Article

Life Cycle Assessment of the Environmental Benefits of Using Wood Products and Planting Trees at an All-Electric University Laboratory

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Abstract: Many countries across the globe have set targets for different economic sectors, aiming to tackle global warming by reducing the overall carbon footprint of human-related activities. Among these sectors, the building industry stands out as a major consumer of materials and energy resources, making it a key player in achieving carbon neutrality. It is one of the main contributors responsible for energy-related greenhouse gas (GHG) emissions, including both operational emissions and embodied emissions in materials and equipment manufacturing. Nature-based design solutions, such as planting trees in urban spaces, or incorporating the use of wood products, have regained attention in recent years due to their potential to mitigate carbon emissions from buildings. Within this context, this paper presents a comprehensive life cycle assessment (LCA) of a recently built research facility, with a focus on demonstrating how the benefits of nature-based solutions, specifically carbon sequestration from trees and biogenic carbon content in wood products, can be quantified and reported using the latest LCA standards and tools. The analysis is provided under three end-of-life scenarios for wood products: wood incineration with energy recovery, wood landfilling, and wood recycling/repurposing. The results indicate that the set of strategies adopted in this building, i.e., tree planting, the use of wood products, and the end-of-life treatment of materials, can potentially offset carbon emission by 37.2% up to 83.9% when included in the LCA, depending on the scenario considered. By continuing to refine LCA standards and tools, and fostering collaboration between researchers, policymakers, and industry professionals, we can advance our understanding and ultimately achieve the widespread adoption of carbon-neutral buildings.

Keywords: life cycle assessment; nature-based solutions; wood products; trees; biogenic carbon; carbon sequestration; end-of-life benefits; carbon neutral buildings

1. Introduction

Wood products, such as plywood and mass timber, are manufactured using wood sourced from trees. During the growth process, trees absorb carbon dioxide from the atmosphere and store it as biogenic carbon in their biomass (trunks, branches, roots, and leaves) [1]. When these trees are harvested and transformed into wood products for construction or other long-term applications, the carbon they have sequestered remains stored in non-atmospheric pools, such as in the timber structure of a building, which is characterized as temporary carbon storage [2]. Temporary carbon storage can help mitigate climate change because it avoids some radiative forcing by delaying the increase in greenhouse gas concentration in the atmosphere [3] and buys time while technology evolves, and society progresses towards low-carbon energy sources [4].

From an environmental standpoint, wood products can offer a substitute for energy-intensive materials like concrete and steel [5,6]. Furthermore, there are benefits related to
the end-of-life (EOL) treatment of wood. Wood waste can be incinerated as a biofuel, reducing fossil emissions from residential heating systems or traditional grid-mix generation [7]. If wood products are disposed of in landfills, where they are consistently covered by other materials, the biogenic carbon within the wood biomass can be permanently stored, since the decay processes are significantly reduced due to limited oxygen penetration [8–10]. Ximenes et al. [11] conducted experiments under laboratory conditions to simulate anaerobic biodegradation in landfills and found almost negligible rates of carbon losses in wood, less than 5%. Alternatively, wood products in good condition can be directly reused at the end of their life, while those unsuitable for reuse can be applied as raw material for, e.g., particle board and OSB [12–14], or repurposed in innovative materials, such as in low-carbon bio-concretes (to replace mineral aggregates [15] or cement [16]), thus contributing to the stimulation of circular economy markets.

In this context, significant efforts have been made to establish methods for quantifying the benefits of wood products and the temporary storage of carbon in biogenic materials [3]. Life cycle assessment (LCA) has emerged as a powerful tool to estimate the environmental impacts of processes and systems and to identify opportunities to reduce these impacts. The ISO 14040/14044 [17,18] standards provide the framework for the application of LCA. However, as a general framework, it does not go into detail about the large variety of processes and products that LCA studies usually address [19]. To narrow down the range of choices left for the individual practitioner and promote consistency and transparency in LCA, additional standards and methods have been developed (EN 15978 [20], EN 15804+A2 [21], ISO 21930 [22], EN 16449 [23], ILCD Handbook [19], PAS-2050 [24], Levasseur et al. [2,25], Moura Costa and Wilson [26], and Vogtländer et al. [27]).

However, when it comes to bio-based materials, the environmental benefits associated with biogenic carbon sequestration and storage, as well as benefits obtained at the end-of-life of materials, are often excluded from the quantification of global warming potential (GWP) or treated as optional supplementary information [22]. To address these issues, this paper presents the carbon life cycle assessment of a case study, focused on the calculation of potential benefits beyond the building’s life (referred to as Module D in LCA) under three end-of-life scenarios for wood products. It also demonstrates how and when to account for biogenic carbon content in wood products according to each end-of-life scenario, and the benefits of carbon sequestration from trees. The life cycle stage defined as Module D by the EN 15978 [20] encompasses all avoided emissions that could be achieved through the end-of-life treatment of building materials such as energy recovery, recycling, and reuse. This stage is one focus of the paper.

