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Feasibility of Planting Trees around Buildings as a Nature-Based Solution of Carbon Sequestration—An LCA Approach Using Two Case Studies

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Abstract: In response to Canada's commitment to reducing greenhouse gas emissions and to making pathways to achieve carbon neutral buildings, this paper presents two real case studies. The paper first outlines the potential of trees to absorb CO_2 emissions through photosynthesis, and the methods used for the estimation of their annual carbon sequestration rates. The net annual carbon sequestration rate of 0.575 kgCO_2eq/m^2 of tree cover area is considered in our study. Then, this paper presents the carbon life cycle assessment of an all-electric laboratory at Concordia University and of a single-detached house, both located in Montreal. The life cycle assessment (LCA) calculations were performed using two software tools, One Click LCA and Athena Impact Estimator for Buildings. The results in terms of Global Warming Potential (GWP) over 60 years for the laboratory were found to be 83,521 kgCO_2eq using One Click LCA, and 82,666 kgCO_2eq using Athena. For the single-detached house that uses natural gas for space heating and domestic hot water, the GWP was found to be 544,907 kgCO_2eq using One Click LCA, and 566,856 kgCO_2eq using Athena. For the all-electric laboratory, a garden fully covered with representative urban trees could offset around 17% of the total life cycle carbon emissions. For the natural gas-powered single-detached house, the sequestration by trees is around 3% of the total life cycle carbon emission. This paper presents limits for achieving carbon neutral buildings when only the emissions sequestration by trees is applied, and discusses the main findings regarding LCA calculations under different scenarios.

Keywords: carbon neutral buildings; carbon sequestration; life cycle assessment; urban trees; embodied carbon emissions; operational carbon emissions

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1. Introduction

It is unequivocal that human activities have contributed to the warming of our planet [1]. Extreme climate events are becoming more frequent, more intense, and longer lasting all over the world [2]. There are warning signs in every continent, showing unprecedented and irrefutable evidence that our climate is rapidly changing [1].

The Spanish Institute of Health Carlos III (ISCIII) has estimated that there have been 510 deaths attributable to high temperatures within one week in July 2022, during another recent record-breaking heat wave [3]. With temperatures above 43 °C, 'Zoe' became the world's first heat wave to be officially named by the Seville's new program for the monitoring and ranking of extreme heat waves [4]. The same kind of event was experienced by British Columbia, Canada, in late June 2021, leading to 619 heat-related deaths [5].

In February 2022, multiple floods and landslides ravaged the city of Petropolis, Rio de Janeiro, Brazil, when a heavy rainfall reached 260 mm in less than 3 h, killing 233 people and leaving a track of destruction all over the city [6]. A similar disaster has also occurred in China's Henan Province, in July 2021. The province's capital, Zhengzhou, recorded a 201.9-mm rainfall within an hour, resulting in floods that submerged entire neighborhoods, trapped passengers in subway cars, caused landslides, and overwhelmed dams and rivers [7].

Unless society works together to deeply reduce greenhouse gas (GHG) emissions in the coming decades, global warming of 1.5 °C and 2 °C above pre-industrial levels will be exceeded well before the end of the 21st century [1], intensifying not only climate events, but also social/migratory issues, as some places might become uninhabitable. In this alarming context, the construction industry can play a critical role in achieving GHG emissions reductions. Currently, buildings are responsible for 39% of global energy-related GHG emissions, with 11% due to materials and construction processes (embodied emissions), and 28% due to operational emissions, which include heating, cooling, and general energy use of buildings [8].

Among the multiple environmental impacts brought about by buildings, energy consumption has always been one of the major concerns [9]. This led many countries to implement new standards for Net-Zero Energy Buildings [10,11], and boosted the development of different certificate programs addressing energy efficiency performance (e.g., Energy Star, LEED).

However, the design and assessment of Net-Zero Energy Buildings (ZEB) commonly focus exclusively on the operational phase, ignoring the environmental impacts of embodied emissions in materials and equipment over the building life cycle [12]. Therefore, a new awareness on accounting for whole building life cycle carbon emissions has refocused the construction industry on developing Net-Zero Carbon Buildings (ZCB) [13], also referred to as carbon neutral buildings.

