including:

- The difference (or not) in the system boundaries for biogenic forest carbon accounting when considering wood fibre that is harvested from primary forest (no previous management or harvest) versus second growth forest (previously managed and harvested);
- The allocation of biogenic forest carbon stock changes, i.e., carbon fluxes (increases or decreases in forest carbon over an assumed geographical area and time horizon) to a single long-lived HWP derived from a forest area;
- The processes and activities and length of time when considering temporary and permanent biogenic carbon storage over the life cycle of a long-lived HWP (e.g., the time horizon to consider in order to accurately account for permanent biogenic carbon storage in a landfill);

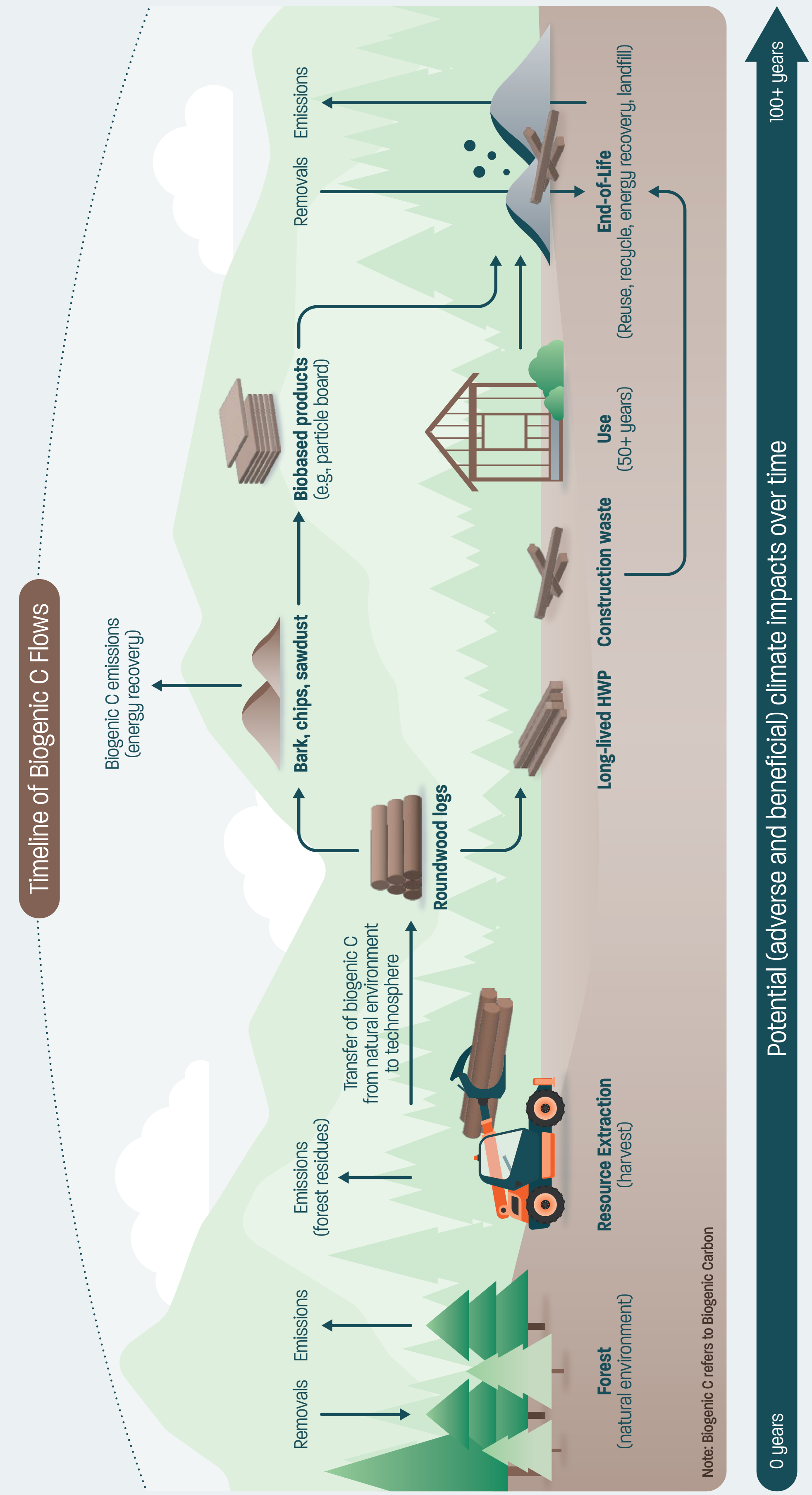


Figure 5 Timeline of carbon removals and emissions for a long-lived HWP

- The communication of the results related to the assumed system boundaries of the study (e.g., potential climate impacts are often communicated as a single net value calculated at a specific point in time or results can be expressed as a time series of GHG emissions and removals over the life cycle of a long-lived HWP) and
- The consideration and potential influence of markets and market effects.

Given that trees require decades to grow, forests are affected by widespread natural phenomena that influence their biogenic forest carbon stocks and fluxes, and biobased wood products store carbon for extended periods of time in the built environment, it is especially important that spatial and temporal boundaries are established to reflect the goal and scope of the study and to accurately provide a realistic representation of both the natural and anthropogenic systems being considered in the analysis.

2.3 Land use and land use change

Forestry involves the management of land and forests to produce long-lived HWP along with other biobased products. Land use and land use change (LULUC) that is related to the production of forest products results in biogenic GHG emissions and removals.