This case study is an expansion of the results presented by Grossi et al. [28] for the life cycle assessment of a recently built research facility located at Concordia University, in Montreal, with a focus on nature-based solutions and their share of contribution to reducing the carbon footprint of buildings.

2. Literature Review

The literature review provided in this paper also expands the literature presented by Grossi et al. [28], with a focus on LCA standards and methodologies to quantify the benefits related to nature-based solutions and the end-of-life treatment of biogenic materials.

Considering LCA standards such as EN 15978 [20], EN 15804 [21], ISO 21930 [22], and the International Reference Life Cycle Data System (ILCD) Handbook [19], as well as relevant studies addressing the cradle-to-cradle life cycle assessment of nature-based solutions for buildings, the research question that guided the literature search was:

“From an LCA perspective, how can we quantify and report the benefits of planting trees and integrating wood products in the design of buildings?”

Additional questions were derived:

- How end-of-life benefits from wood products are calculated and reported in LCA?
- How the benefits of biogenic carbon storage in wood products are estimated?
- How the benefits of carbon sequestration from trees are estimated?
• What are the LCA standards addressing the calculations related to biogenic carbon?
• Is there any standard (ISO, EN, ILCD, PAS) that provides credits for delayed emissions?

2.1. LCA Studies in the Literature

Wood products and trees have regained attention in recent years as sustainable solutions due to their renewable nature and potential for climate mitigation. Several studies have examined the environmental benefits of using wood products as an alternative solution for concrete, steel, and other energy-intensive materials [29–33]. However, most of these studies focus on the manufacturing, use, and disposal phases (cradle-to-grave). Studies that include potential end-of-life benefits (Module D) and biogenic carbon content in their LCA analysis are scarce in the literature [34], as they require an optional calculation step and product-level information that is often unavailable [35].

In addition to that, many LCA studies considered on-site photovoltaic electricity production as the primary strategy for balancing carbon emissions and reducing the carbon footprint of buildings [36–38]. However, about 80% of the worldwide commercially available PV panels are manufactured in China [39], a country with 88% of its energy grid-mix relying on fossil fuels [40]. Consequently, since PV manufacturing is highly energy-intensive, it is possible that the net environmental benefits associated with photovoltaic solutions have been overestimated in some LCA studies.

Alternatively, there are other design strategies that could be integrated into the portfolio of sustainable solutions for buildings. In the case of nature-based solutions, there is only a small number of papers [28,41,42] that account for the direct carbon sequestration of trees. None of these studies includes the assessment of biogenic carbon content or the consideration of end-of-life benefits from wood products among the strategies to reduce the carbon footprint of buildings. As a result, there is a gap in the literature regarding the completeness of LCA studies, either in terms of building components/materials or in terms of life cycle stages included in the assessment.

The novelty of this paper lies in its comprehensive LCA approach, specifically applied to a real building constructed with wood-based materials. Unlike most LCA studies, this research considers all stages of the life cycle, from cradle to cradle, with a focus on estimating the potential advantages offered by nature-based design, an aspect not included in our previous LCA analyses.

2.2. LCA Standards

The ISO 14040/14044 [17,18] standards present the general framework, requirements, and guidelines for conducting life cycle assessments of any kind. In the context of buildings and construction products, EN 15978 [20] and ISO 21930 [22] cover these aspects, respectively. Both standards provide information about module D (benefits beyond a building’s life), but EN 15978 [20] treats this module as supplementary information (separated from final results, but mandatory), while ISO 21930 [22] treats it as an optional module.

Regarding the estimation of biogenic carbon, ISO 21930 [22], EN 15804+A2 [21], EN 16449 [23], ILCD Handbook [19], and PAS 2050 [24] provide guidance. All of these standards adopt a default $-1/+1$ approach, but ILCD and PAS have an additional ‘optional’ method using a discounting system for delayed emissions. In the default $-1/+1$ approach, the biogenic CO$_2$ uptake during forest growth (which is transferred to the building system) is reported as a negative ($-1$) emission in module A as separate information. At the end-of-life of the building, the release of biogenic CO$_2$ is reported as a positive emission (+1) in module C, or it is transferred to a subsequent product system in the case of recycling or reusing, in module D.