A Net-Zero Carbon Building is a highly efficient building, operated using 100% fossil-free renewable energy [14], that is designed following best practice sustainable construction [15]. The term 'best practice sustainable construction' stands for a number of strategies to reduce carbon emissions in buildings, such as promoting energy savings and the wellbeing of occupants through passive design, maximizing the use of recycled and nature-based materials, minimizing energy use in all stages of a building's life cycle, and also creating new green spaces [16]

At the city level, becoming 'net-zero' means exerting zero impact on the environment. Cities like Montréal, New York City, Paris, and Toronto have developed climate and environmental action plans, such as creating parks and planting trees to recover GHG-absorbing potentials formerly destructed by the built environment [17].

Aligned with commitments set by the Paris Agreement in 2015, this study aims to contribute to the efforts for achieving carbon neutral buildings, by establishing a framework to evaluate the feasibility of using urban trees around buildings as a way to sequestrate carbon emissions and mitigate part of its life cycle embodied and operational emissions. To demonstrate this approach, the life cycle assessment (LCA) of two real case studies in Montreal were performed using two LCA software tools specific to the environmental impact assessment of buildings.

2. Literature Review

2.1. Keyword Search in Databases

Relevant publications were selected if they contained information on:

1. Real case studies, with details about design solutions, materials, energy consumption, and energy sources;
2. Results about life cycle carbon balance, based on LCA calculations;
3. Methods, software tools, and databases used for the assessment of carbon emission;
4. The carbon sequestration potential of vegetation applied to the building context;
5. The estimation of annual carbon sequestration rates of trees and vegetation.

The main research databases used in the literature review were Scopus and Elsevier Engineering Village, which has Compendex, Inspec, and GEOBASE subsets, covering all engineering disciplines. Although most publications were selected in the period

2010–2022, some previous studies with relevant information were also included. The following keywords and terms were used:

Carbon neutral building AND case study; Zero carbon buildings AND case study; Life cycle assessment AND embodied emissions AND operational emissions; Carbon neutral buildings AND carbon sequestration; Carbon sequestration AND vegetation AND buildings; Carbon sequestration AND trees AND buildings; Life cycle assessment AND green roofs.

Since previous studies have not addressed some key issues, the current paper contributes two items to the discussion about carbon neutral buildings:

1. An assessment of the positive impacts of planting urban trees near buildings as a nature-based solution to offset buildings' life cycle embodied and operational GHG emissions, by considering direct carbon sequestration potential;
2. A discussion of the quality and completeness of whole building life cycle carbon analysis, with applications for real case studies.

2.2. Low-Carbon Design and Vegetation

Progress has been made towards designing and constructing carbon neutral buildings, but there is still no consensus either on their practical large-scale application for achieving carbon neutrality, or on the reliability of available tools for estimating a building's life cycle carbon emissions. Pomponi and Moncaster [18] reported that most of life cycle assessment (LCA) studies are cradle-to-gate analyses, which disregard what happens with the materials after they leave the manufacturing plants. Some LCA case studies reported only structural and envelope materials in calculations [19,20] neglecting the environmental impacts related to the manufacturing of building components such as mechanical systems, photovoltaic (PV) panels, and internal partitions, which have high embodied energy and carbon emissions.

Most of the reviewed papers considered the on-site PV electricity production as the main strategy to balance carbon emissions and reach carbon neutrality [19,21,22]. This approach might be consistent for those places where the grid-purchased electricity is not generated by renewables sources (e.g., the province of Alberta, Canada, where 90% of all electricity production is based on natural gas and coal burning [23]. However, for places like Quebec, Canada, where the energy grid profile is based on hydropower [24], the positive impacts of the PVs do not have the same potentials. Thus, it seems that if society achieves a zero-carbon grid in the future, the on-site electricity generated by PVs will no longer represent an avoided emission when calculating a building's life cycle carbon balance [13].

Some projects have been integrating green areas and trees to the design as a way to improve user comfort [25–27]. When planted near buildings, trees can indirectly mitigate carbon emissions by moderating the local microclimate, reducing the required amount of energy related to space-cooling in the summer, as well as protecting buildings from strong winds, reducing air infiltration rates and heating loads in winter [28,29]. As shown by Botallico et al. [30], the urban green infrastructure can contribute to improving urban air quality by abating ozone (O3) and particulate matter (PM10), which are highly detrimental pollutants to human health. Furthermore, the development and conservation of urban forests can also contribute to public well-being by reducing noise pollution, and creating a desired soundscape, stimulating for example the pleasantness of perceived birdsongs, as presented in studies by Hong et al. [31].