Land use change is generally described as the change in the use or management of land by humans. In the context of forest products, land use change is often discussed in relation to deforestation (the permanent change of forest land to another use such as agriculture or urban development) or afforestation. Management of forest lands for the production of wood products does not constitute land use change when forests are replanted and regrowth occurs following a harvest event. As long as forest land remains forest land, then the cycle of forest growth, harvest and regrowth is not considered to be land use change, i.e., biogenic carbon emissions resulting from land use change are considered as zero with the context of an LCA study.

Land use is different than land use change, in that it is generically described as human use or management of land within a relevant boundary. The following is a non-exhaustive list that provides examples of activities that result in GHG emissions and removals attributable to land use:

- Thinning, pruning and harvesting forests (e.g., clearcutting or selective logging that results in changes to above-ground biomass composition);
- Open burning of forest harvest residues (e.g., slash burning);
- Changes to below-ground biomass (e.g., composition of soil organic matter);
- Land preparation for forest establishment;
- Replanting and reforestation;
- Application of synthetic fertilizers; and
- Establishment and maintenance of temporary forest service roads.

Biogenic carbon emissions resulting from land use will result in zero emissions if the average biogenic carbon stocks within all the carbon pools (above- and below-ground live biomass, soil organic matter and dead organic matter) over the landscape do not change over time (i.e., pre- and post-harvest).

In addition to human interventions that can cause GHG emissions and removals in forest systems, there are other naturally occurring influences such as disturbances (e.g., fire, insect infestation, disease, etc.) and climatic changes that can affect regrowth and decomposition rates, causing changes to biogenic forest carbon stocks over time.

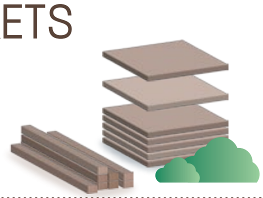
Within LCA studies, the analysis frameworks for biogenic carbon accounting of forest carbon fluxes are not well linked or integrated with the biogenic carbon accounting that occurs at the product level, i.e., within the product system of a wood building product. This becomes problematic when consumers and market requirements move toward transparency and quantitative metrics that demand the disclosure of biogenic carbon impacts related to LULUC (resulting from both human interventions and natural processes) be attached to a wood building product that is sold in the marketplace.

As described by NCASI (2013), this is a complicated task:

> A single forest area may produce many types of biomass, for example thinnings, harvest residuals and saw [sic] timber. A forest may also produce both wood products and nonwood products (e.g., food and fodder). A single forest may supply many users, further complicating the process of attributing stock changes [i.e., carbon fluxes]. In addition, forests are affected by many factors besides harvesting and management. Natural disturbances, for instance, can have very large impacts on forest carbon stocks… Isolating the effects of one particular type of biomass in a system subject to many other anthropogenic and natural disturbances is often difficult to impossible.

CONSUMERS & MARKETS

moving toward the disclosure of biogenic carbon impacts attached to a wood building product



There are several methodological and quantification challenges in LCA studies that can surface when attempting to investigate and quantify the biogenic forest carbon flows associated with all the anthropogenic and natural processes attributable to a long-lived HWP, including:

- Identification of all the forest land involved in growing the wood fibre that is used to produce a long-lived HWP;
- Allocation of biogenic carbon emissions and removals to different biobased products that are derived from the forest land (e.g., solid sawn lumber, sheathing and panel products, wood pulp, bioenergy, etc.);
- Quantification and allocation of the forest carbon stock changes, i.e., carbon fluxes, resulting from alternative forest management regimes within multiple harvest sites;
- Differentiating between the biogenic carbon stock changes, i.e., carbon fluxes, in forests that have been sustainably managed over several rotation cycles compared with forests that have not been previously logged;
- Allocation of the biogenic carbon losses or gains associated with conversion of primary (typically unmanaged) forest to a managed forest (also known as a working forest);
- Estimation of the changes in biogenic forest carbon stocks, i.e., carbon fluxes, that result from uncertain and variable natural phenomena (e.g., climate change effects on regrowth rates and fire disturbances (Metsaranta et al., 2011)); and
- Estimation and allocation of indirect land use effects (i.e., unintended consequences; GHG emissions or removals, that occur outside the product system under study as a result of activities occurring within the system boundary).

Despite the fact there has been focused research conducted on certain aspects of biogenic forest carbon stocks and fluxes, such as forest harvesting impacts on soil carbon, biomass fertilization options and alternative forest management practices (Eriksson et al., 2007; Lippke et al., 2011), there is no overarching consensus or standardized framework with regards to an amalgamated calculation methodology for all the aforementioned issues to be quantified and linked to an individual long-lived HWP. There is agreement that biogenic carbon emissions and removals related to LULUC, whether occurring as a pulse emission or gradually over time, can be divided amongst the biobased products that are produced from a forest area over a specified period of time (ISO 14067, 2018). Despite this general agreement within the LCA community, no guidance or requirements on how to execute this in a standardized manner have yet been developed. Typically, these biogenic forest carbon fluxes (associated with LULUC) are distributed and allocated linearly to the primary product under study, over an assumed time horizon. The chosen time horizon within a study could be related to an average rotation period, the lifetime of the long-lived HWP or the default time horizon specified under the IPCC guidelines for national GHG reporting of LULUC emissions and removals (note that IPCC refers to LULUCF, representing land use, land use change, and forestry).