Although out of the scope of this paper, if the time when an emission takes place is considered, the benefits from temporarily stored biogenic carbon can be expressed as a ‘credit’, as described in the additional optional method from ILCD and PAS 2050. For instance, if 1 kg CO$_2$ absorbed from the atmosphere is stored as biogenic carbon for 60 years and then released back into the atmosphere, the carbon flow would be represented by
a negative value indicating uptake (−1 kgCO₂eq), a positive value indicating release (+1 kgCO₂eq), and an additional negative value of −0.6 kgCO₂eq as a reward for the 60-year delay in emission. In this case, the final carbon balance would be −0.6 kgCO₂eq, even though the net balance in practice is zero. This rewarding system incorporates an impact factor of −0.01 kgCO₂eq per kg of CO₂ stored per year, based on the GWP100 perspective, which categorizes emissions delayed for over 100 years as long-term storage.

As explained in ISO 21930 [22], various approaches have been proposed to address delayed emissions in the quantification of the GWP, including approaches based on discounting systems (ILCD and PAS 2050) or based on time-dependent characterization factors within a predefined reference study period (such as the dynamic LCA proposed by Levasseur et al. [2,25]).

However, due to the lack of common acceptance for these approaches, such calculations are not included in the quantification of GWP. Therefore, following the precautionary principle of LCA, no extra credit (e.g., −0.6 kgCO₂eq) related to delayed emission (temporary carbon storage for less than 100 years) was considered in this paper.

3. Materials and Methods

3.1. Life Cycle Assessment of Future Buildings Laboratory

Using the case study of Future Buildings Laboratory (FBL), this paper estimates the impact mitigation potential associated with end-of-life treatment and biogenic carbon content in wood products, and direct carbon sequestration from trees that could potentially be planted around the research facility. The investigation was carried out using One Click LCA [43], automated LCA software developed for the estimation of the carbon footprint of buildings and products. The software’s datasets are regionally customized, taking into account factors such as electricity grids, transportation modes, and material options based on the building’s location. One Click LCA employs data cards to provide the calculation steps and characterization factors used in the assessment, allowing users to understand the impact contribution of each design decision. Additionally, the software is third-party certified for compliance with ISO and EN general and construction-specific LCA standards.

The impact assessment started with the quantification of all materials and equipment specified in the design drawings, including those used in foundations, superstructure, roof, exterior walls, interior walls, finishes, windows, doors, HVAC, and BIPV system. This list of materials, organized by building assembly, was mapped within the LCA software, where each input from the design was linked to an inventory data point (e.g., a specific construction material option). When necessary, additional information about thickness, density, and other properties was provided. Then, the next input was the annual electricity consumption, which was previously estimated based on the simulation results described by Grossi et al. [28]. The last software input was the vegetation carbon withdrawals, (i.e., the number and type of trees that could be planted around the building).

The LCA results are presented in terms of GWP, under three end-of-life scenarios for wood products: (1) wood incineration with energy recovery, (2) wood landfilling, and (3) wood reusing. The calculation period was defined as 60 years. The benefits beyond the building’s life, referred to as module D in the life cycle stages, were included in the final results, as well as the biogenic carbon content of wood products (where applicable) and trees. Further information regarding the inclusion or exclusion of biogenic carbon is provided in the Results and Discussion section.

3.2. Case Study Building Description

Opened in 2021, the Future Buildings Laboratory is a research facility situated at Concordia University’s Loyola Campus in Montreal. Spanning an area of 125 m², this wood-based laboratory operates entirely on electricity and is dedicated to developing innovative concepts for carbon-neutral buildings. The facility is designed to accommodate the testing of various technologies, including building-integrated photovoltaics (BIPV), motorized shading devices, diverse building envelope systems, cutting-edge building
materials, HVAC systems, urban wind energy, and more. Additionally, the laboratory has a garden area measuring 410 m\(^2\).

As shown in Figure 1, the building is composed of a concrete slab-on-grade foundation, engineered wood structure made of glued laminated timber, insulated wood frame walls, and insulated metallic roof. The HVAC system consists of air-source heat pump, air-handling unit with heat recovery, humidifier, and electric heater. Presently, the four test cells on the southern facade feature building-integrated photovoltaic/thermal (BIPV/T) and semi-transparent PV curtain wall systems; however, these systems have only been utilized for research purposes, and have not yet been used to generate electricity for the facility’s operation. Therefore, their potential to displace carbon emissions from grid-purchased electricity is not considered in this study.

![Figure 1. Future Buildings Laboratory in different construction stages.](image)

The annual electricity consumption related to the HVAC system, equipment, and interior lighting was modeled in Design Builder (EnergyPlus) (v7.0.2.004, 2022), using the design parameters detailed in Grossi et al. [28]. The simulated electricity consumption is 8868 kWh/year, which is equivalent to 70.94 kWh/m\(^2\) of heated floor area per year and 11.42 kWh/m\(^3\) of heated internal volume per year.