However, there is only a small number of papers [32,33] applying the direct carbon sequestration potential of greeneries among the strategies to abate part of a building's life cycle CO_2eq emissions. Liu [34] studied a low-carbon dwelling built on Kinmen, Taiwan, and reported a total CO_2eq reduction of 416.5 kg/year provided by a garden with 481 m^2 of lawn and 16 units of 20-year-old urban trees (240.5 kg/year from lawn and 176 kg/year from trees). The author based her estimations on studies from Lin et al. [35] and Lin et al. [36] which considered the carbon sequestration rates applicable for a period of

40 years; Kuittinen et al. [33] assessed the life cycle carbon emissions of different buildings in Finland, and found that the carbon sequestered in the biomass of shrubs and trees could mitigate around 12% of the total emissions related to a single-detached house. Their approach was based on data from literature, but also included basic field samples, in order to identify the different species of vegetation.

Some papers assessing the annual carbon sequestration rates of particular types of vegetation used in green roofs, living walls, and urban gardens were found in literature for different countries [32,37–43]. However, these studies do not provide an assessment of the share of the contribution of greeneries in relation to the total life cycle GHG emissions of a case study building, which is the objective of the current paper.

For instance, Heusinger and Weber [37] measured the CO_2 surface–atmosphere exchange of an unirrigated, extensive green roof composed of sedum species and herbaceous plants over a full annual cycle. They found that the 9 cm-depth green roof was able to sequestrate 0.313 $kgCO_2eq/m^2$ per year. Getter et al. [42] conducted a two-year study on an extensive green roof composed of four different sedum species with a substrate depth of 6 cm. The results after two years showed that the entire system sequestered 1.37 $kgCO_2eq/m^2$, compared with the initial conditions. Luo et al. [32] assessed the carbon sequestration potential of different irrigated green roofs using a mixed-sewage-sludge substrate (MSSS) over a year. The best configuration in their study was found with a 25 cm-depth MSSS with Ligustrum vicary vegetation that resulted in an annual carbon sequestration of 25.8 $kgCO_2eq/m^2$. This high rate of carbon sequestration is due to soil treatment and greater substrate depth. Seyedabadi et al. [39] implemented a green roof on a four-story building and assessed the performance of different plants in a cold and dry climate by measuring the plant's dry weight biomass increase over one year. They found that the annual carbon sequestration rates ranged from 0.513 $kgCO_2eq/m^2$ to 7.59 $kgCO_2eq/m^2$ of green roof area. Additionally, they estimated through an energy simulation that the green roof could indirectly mitigate up to 28.16 $kgCO_2eq/m^2$year as a result of an 8.5% reduction of energy consumption.

However, all these measurements were based on short-time observations, for green roofs aging from 1 to 6 years. After the green roof's vegetation has reached a grown stage, it is very likely that the direct amount of carbon taken in by photosynthesis will just balance out the amount of carbon emitted by the decay of plant material [44].

Different from trees that keep growing for decades, the long-term direct carbon sequestration performance of green roofs is still uncertain [45]. In urban areas, trees are stimulated by the increased concentration of CO_2, which provides a fertilizing effect, rendering a more efficient carbon sequestration potential [46]. Therefore, it seems that urban trees can provide a more reliable and longer-lasting contribution to the achievement of carbon neutral buildings.

2.3. Life Cycle Assessment in Canadian Context

Despite the credibility of many available certifications worldwide, and all the efforts from different Green Building Councils on providing standards and design guides for sustainable constructions, there are still some gaps on their approach regarding the scope of LCA calculations. The most recent version of the Design Standard for Zero Carbon Building (v.03), released by the Canadian Green Building Council in June 2022, only requires for carbon emissions assessment related to structure materials, and envelope and operational energy use [14]. As a result, important building elements such as internal partitions, finishes, and mechanical/electrical equipment (e.g., HVAC, PV system) have been excluded from the LCA analysis in several of LEED- and ZCB-Performance-certified projects. This limitation can lead to an underestimation of 19% to 34% of a project's material-related embodied CO_2 emissions, depending on the type of building [47].