In order to provide a high-level quantitative understanding of the biogenic forest carbon fluxes over time, it is often necessary to refer to national forest inventory data in an attempt to demonstrate that, historically, long-term forest carbon stocks in the specific region that is providing wood fibre have remained stable. Over the last 20 years, the Canadian Forest Service (Natural Resources Canada, 2021) has developed the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). The CBM-CFS3 is a stand and landscape level modelling framework that can be used to simulate the dynamics of forest carbon stocks, i.e., carbon fluxes, and is compliant with the carbon estimation methods outlined in the guidelines of the IPCC and the reporting requirement under the UNFCCC. It is possible to use the CBM-CFS3 computer model to calculate how much carbon is contained within the above- and below-ground carbon pools (e.g., trees and soil) and how much carbon is released to the atmosphere under different management, disturbance and harvesting regimes, all defined by specific physical, spatial and temporal parameters and boundaries. In addition, other coarse estimates of forest carbon stock changes, i.e., carbon fluxes, over time might also be approximated using satellite imaging data and land use modelling approaches. The National Forest Carbon Monitoring, Accounting, and Reporting System for Harvested Wood Products is an add-on to the CBM-CFS3 tool that is used to track the fate of carbon in all woody biomass harvested in Canada. This add-on tool accounts for both annual forest harvests and forest conversion activities, and tracks additions and end-of-life removals to the in-use carbon pool consisting of solid wood and paper products that were produced in Canada.

2.3.1 Forest harvest residues

There are alternative fates for the above-ground forest harvest residues, e.g., unmerchantable tops, branches and tree stumps of felled trees, that remains in the forest following harvest activities. In some instances, different types of forest harvest residues (e.g., branches, leaves) are left to decay over decades, resulting in long-term biogenic carbon emissions over time and the slow conversion of litter and deadwood to below-ground soil organic carbon. In other instances, a significant portion of the forest harvest residues are collected from the harvest site, piled together and combusted following the extraction of the merchantable wood fibre, resulting in a pulse emission of biogenic carbon dioxide and particulate matter after the harvest activities. Despite the different amounts and rates of biogenic GHG emissions associated with the fate of the biomass harvest residues (i.e., lower levels of GHG emissions occurring over an extended time horizon during the long-term decay of harvest residues versus larger pulse emissions occurring as a result of on-site combustion of biomass residues) and the alternative climate impacts, it is commonplace to make the assumption within an LCA study that the biogenic GHG removals from the forest landscape, within the system boundary, are equal to the emissions resulting from the biomass harvest residues over the life cycle of the product.

Therefore, when considered at a landscape level, the quantification and reporting of forest harvest residues in LCA studies is typically assumed to be zero within the global warming potential impact indicator, as biogenic GHG removals (CO_2 uptake by the subsequent regrowth of the forest landscape) over the life cycle of the long-lived HWP are considered equal to the biogenic GHG emissions resulting from the decomposition and combustion of harvest residues.

2.3.2 Soil organic carbon

The ground level and below-ground biogenic carbon pools that comprise the soil organic carbon within a defined system boundary are typically the largest carbon pools within the forest ecosystem (Nave et al., 2019). The changes (i.e., fluxes) in soil carbon occur very slowly over extended periods of time (decades) and can be impacted by both natural and anthropogenic events, such as fire or insect disturbances, harvest activities, and alternative forest management strategies (e.g., replanting, fertilization, thinning). The magnitude of the changes to soil organic carbon and the direct linkage to natural and human-induced stressors is subject to a high degree of uncertainty (Shaw et al., 2014). Alternative analyses across different geographies, forest types, management regimes, harvesting and replanting activities have indicated increases, decreases and no changes to soil organic carbon over varying time horizons following a harvest event. The total stock and the changes (fluxes) over time to soil carbon are highly variable and site specific, as the interaction and feedback loops between the naturally occurring elements (carbon, nitrogen and phosphorus) and the nutrients in the soil, on a particular plot, establish a unique soil carbon carrying capacity for each site that can fluctuate by an order magnitude from one site to another. Losses in soil carbon are avoidable through alternative forest management practices, and soil carbon losses that do occur following harvest are typically always regained throughout the regrowth cycle (James & Harrison, 2016).

The meta-analysis conducted by Lippke et al. (2011) provides a valuable summary of the knowns and unknowns about soil carbon fluxes and their relationship to harvest activities:

> The most basic conclusion is that adding more carbon to the forest soils through maintaining all the dead wood on site after harvest, or foregoing harvest entirely will not necessarily result in a significant increase in carbon stored in forest soils… The carbon accumulation in forest soils is largely driven by soil moisture, carbon-nitrogen dynamics and climate, but not by the amount of wood retained on site. Processes related to nutrient availability, litter fall input rates, decomposer community, decomposition rates and relative intractability of lignin to decay, will drive the equivalent of the soil carbon carrying capacity for a given forest site. The larger research question that has yet to be fully explored is how best to identify the soil carbon carrying capacity for a given site and across landscapes with any degree of accuracy. Knowing this information will help identify best biomass removal practices while retaining long term sustainability.

Given the myriad of differences between the site specific aspects associated with soil carbon fluxes (e.g., harvest practices, treatment of biomass residues, replanting and fertilization following harvest, forest management during (re)growth) and the fact that changes in soil carbon are rarely ever permanent over a single rotation period, a consensus and standardized framework and calculation methodology for the quantification and allocation of soil carbon fluxes to be directly linked to an individual wood product derived from a forest landscape is not yet established or commonly included within LCA studies of long-lived HWP.