4. Results and Discussion

The LCA conducted for the case study building assessed three end-of-life scenarios for wood products: (1) wood incineration with energy recovery, (2) wood landfilling, and (3) wood reusing. The remaining material types were assigned default end-of-life treatments provided by One Click LCA software, which are based on local market practices.

The results presented in Table 1 are divided into two parts. The first part displays the impacts associated with modules A to C, representing the building’s embodied and operational emissions from a cradle-to-grave perspective. The second part shows the benefits that can be achieved beyond a building’s life through the end-of-life treatment of materials (module D), as well as the benefits derived from biogenic carbon storage in wood products and carbon sequestration from trees. In module D, ‘benefits’ refers to avoided
emissions such as those achieved through energy recovery from wood incineration, while the biogenic carbon ‘benefit’ refers to the amount of carbon contained within bio-based products and the carbon sequestered by trees. Positive GWP values correspond to the emissions, while negative values correspond to the avoided emissions.

Table 1. Whole building LCA results for Future Buildings Laboratory.

<table>
<thead>
<tr>
<th>Modules</th>
<th>Result Category</th>
<th>Global Warming Potential (kgCO$_2$ eq over 60 years) *</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SCENARIO 1 Wood Incineration w/Energy Recovery</td>
</tr>
<tr>
<td>A1–A3</td>
<td>Construction Materials</td>
<td>55,715</td>
</tr>
<tr>
<td>A4</td>
<td>Transportation to site</td>
<td>2131</td>
</tr>
<tr>
<td>A5</td>
<td>Construction/installation processes</td>
<td>2614</td>
</tr>
<tr>
<td>B4–B5</td>
<td>Material replacement and refurbishment</td>
<td>14,291</td>
</tr>
<tr>
<td>B6</td>
<td>Energy consumption</td>
<td>5445</td>
</tr>
<tr>
<td>C1–C4</td>
<td>End-of-life process (transport, processing, disposal)</td>
<td>3139</td>
</tr>
<tr>
<td>TOTAL A to C</td>
<td>Impacts from modules A to C</td>
<td>83,338</td>
</tr>
<tr>
<td>D</td>
<td>Benefits beyond building’s life (wood products)</td>
<td>–1070</td>
</tr>
<tr>
<td>D</td>
<td>Benefits beyond building’s life (other products)</td>
<td>–10,533</td>
</tr>
<tr>
<td>Other</td>
<td>Benefits biogenic carbon in wood products</td>
<td>0.00</td>
</tr>
<tr>
<td>Other</td>
<td>Benefits biogenic carbon in trees (CO$_2$ sequestration)</td>
<td>–19,361</td>
</tr>
<tr>
<td>TOTAL D + biogenic carbon</td>
<td>Benefits from module D + biogenic carbon</td>
<td>–30,964</td>
</tr>
<tr>
<td>TOTAL Final balance (impacts + benefits)</td>
<td>52,373</td>
<td>21,006</td>
</tr>
</tbody>
</table>

* Obs.: Global warming potential (GWP) is used in LCA to assess the impact of any GHG on the environment expressed by the equivalent amount of CO$_2$ emission.

In the first part (modules A to C), the results are nearly identical for all the scenarios, ranging from 82,995 to 83,338 kgCO$_2$eq. The differences are attributed to process-specific burdens that are adjusted when the end-of-life scenario for wood is changed (e.g., adjusts for the construction site wood waste processing).

However, in the second part, when the benefits from module D and the biogenic carbon in wood products and trees are included, there is an overall reduction in the final balance results, which significantly vary across each scenario.

The final balance in scenario 1 (wood incineration) is 52,373 kgCO$_2$eq; in scenario 2 (wood landfilling), it is 21,006 kgCO$_2$eq; and in scenario 3 (wood reusing), it is 13,309 kgCO$_2$eq. Thus, the wood reusing scenario resulted in the lowest carbon footprint, assuming that all wood products can be repurposed in new applications, either through direct reinstallation or as raw material for secondary products. The wood landfilling scenario presented slightly higher GWP results, as there is no direct benefit from landfilling that can be assigned to wood products in terms of avoided emissions, only in terms of biogenic carbon storage. In the case of wood incineration, the benefits from energy recovery are diminished due to the case study location (Quebec), where the grid electricity is predominately sourced from renewable hydropower. If the wood waste could be transported to other provinces (where grid electricity still relies on fossil fuels) or used to power district heating systems based on natural gas, the benefits would be significantly greater.

A detailed breakdown of benefits related to module D and biogenic carbon, as well as the share of contribution of each benefit (expressed as the percentage of carbon reduction compared to impacts from modules A to C), is presented in Table 2.

It is important to emphasize that, apart from the wood products, all other material types received the same end-of-life treatment in all scenarios, which is based on current market practices (i.e., recycling for steel, incineration with energy recovery for plastics, and landfill to inert materials (One Click LCA, [43])). Therefore, module D encompasses benefits other than those specifically related to wood products.
Table 2. Avoided impacts from benefits in module D, biogenic carbon, and carbon sequestration.