2.3.3 Reference baselines and counterfactual scenarios

To facilitate the calculation of biogenic carbon fluxes that result from the use and management of land to produce forest products, it is necessary to establish counterfactual scenarios and reference baselines. It is also necessary to develop points of reference in order to establish comparisons (i.e., comparison of the actual scenario versus a reference land use scenario or baseline) that estimate potential impacts associated with the management of forestland that is used for production of HWP. Similar to the decisions related to the system boundaries within a study that consider the biogenic carbon flows associated with long-lived HWP, the decisions for the establishment of counterfactual scenarios and reference baselines for biogenic carbon land use impacts are also subjective and taken at the discretion of the study's practitioner.

There are alternative views amongst practitioners as to how forest carbon fluxes resulting from management of forestlands should be incorporated into a LCA study. There are different types of baselines against which biogenic land use emissions and removals are calculated. These alternative approaches can be summarized according to the baseline that each considers in the accounting:

- Reference point baseline: The accounting begins with a point in time (e.g., immediately preceding or following harvest), and all the GHG emissions and removals that subsequently occur over a defined time period are accounted for and attributed to the product.
- Counterfactual baseline: The accounting considers biogenic carbon emissions and removals relative to an alternative scenario (also known as a counterfactual scenario or an anticipated future), e.g., the net difference, over a defined period of time, in carbon flows (removals and emissions) between a 'business-as-usual' scenario and a 'no harvest' scenario is attributed to the product.

Furthermore, the international standard for the calculation of carbon footprint of products (ISO 14067, 2018) describes several options for the practitioner to select as the 'reference land use,' i.e., the baseline to compare against in order to calculate the biogenic carbon stock changes associated with the use and management of land for the production of timber:

- Business-as-usual: continuation of current practice based on historic data, considering a time period that is similar in extent and conditions to the time period selected for analysis;
- Projected future: projecting future changes using, e.g., knowledge of changing underlying drivers for land use and land use change, relative to business-as-usual, such as anticipated changes in intensity of production, technology or other relevant variables (e.g., climate change effects);
- Target: reference land use based on, e.g., policy targets for land use;
- Potential natural regeneration: vegetation that would potentially become established in the absence of human activity; and
- Historic baseline: using land use patterns at a specific point in time as the reference land use.

Based on the variety of options for the selection of a reference land use baseline and counterfactual scenarios, the results of a study which includes the biogenic carbon flows resulting from land use effects during the production of long-lived HWP can have significant variability. Given that forest systems are dynamic and subjected to naturally occurring phenomena, there are substantial differences in uncertainty associated with the establishment of different reference land use assumptions and counterfactual scenarios. The debate over the most appropriate assumptions for land use baselines in LCA studies has been ongoing for several years and still remains unresolved (Soimakallio, 2015; Brander, 2015; Brander, 2016).

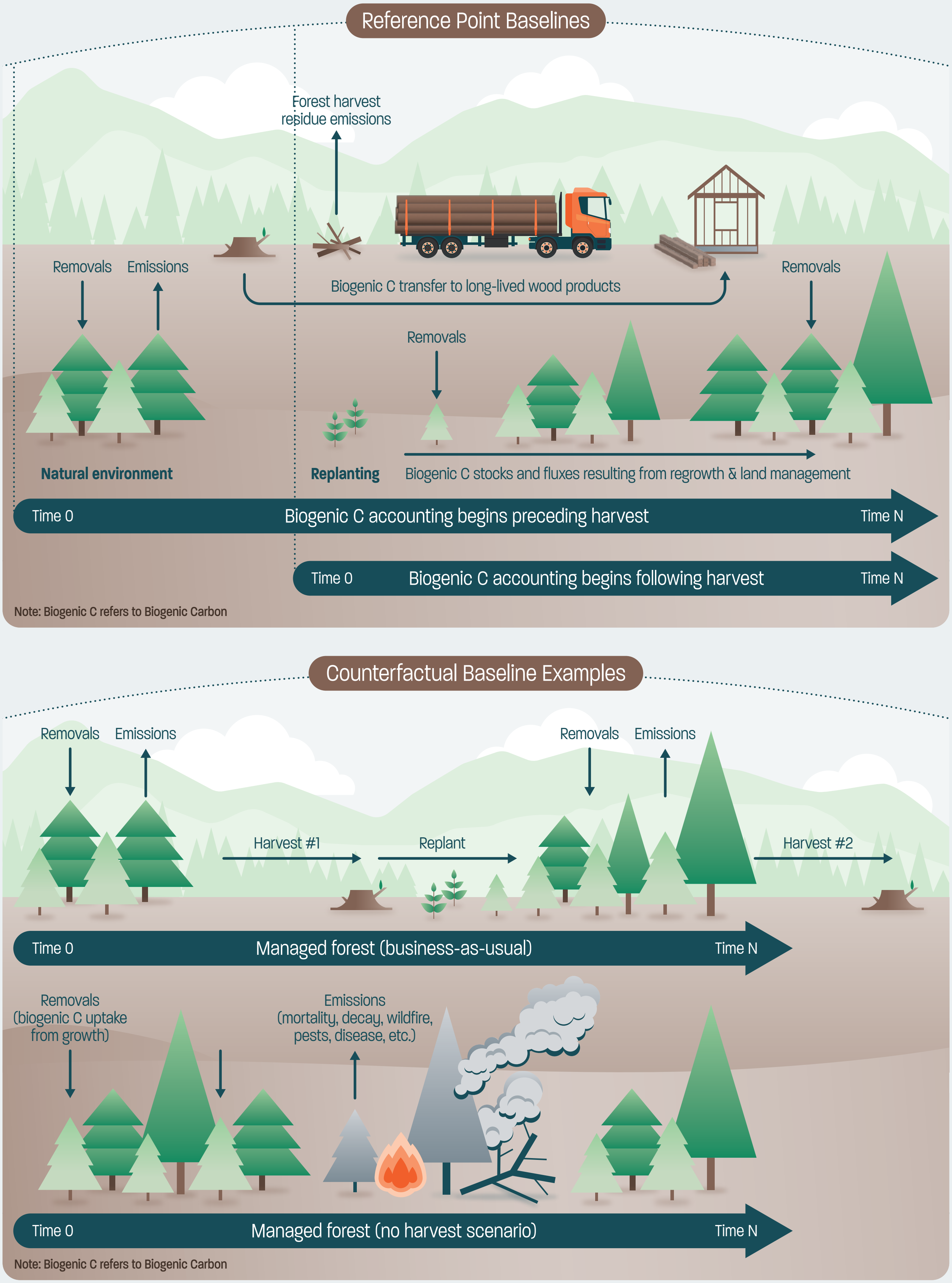


Figure 6 Alternative baselines to estimate land use effects

3. Alternative biogenic carbon accounting methods

3.1 Background

When a tree is cut, 45 to 55% of the biogenic carbon is removed as logs and a portion of this biogenic carbon is then stored within long-lived HWP and the built environment (Bowyer et al., 2012; Dymond, 2012).

45 TO 55% OF BIOGENIC CARBON IN A STANDING TREE

is removed as logs and stored within long-lived HWP

Wood building products and construction systems have the ability to store large amounts of carbon; one cubic metre of spruce-pine-fir (SPF) lumber stores approximately 0.8 tonnes of biogenic carbon dioxide (CO_2) equivalent (1 m^3 SPF x 420 kg/m^3 x 0.5 x 44/12). Wood products continue to store this biogenic carbon, often for decades in the case of wood construction, significantly delaying or permanently preventing the release of biogenic GHG emissions. While this biogenic carbon is being stored within the built environment, the forest regenerates, and once again continues to uptake and store carbon over time.

At the end-of-life of a long-lived HWP, the biogenic carbon that is stored in the wood building material can have several fates: reuse, recycle, energy recovery, or landfill. Alternative end-of-life fates result in different GHG profiles and potential climate impacts. Reuse and recycling allow for the biogenic carbon to be transferred, in part, and continue being stored within a subsequent product system. Energy recovery results in a pulse emission at the end-of-life when the wood product is combusted. Disposal in landfill results in slow decay and emissions releases over time, with a portion of the biogenic carbon stored permanently within the landfill and a portion being converted to landfill gas, which can be captured and recovered for energy.

The GHG removals from and emissions to the atmosphere that occur over the life cycle of long-lived HWP do not occur at the same time, e.g., biogenic CO_2 removals occur in the forest system and then decades later, potential biogenic emissions can occur at end-of-life. There is no debate over the notion that wood building products and construction systems store biogenic carbon over their life cycle. The current debate around the climate benefits of long-lived HWP (which result from delaying emissions and permanently storing carbon) questions the validity of such a claim given the relative amount of carbon that is transferred from the forest to the HWP carbon pool, how the climate effects are quantified and communicated, and whether or not the climate benefits are immediate or delayed (carbon debt).

The vast majority of contemporary LCA studies that aim to evaluate the life cycle environmental performance of long-lived HWP disregard the dynamic nature of biogenic carbon flows by assuming that all biogenic carbon removals and emissions occur at the beginning of the study period, i.e., time zero. In addition, it is also common practice to express the climate change impact indicator (e.g., global warming potential over a 100-year period, GWP_{100}) as a single value reflecting the total net transfer of GHGs to and from the atmosphere over the life cycle. Although it is possible to include the effects of timing within the GWP_{100} indicator (e.g., through the use of factors that reduce the potential climate impacts as the carbon storage time increases), the exact point in time of a biogenic carbon removal or emission, and the associated climate effect, is typically unaccounted for.

Despite the recognition that biogenic carbon removals equal biogenic carbon emissions over the product life cycle and all biogenic removals and emissions occur at harvest (time zero) is an oversimplification, these assumptions continue to persist within contemporary LCA studies. Breton et al. (2018) suggests that a consensus is slowly emerging, with most scientists recognizing the value of accounting for temporary biogenic carbon storage, the impact and sensitivity of study results to the timing of emissions and removals, the significance of the chosen time horizon and climate impact indicator, and the lack of consensus between the use of static and dynamic approaches to quantify biogenic carbon fluxes over the life cycle of long-lived HWP.

NCASI (2020) informs that the "two important parameters determining the warming impacts of a GHG are its radiative forcing, which can be thought of as a GHG's potency, and its lifetime in the atmosphere. The warming potential of a GHG is often expressed in terms of its cumulative radiative forcing over a specified period, often 100 years".

Using the *DynCO₂* calculator (Levasseur et al., 2013), it is possible to visualize the annual radiative forcing of an emission of 1 kg of CO_2 over 100 years. After 100 years, the climate impact is about 42% of what it was in year 1. See Figure 7.