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Benefit</th>
<th>SCENARIO 1 Wood Incineration</th>
<th>SCENARIO 2 Wood Landfilling</th>
<th>SCENARIO 3 Wood Reusing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>Energy for district heating (avoided grid-mix emissions)</td>
<td>−1070 (1.3%)</td>
<td>0.00 (0.0%)</td>
<td>0.00 (0.0%)</td>
</tr>
<tr>
<td></td>
<td>Landfill disposal (no direct benefits from EOL treatment)</td>
<td>0.00 (0.0%)</td>
<td>0.00 (0.0%)</td>
<td>0.00 (0.0%)</td>
</tr>
<tr>
<td></td>
<td>Reuse material (avoided emissions from new manufacturing)</td>
<td>0.00 (0.0%)</td>
<td>0.00 (0.0%)</td>
<td>−7473 (9.0%)</td>
</tr>
<tr>
<td>Plastic</td>
<td>Energy for district heating (avoided grid-mix emissions)</td>
<td>−186 (0.2%)</td>
<td>−186 (0.2%)</td>
<td>−186 (0.2%)</td>
</tr>
<tr>
<td>Steel</td>
<td>Recycling (avoided emissions from new manufacturing)</td>
<td>−10,296 (12.4%)</td>
<td>−10,296 (12.4%)</td>
<td>−10,296 (12.4%)</td>
</tr>
<tr>
<td>Gypsum</td>
<td>Recycling (avoided emissions from new manufacturing)</td>
<td>−50 (0.1%)</td>
<td>−50 (0.1%)</td>
<td>−50 (0.1%)</td>
</tr>
<tr>
<td>Inert</td>
<td>Landfill disposal (no direct benefits from EOL treatment)</td>
<td>0.00 (0.0%)</td>
<td>0.00 (0.0%)</td>
<td>0.00 (0.0%)</td>
</tr>
<tr>
<td></td>
<td>Module D, benefits from end-of-life treatment</td>
<td>−11,603 (14.0%)</td>
<td>−10,533 (12.7%)</td>
<td>−18,006 (21.7%)</td>
</tr>
<tr>
<td>Wood</td>
<td>Biogenic carbon in products (permanent storage)</td>
<td>0.00 (0.0%)</td>
<td>−32,220 (38.8%)</td>
<td>−32,318 (38.9%)</td>
</tr>
<tr>
<td>Trees</td>
<td>Biogenic carbon in trees (carbon sequestration and storage)</td>
<td>−19,361 (23.2%)</td>
<td>−19,361 (23.3%)</td>
<td>−19,361 (23.3%)</td>
</tr>
<tr>
<td>Benefits from biogenic carbon</td>
<td></td>
<td>−19,361 (23.2%)</td>
<td>−51,581 (62.1%)</td>
<td>−51,679 (62.2%)</td>
</tr>
<tr>
<td>TOTAL BENEFITS (module D + biogenic carbon)</td>
<td></td>
<td>−30,964 (37.2%)</td>
<td>−62,115 (74.8%)</td>
<td>−69,686 (83.9%)</td>
</tr>
</tbody>
</table>

* Obs.: Share of contribution (i.e., % carbon reduction) in relation to LCA results for modules A to C.

4.1. Scenario 1: Wood Incineration with Energy Recovery

In Scenario 1, where wood products are incinerated in centers of district energy (typically for powering district heating systems), the life cycle GWP decreases from 83,338 kgCO₂ eq (total of A to C, Table 1) to 52,373 kgCO₂ eq (final balance, Table 1). As presented in Table 2, this represents an overall impact mitigation of 37.2%, with only 1.3% (−1070 kgCO₂ eq) attributed to avoided grid emissions by using wood as a power source, 23.2% (−19,361 kgCO₂ eq) attributed to carbon sequestration by trees, and the remaining 12.7% due to end-of-life benefits from other materials, mainly steel recycling.

Although the biogenic carbon from wood products cannot be accounted for in this scenario (because the carbon is released when the wood is burned for energy recovery), there is still the benefit of avoiding some fossil fuel emissions from Quebec’s traditional grid-mix, and the unaccounted value of temporary carbon storage for 60 years.

The estimation of benefits from this end-of-life scenario was based on the information provided in Table 3 and Equation (1).

Avoided Emissions = (−) \frac{\text{Total mass of wood products}}{\text{Heating value of wood}} \times \frac{\text{Quebec’s electricity grid GHG intensity}}{\text{Quebec’s electricity grid GHG intensity}}

where the avoided emissions from burning wood waste instead of using electricity from the Quebec electricity grid are provided in kgCO₂ eq, the total mass of wood products in kg of wood (calculated using product-specific densities), the heating value of wood in kWh/kg of wood, and Quebec’s electricity grid GHG intensity in kgCO₂ eq/kWh. The total benefit of burning the wood waste is estimated at −1070 kgCO₂ eq.