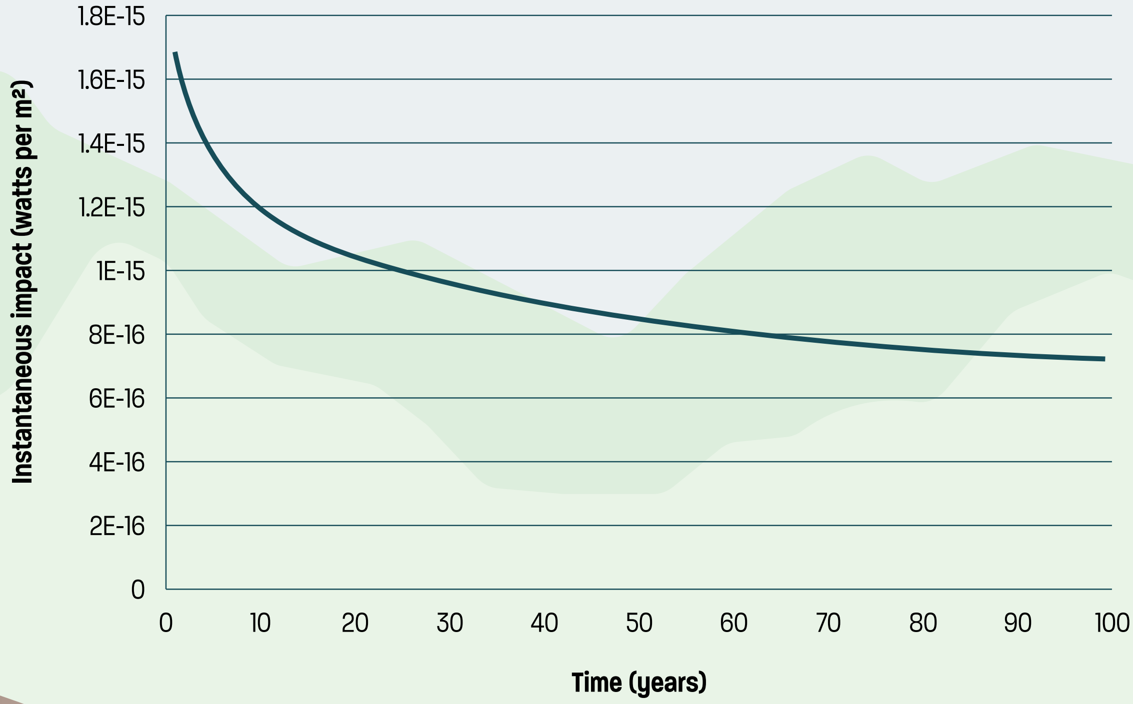


Figure 7 Decrease in radiative forcing of CO_2 over time

Over the last decade, a variety of calculation methodologies and climate impact indicators have been developed with the intent of more accurately quantifying the impacts associated with biogenic carbon removals and emissions (Ganguly et al., 2020). According to Head (2019), most approaches differentiate between biogenic and fossil CO_2 emissions, considering biogenic carbon as part of the Earth's carbon cycle and usually considering the timing of biogenic emissions and removals. These available calculation methodologies often involve a metric that estimates the cumulative radiative forcing associated with biogenic carbon emissions, in conjunction with the avoided radiative forcing associated with long-term biogenic carbon storage (delayed emissions). Conceptually, all the calculation methods are similar, in that they attempt to estimate the absolute or relative cumulative radiative forcing over time attributable to a GHG emission or removal that occurs at a specific point in time. The primary difference in the methodologies is related to the different approaches, assumptions and mathematical models that are employed to calculate the cumulative radiative forcing value.

There are two methodological approaches, neither of which have been standardized, that are often cited as the most relevant and appropriate for the quantification of the climate benefits and timing effects associated with biogenic carbon removals and emissions over the life cycle of long-lived HWP. The first approach was published by Levasseur et al. (2010, 2013) and is commonly referred to as 'Dynamic LCA' (DLCA). The second approach was published by Cherubini et al. (2011) and is commonly referred to as 'GWP_{bio}'.

3.2 Dynamic LCA and GWP_{bio}

DLCA is a generic approach that considers biogenic CO_2 emissions and removals as a function of time and allows for the assessment of the cumulative radiative forcing impacts and avoided climate impacts resulting from delayed GHG emissions that occur in the future. This quantification framework does not set specific temporal or spatial boundaries around the analysis, but these parameters must be established by the study practitioner and included within the analysis framework in order to generate results. DLCA requires that any biogenic emission or removal be inputted at a specific point in time and calculates an output of the estimated cumulative radiative forcing over a specified time horizon. DLCA also allows for the analysis of changes in emissions profiles over time, e.g., future carbon uptake expectations (Forster et al., 2021).

The GWP_{bio} methodology is based upon the ratio of cumulative radiative forcing of biogenic CO_2 to the cumulative radiative forcing of fossil CO_2 over a 100-year time horizon. This calculation approach has fixed temporal and spatial boundaries, along with other assumptions such as biomass regrowth responses. The GHG emissions and removals are not required to be input at a specific point in time, as the time effects related to delayed emissions are accounted for dynamically within the climate impact indicator itself, GWP_{bio}.

A comprehensive review of the GWP_{bio} calculation methodology was conducted by NCASI (2020) and concluded:

- GWP_{bio} assumes that the biogenic carbon accounting begins at harvest, meaning that GWP_{bio} is modelling the regrowth of trees after harvest instead of the initial growth prior to harvest and attributing the biogenic carbon removals from a newly planted tree (after harvest) to the product system under study, with an absence of any physical link between the biogenic carbon flows occurring in the forest and the biogenic carbon in the product;
- The GWP_{bio} methodology is extremely sensitive to the assumption that biogenic carbon accounting should begin at harvest. If the biogenic carbon accounting was started at the time when a plot began to grow (e.g., 60 years before harvest), the results would be completely opposite;
- The methodology uses a stand level analysis approach instead of the landscape level approach, the latter viewed as more appropriate for long-lived HWP;
- Despite its apparent ease of application, the use of the methodology requires a significant amount of data to define the length of time a biobased product is stored in the anthroposphere (in use and in landfills) and lacks the flexibility of more general methods such as DLCA; and
- The calculation methodology contains several fixed assumptions and conventions that have large impacts on the results and are not always contextually appropriate, e.g., time horizon of the analysis, forest regrowth function and atmospheric CO_2 removal rate, and length of time biogenic carbon is stored in use and in landfills.

In addition, Breton et al. (2018) suggested that GWP_{bio} is an accurate and conservative approximation for short-lived biobased products, however the calculation methodology can be overly conservative for long-lived HWP, which exhibit dynamic biogenic carbon removal and emissions profiles over the life cycle, i.e., forest carbon uptake and removals during tree growth, maintenance and replacement cycles while a product is in use, and end-of-life scenarios. The large time lags between the biogenic carbon emissions and removals over the life cycle of long-lived HWP have the potential to introduce temporal inconsistencies that could significantly affect the results and lead to an underestimate of the climate benefits.

The scientific literature has provided examples for modelling the biogenic carbon storage attributes and related time effects using both DLCA (Levasseur et al., 2013) and GWP_{bio} (Guest et al., 2013a; 2013b).

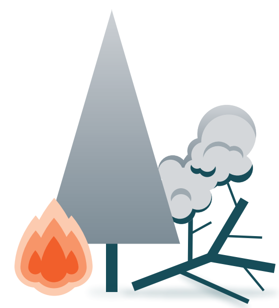
A Canadian study compared the appropriateness of DLCA and GWP_{bio} in the context of environmental performance evaluation of buildings (Breton et al., 2018), with the following summary findings:

- The results for both approaches are highly sensitive to the choice of time horizon, e.g., pushing biogenic emissions further out into the future results in lower climate impacts, and biogenic emissions occurring outside of the period of assessment (assumed time horizon) results in no climate impacts at all;
- GWP_{bio} will be easier to implement in conventional LCA practice and software tools because it does not require a dynamic life cycle inventory of biogenic carbon emissions and removals;
- To suit specific situations and to be able to provide a reliable proxy for DLCA results, it is possible to tailor the regrowth emissions and removals functions, as well as other coefficients and scaling factors within the GWP_{bio} calculation; and
- DLCA provides a more comprehensive and accurate approach, but is more complex and resource intensive than GWP_{bio}, e.g., DLCA requires a dynamic life cycle inventory of biogenic carbon emissions and removals over the life cycle of a long-lived HWP.

When applied in practice to material use over the life cycle of buildings, dynamic approaches that consider the climate effects resulting from delayed emissions were found to be most sensitive to the assumed time horizon of the analysis period, the building lifetime, and waste generation and treatment over the life cycle (Resch et al., 2021). Despite the challenges with dynamic approaches such as DLCA and GWP_{bio}, it is clear that static analysis approaches, which are the norm in LCA studies within the current marketplace, are disadvantaging long-lived HWP by not considering the climate effects associated with the timing of biogenic carbon uptake and emissions over the life cycle (Zieger et al., 2020).

DYNAMIC APPROACHES

more accurately reflect the climate profiles of wood products



4. Conclusions and implications

Many Canadian studies have concluded that one of the best approaches for minimizing climate change risk and promoting mitigation efforts is to focus on the health of forest ecosystems, utilize wood fibre within long-lived HWP, and keep this biogenic carbon stored in the built environment and out of the atmosphere for as long as possible in order to delay GHG emissions (Smyth et al., 2018, 2020).

4.1 Alternative biogenic carbon quantification approaches

As discussed previously, there are alternative approaches for valuing the climate benefits associated with the timing of biogenic carbon removals and emissions over the life cycle of long-lived HWP, with the most promising and suitable calculation methodologies being DLCA and GWP_{bio}. When compared to the standardized static approach for the quantification and reporting of biogenic carbon flows, as defined within ISO 21930:2017, these alternative approaches take into account the dynamic nature of GHG removals and emissions over the life cycle of long-lived HWP (and the resulting potential adverse and beneficial climate impacts). Both DLCA and GWP_{bio} can provide significantly different results for the global warming potential impact indicator when compared to the static approach outlined in ISO 21930:2017.

Breton et al. (2018) suggested that GWP_{bio} is an accurate and conservative approximation for short-lived biobased products, however the calculation methodology can be overly conservative (when compared to either the static approach within ISO 21930:2017 or the DLCA method) for long-lived HWP when considering the large time lags between CO_2 uptake early in the life cycle, maintenance and replacement while the product is in use, and end-of-life fates and the resulting biogenic carbon flows. Given that GWP_{bio} assumes that time zero for the biogenic carbon accounting begins at harvest, the methodology is modelling the regrowth and CO_2 uptake of the forest after harvest, instead of the initial growth and CO_2 uptake prior to harvest. GWP_{bio} results are more favourable for long-lived HWP that originate from shorter rotation forests (e.g., US Southeast) because the resultant metric is directly related to the time a pulse emission of biogenic CO_2 remains in the atmosphere following harvest, and shorter regrowth cycles provide faster removal of biogenic CO_2 from the atmosphere.