Table 3. Information used to calculate the benefits of wood incineration with energy recovery.

<table>
<thead>
<tr>
<th>Components</th>
<th>Value</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass of wood products</td>
<td>20,913</td>
<td>kg wood</td>
<td>Design specifications</td>
</tr>
<tr>
<td>Heating value of wood (approx.)</td>
<td>5.00</td>
<td>kWh/kg wood</td>
<td>One Click LCA, 2023</td>
</tr>
<tr>
<td>Quebec’s electricity grid GHG intensity</td>
<td>0.010234</td>
<td>kgCO₂ eq/kWh</td>
<td>StatCan 2020, Ecoinvent 3.4</td>
</tr>
</tbody>
</table>

* Including methane emissions from rotting vegetation in hydro reservoirs.

Since Quebec’s electricity grid relies mostly on hydropower, the GHG intensity of electricity generation is low (i.e., 0.010234 kgCO₂ eq/kWh). Therefore, the benefits (avoided grid-mix emissions) that can be offset by wood incineration are also low. However, considering the case of other provinces such as Ontario, with a grid GHG intensity of 0.0671 kgCO₂ eq/kWh, or Alberta, with a GHG intensity of 0.37 kgCO₂ eq/kWh (One Click LCA [43], based on StatCan [44]), the benefits of end-of-life incineration could be significantly greater.
4.2. Scenario 2: Wood Landfilling

In Scenario 2, where wood products are landfilled, the life cycle GWP decreases from 83,121 kgCO$_2$eq (Table 1, total of A to C) to 21,006 kgCO$_2$eq (Table 1, final balance). The overall impact mitigation is 74.8% (Table 2), with 38.8% attributable to the biogenic carbon content permanently stored in landfilled wood waste, 23.2% attributable to carbon sequestration by trees, and the remaining portion due to end-of-life benefits from other materials. Therefore, in this scenario, the benefits from nature-based solutions are not included in module D (because there is no direct benefit related to the landfilling process), but they are accounted for separately, as permanent carbon storage in landfilled wood products (−32,220 kgCO$_2$eq) and carbon sequestration by trees (−19,361 kgCO$_2$eq).

Several studies and LCA methodologies [8–10,45] demonstrate that only a small proportion of wood degrades in landfills, which can take decades to occur. Most of the carbon is kept permanently stored. According to calculations in One Click LCA (based on the Ecoinvent v3.4 upstream database), the environmental impacts from landfilling biogenic materials were estimated using an overall emission factor of 0.0046 kgCO$_2$eq/kg dry wood. Since no direct benefits are derived from the landfilling process (only those related to biogenic carbon storage), the impacts from wood decay are included in modules C1–C4.

4.3. Scenario 3: Wood Reusing

In Scenario 3, where wood products are reused after their end-of-life, the life cycle GWP decreases from 82,995 kgCO$_2$eq (Table 1, total of A to C) to 13,309 kgCO$_2$eq (Table 1, final balance). The overall impact mitigation is 83.9% (Table 2), with 9.0% (−7473 kgCO$_2$eq) attributed to wood product reuse (avoided emissions from new manufacturing), 38.9% (−32,318 kgCO$_2$eq) attributed to biogenic carbon content within the wood products, 23.3% (−19,361 kgCO$_2$eq) from carbon sequestration by trees, and the remaining portion due to end-of-life benefits from other materials.

It is important to note that in this scenario, the benefits from wood products in module D were calculated considering potential emissions avoided from manufacturing the exact same product. However, in practice, part of the wood waste may be redirected as raw material for secondary applications and part may be directly reused (see Höglmeier et al. [12] for further examples). Therefore, the end-of-life benefits (in module D) attributed to wood products were estimated using manufacture-specific impacts according to One Click LCA datasets, listed in Table 4.

Table 4. Manufacturing impacts for different wood products.

<table>
<thead>
<tr>
<th>Wood Product</th>
<th>Value</th>
<th>Unit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Softwood plywood</td>
<td>0.39</td>
<td>kgCO$_2$eq/kg wood</td>
<td>Athenasmi [46]; PCR FPInnovations [47]</td>
</tr>
<tr>
<td>Softwood lumber</td>
<td>0.14</td>
<td>kgCO$_2$eq/kg wood</td>
<td>UL Env. PCR Part B [45]; Athenasmi [48];</td>
</tr>
<tr>
<td>W. red cedar bevel siding</td>
<td>1.07</td>
<td>kgCO$_2$eq/kg wood</td>
<td>WRCLA [49]; PCR FPInnovations [50]</td>
</tr>
<tr>
<td>Glued Laminated Timber</td>
<td>0.39</td>
<td>kgCO$_2$eq/kg wood</td>
<td>Athenasmi [51]; PCR FPInnovations [47]</td>
</tr>
<tr>
<td>I-joist manufacturing</td>
<td>0.33</td>
<td>kgCO$_2$eq/kg wood</td>
<td>Athenasmi, [52]; PCR FPInnovations, [50]</td>
</tr>
</tbody>
</table>

4.4. Biogenic Carbon in Wood Products (Storage)

In the case of wood products, the biogenic carbon content presented in Sections 4.1–4.3 is incorporated into One Click LCA calculations in two ways: (1) the value is provided in the building material EPD using a functional unit (e.g., kgCO$_2$eq/kg of product), which represents the best-case scenario; and (2) the value is not declared in the EPD, and One Click LCA provides a close estimation.

In both situations, the guidelines of ISO 21930 [22] and EN 16449 [23] are followed. The conversion from the biogenic carbon content of wood products to carbon dioxide is presented in Equation (2),

\[
P_{CO_2} = \frac{44}{12} \times c_f \times \frac{\rho_\infty}{1 + \frac{\infty}{\infty}}
\]  

(2)
where $P_{CO_2}$ is the biogenic carbon content in terms of carbon dioxide, $44/12$ is the molecular weight ratio between carbon dioxide and carbon, $C_f$ is the carbon fraction of wood biomass (0.5 as the default value), $\omega$ is the moisture content of the product (e.g., 12%), $\rho_\omega$ is the density of product’s wood biomass (in kg/m$^3$), and $V_\omega$ is the volume of the solid wood product (m$^3$).

When biogenic carbon is not declared in the EPD, there are a few assumptions used for this calculation (i.e., carbon content is assumed to be 50%, and material is assumed to be fully dry).

4.5. Biogenic Carbon in Trees (Carbon Sequestration)

In all scenarios, the benefit of biogenic carbon from trees was integrally accounted for in the final balances. The selected tree species have a life span that can reach two or three times the life span of the building, allowing the carbon absorbed through photosynthesis to be considered permanently stored in the biomass of trees. Additionally, when trees reach the end of their life, they can be replaced with new trees, thus reestablishing carbon sequestration. In terms of radiative forcing impacts, emissions related to the decay of a tree occurring 200 years from now may not have the same significance as current emissions.

Based on the available garden area of 410 m$^2$, we estimated that it is possible to plant 13 units of typical eastern Canadian trees without affecting the building-integrated photovoltaic system or pedestrian pathways. The species and number of trees included in the design (i.e., 1 eastern white pine, 10 white spruce, and 2 Balsam fir), were defined based on their average crown size, carbon sequestration rates, and tolerance to urban conditions. According to Tree Canada [53], these trees generally grow to a height of 20–30 m, with a crown spread of 6–10 m, and have a lifespan of over 100 years.

Carbon sequestration rates were obtained from One Click LCA data points, which utilize background information from the Environmental Information Administration (EIA) [54] to estimate carbon withdrawals by vegetation in urban and suburban areas. As shown in Table 5, we estimated that the set of trees planted around the laboratory could remove 19,361 kgCO$_2$eq from the atmosphere over a 60-year calculation period (also refer to Tables 1 and 2).

<table>
<thead>
<tr>
<th>Tree Specie</th>
<th>Carbon Sequestration (kgCO$_2$eq/Unit-Year)</th>
<th>Tree Height (m)</th>
<th>Crown Width (m)</th>
<th>Life Span (Years)</th>
<th>No. Trees Planted (Units)</th>
<th>Sequestration Over 60 Years (kgCO$_2$eq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern white pine</td>
<td>47.82</td>
<td>30</td>
<td>10–12</td>
<td>200+</td>
<td>1</td>
<td>−2869</td>
</tr>
<tr>
<td>White spruce</td>
<td>25.33</td>
<td>25</td>
<td>4–6</td>
<td>200+</td>
<td>10</td>
<td>−15,200</td>
</tr>
<tr>
<td>Balsam fir</td>
<td>10.77</td>
<td>25</td>
<td>5–7</td>
<td>80+</td>
<td>2</td>
<td>−1292</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td><strong>13</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>13</strong></td>
<td><strong>−19,361</strong></td>
</tr>
</tbody>
</table>

This result, calculated using One Click LCA, is compared with Grossi et al. [28] for the same case study (but calculated using the tree cover area methodology proposed by Nowak et al. [55,56], and Pascher et al. [57], when the specific tree species were not defined). As shown in Table 6, Grossi et al. [28] estimated a total carbon sequestration of 14,145 kgCO$_2$eq (0.575 kgCO$_2$eq/m$^2$ of tree cover area per year), while in this paper, using One Click LCA, the total sequestration is estimated to be 19,361 kgCO$_2$eq (0.787 kgCO$_2$eq per m$^2$ of tree cover area per year). This difference is likely due to the fact that Grossi et al. [28] used a standardized approach based on countrywide samples of trees from the US and Canada, whereas the calculation performed in this paper is based on only three local tree species, which increases the sensitivity of the results.
Table 6. Comparison of carbon sequestration results between Grossi et al. [28] and this paper.