DLCA provides the most comprehensive and accurate approach for modelling the potential climate impacts related to the GHG removals and emissions over the life cycle of long-lived HWP, but this methodology is the most complex and resource intensive, as it requires a dynamic life cycle inventory of biogenic carbon flows over the life cycle. When compared to the static accounting approach defined in ISO 21930:2017, DLCA typically results in significantly more favourable potential climate impacts for long-lived HWP, when considering study periods and analysis time horizons that align with the typical design life of structural wood building products and the common length of rotation periods in the Canadian Boreal Forest.

Zieger et al. (2020) concluded that the traditional static approach to biogenic carbon accounting in LCA (as defined in ISO 21930:2017) is disadvantaging long-lived HWP by overestimating the potential adverse climate impacts over their life cycle.

4.2 Future methodological development and practices

The analysis of biogenic carbon flows requires many assumptions to define the spatial and temporal boundaries, reference land use baselines and counterfactual scenarios, and end-of-life fates for wood building products, all of which introduce variability and uncertainty into the study results (Lippke et al., 2011). The pursuit of optimizing and quantifying the contributions of wood building products to sustainable development and climate change mitigation will require holistic considerations of forest management, land use, and land use change combined with the complex environmental flows of long-lived HWP over their life cycle. In order to more comprehensively understand the climate effects associated with long-lived HWP, it might be necessary to couple forest carbon modelling tools, dynamic approaches to quantify HWP in-use carbon pools, i.e., the amount of biogenic carbon stored in products in the technosphere, and traditional LCA-based methodologies and tools. There are complexities and variability associated with the calculation approaches for biogenic carbon flows over the life cycle of long-lived HWP that remain unresolved and not yet standardized. In addition, the results and uncertainty of biogenic carbon accounting for long-lived HWP are sensitive to a multitude of assumptions, including spatial and temporal boundaries, reference land use baselines and counterfactual scenarios, and end-of-life fates for wood building products. Alignment of these assumptions and estimates of the uncertainty and variability are necessary in order to produce valid comparisons between LCA studies.

Recently, the Food and Agricultural Organization of the United Nations (Steel, 2021) has summarized that:

> While there is general consensus that HWP have the potential to reduce carbon emissions and contribute to climate change mitigation strategies, there is confusion surrounding the pathways by which those benefits can be accrued and the types of analyses which can be used to quantify benefits. There exist a large number of studies reporting on the climate change mitigation potential of HWP but each study uses a somewhat different methodology; studies rarely report outcomes in the same units; and studies may report on different types of mitigation pathways.

In addition, Lippke et al. (2011) reflects on the areas of high uncertainty related to biogenic carbon accounting of long-lived HWP, indicating that:

> end-of-life strategies for products and buildings, landfill emissions and methane capture from landfills, and soil carbon changes under forest management regime changes are most prominent. While the main focus is on managed forests producing wood products, there are high uncertainties in unmanaged forests, particularly the increasing rates of fire and consequent impact on both forest and product-carbon pools.

As a guiding light for the future development of LCA methodologies and harmonized practices, a 2011 workshop composed of experts in biogenic carbon accounting and LCA provided several recommendations that are still relevant more than a decade later (Brandão & Levasseur, 2011):

- Biogenic carbon assessment requires a better understanding of the dynamics of the global carbon cycle;
- The definition of time boundaries is highly sensitive and subjective, but temporal issues should be included in the assessment of biogenic carbon;
- For any form of temporary carbon storage, defining assumptions and methodologies clearly and explicitly is important, and both short- and long-term impacts should be considered; and
- The use of single metrics (e.g., GWP$_{100}$) is insufficient, as only a combination of multiple indicators can express the full scale of potential climate impacts.

The report from the Food and Agricultural Organization of the United Nations (Steel, 2021) illuminated several issues that should be addressed to improve the understanding of the quantitative contributions of long-lived HWP to climate change mitigation:

- The considerable range in estimates of carbon emissions associated with storage of carbon in HWP results from (a) unknowns associated with end-of-life pathways, (b) the range of methods used in estimating carbon storage within HWP (e.g., static approaches such as ISO 21930:2017 versus dynamic approaches such as DLCA and GWP$_{bio}$), and (c) uncertainties in input values (e.g., national estimates of HWP activity, conversion factors, and half-lives for HWP categories);
- Uncertainties in the calculation of avoided impacts associated with HWP (e.g., substitution effects); and
- Uncertainties associated with definitions, model formulation, and analysis boundaries.

Although there are many approaches and tools for the accounting of biogenic carbon flows, there is not a consistent and internationally accepted framework and approach for the treatment and accounting of biogenic carbon flows throughout the life cycle of long-lived HWP. It is necessary for industry, academia and government to work together to develop a harmonized and consistent quantification and reporting approach that will accurately depict and communicate the potential adverse and beneficial climate impacts of long-lived HWP over their life cycle.

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Life Cycle Biogenic Carbon Accounting

A Primer for Wood Building Products and Construction Systems

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