<table>
<thead>
<tr>
<th>Calculation Methods/References</th>
<th>Results from Grossi et al. [28]</th>
<th>Results from this paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Carbon Sequestration</td>
<td>14,145</td>
<td>19,361</td>
</tr>
<tr>
<td>(kgCO₂eq Over 60 Years)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual Carbon Sequestration</td>
<td>0.575</td>
<td>0.787</td>
</tr>
<tr>
<td>per Area (kgCO₂eq/m² Tree Cover)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.6. Assumptions, Uncertainties, and Limitations

Some assumptions and uncertainties in this method have led to limitations and drawbacks, which are described below:

- As per ISO 21930 [22], for wood products entering the building system, the benefits from considering the biogenic carbon may only be accounted when the wood originates from sustainably managed forests (e.g., certified by Forest Stewardship Council (FSC), Sustainable Forestry Initiative (SFI), Canadian Standards Association (CSA)).
- The extent of wood degradation in landfills (i.e., GHG emissions from wood decay) may vary depending on the landfill design and location.
- In the wood reusing scenario, the benefits from wood products in module D were calculated based on potential emissions avoided from manufacturing the exact same product. However, in practice, part of the wood waste may be redirected as raw material for secondary applications and partly directly reused.
- Only three species of trees have been considered in the current study. If other species (having different carbon sequestration rates) had been included, the impact mitigation results could have been different.
- Since the lab is not yet in operation at full capacity, the annual electricity consumption considered in the LCA was based on the energy simulation results with EnergyPlus, as described in Grossi et al. [28].
- The indirect benefits of trees such as energy savings, wildlife conservation, and air quality, as well as the impacts related to land-use change in FBL’s garden were not addressed in this paper’s scope.

5. Conclusions

This paper presents an LCA framework that architects, designers, and engineers may consider when conducting environmental impact assessments for buildings. This work highlights the practical significance and potential benefits of nature-based design solutions, especially applied to a real building constructed with engineered wood materials, accounting for all building components and mechanical systems as they were designed. As presented in Tables 1 and 2, the benefits from wood products can be related to end-of-life treatment (e.g., avoided grid-mix emissions by using wood as biofuel, or by recycling other types of materials) and/or biogenic carbon storage in a product’s biomass. The benefits from trees are related to carbon sequestration. In terms of impact mitigation, wood products contributed 1.3% in scenario 1, 38.8% in scenario 2, and 9% (end-of-life benefit) plus 38.9% (biogenic carbon content) in scenario 3. For all scenarios, the benefits from carbon sequestration by trees contributed 23.3%, and the benefits from the end-of-life treatment of other types of products contributed 12.7% (mainly steel recycling). From a cradle-to-cradle life cycle perspective, integrating nature-based solutions such as wood products and trees into the design of buildings and their surroundings always yields environmental benefits, but depending on the building location, one end-of-life scenario might be more favorable than the other. A combination of scenarios may be a practical approach for future studies. For the case presented in this paper, the best approach consists of reusing all wood products in good condition and repurposing the rest as secondary products. Applying them as biofuel in regions outside of Quebec, or sending them to landfills, can be an alternative. Future work could involve tracking wood waste products in the Canadian context and identifying circular economy markets for bio-based products.
Author Contributions: Conceptualization, F.G., H.G. and R.Z.; methodology, F.G., H.G. and R.Z.; software, F.G.; validation, F.G., H.G. and R.Z.; formal analysis, H.G. and R.Z.; investigation, F.G., resources, H.G. and R.Z.; data curation, F.G., H.G. and R.Z.; writing—original draft preparation, F.G.; writing—review and editing, F.G. and H.G.; visualization, H.G.; supervision, H.G. and R.Z.; project administration, H.G. and R.Z.; funding acquisition, H.G. and R.Z. All authors have read and agreed to the published version of the manuscript.

Funding: We acknowledge the financial support from the Natural Sciences and Engineering Research Council (NSERC) Discovery Grants (Grant no. RGPIN/6994-2001 and RGPIN/2021-04030), and the Gina Cody School of Engineering and Computer Science of Concordia University.

Data Availability Statement: All relevant data used in this study is contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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