Moreover, the environmental impact assessment of a building can be very sensitive to the assumptions and limitations related to the LCA tool considered for calculations. In

North America, Athena Impact Estimator for Buildings and One Click LCA are commonly used softwares, with regionalized inventory databases for USA and Canada.

Both tools are compliant with ISO 14044 [48]/ISO 14040 [49] and EN 15978 [50]/EN 15804 [51] standards, and both provide a cradle-to-grave LCA of a building, as presented in Table 1.

Table 1. Life cycle stages available in the LCA tools used in current work.

Modules	Life Cycle Stages	Included
A1–A3	Raw material supply; Transport; Manufacturing	✔
A4	Transport from manufacturing plant to construction site	✔
A5	Construction–installation process (equipment energy use)	✔
B1	Installed product in use	
B2	Maintenance	
B3	Repair [1]	✔
B4–B5	Replacement; Refurbishment (according to materials' service life)	✔
B6	Operational energy use	✔
B7	Operational water use	
C1–C4	De-construction/demolition; Transport; Waste Processing; Disposal	✔
D	Benefits beyond building life (biogenic carbon in wood products) [2]	✔

[1] Results for "Repair" could be included manually on One Click (times/year), but are not considered in current work; [2] Results for "benefits beyond building life" are presented separately.

The main difference is the list of materials available in each software. Athena has a concise inventory, based on common local practice. One Click LCA has a more comprehensive database, including generic and manufacturer-specific material options, based on Environmental Product Declarations (EPDs). The calculations performed by these tools include (i) embodied emissions related to raw material extraction, manufacturing, transportation, use, replacements and disposal, and (ii) operational emissions related to the use of local grid-purchased energy. The benefits beyond a building's life (referred to as 'module D' on life cycle stages) related to the positive impacts of biogenic carbon stored in wood products is not mandatory in cradle-to-grave approaches according to EN 15978 [50], and therefore it is presented separately from other stages.

Athena's inventory database does not provide options for HVAC and PVs, which are items that carry high embodied impacts. For that reason, when necessary, we incorporated One Click's results for those elements into Athena's results.

3. Materials and Methods

3.1. Overview

This paper focuses on the feasibility of planting urban trees around buildings as a nature-based solution to mitigate part of the life cycle carbon emissions related to two real case studies located in Montreal. The environmental impacts (i.e., Global Warming Potential, GWP) of each case study was quantified using two LCA tools commonly used for buildings in North America, One Click LCA (v.0.5.2) and Athena Impact Estimator for Buildings (v.5.4). The carbon sequestration rate of standardized urban trees was estimated based on the studies of Nowak et al. [53–55] for USA, and Pasher et al. [52] for Canada. The GWP results related to each case study are presented for different scenarios, before and after considering the direct carbon sequestration potential from urban trees.

Indirect benefits of vegetation (e.g., energy savings) and scenarios including other greeneries (e.g., green roofs, living walls) were out of the main scope of the current work.

To demonstrate this approach, we performed the carbon LCA of two real buildings in Montreal: a recently constructed research facility at Concordia University, the Future Buildings Laboratory (FBL); and a single-detached house, not energy efficient, built in 1967. The selection of materials in each software was carefully made to best represent the case studies' design specifications, using only locally regionalized data for Canada. A time horizon of 60 years was assumed in LCA calculations, since this is the lifespan considered as the benchmark in EN 15978 [50], which is one of the standards followed by both software tools. The results provided by each software were compared in terms of life cycle environmental impacts, as well as their background assumptions, calculations, and inventory limitations.

Once the GWP was estimated for both case studies, we presented the total amount of carbon that could be removed if each case study had their garden area fully covered by representative units of urban trees (410 m^2 garden at FBL, and 505 m^2 at the single-detached house). The passive (indirect) effects related to vegetation on moderating local microclimate (by reducing air infiltration, reflecting heat, providing shading, and therefore reducing energy consumption), and other types of greeneries were out of the scope of this paper.

Figure 1 shows the framework developed for this paper, starting with the life cycle assessment of the case studies (resulting in GWP values), followed by the application of carbon sequestration potential of urban trees, leading to a net final carbon balance.

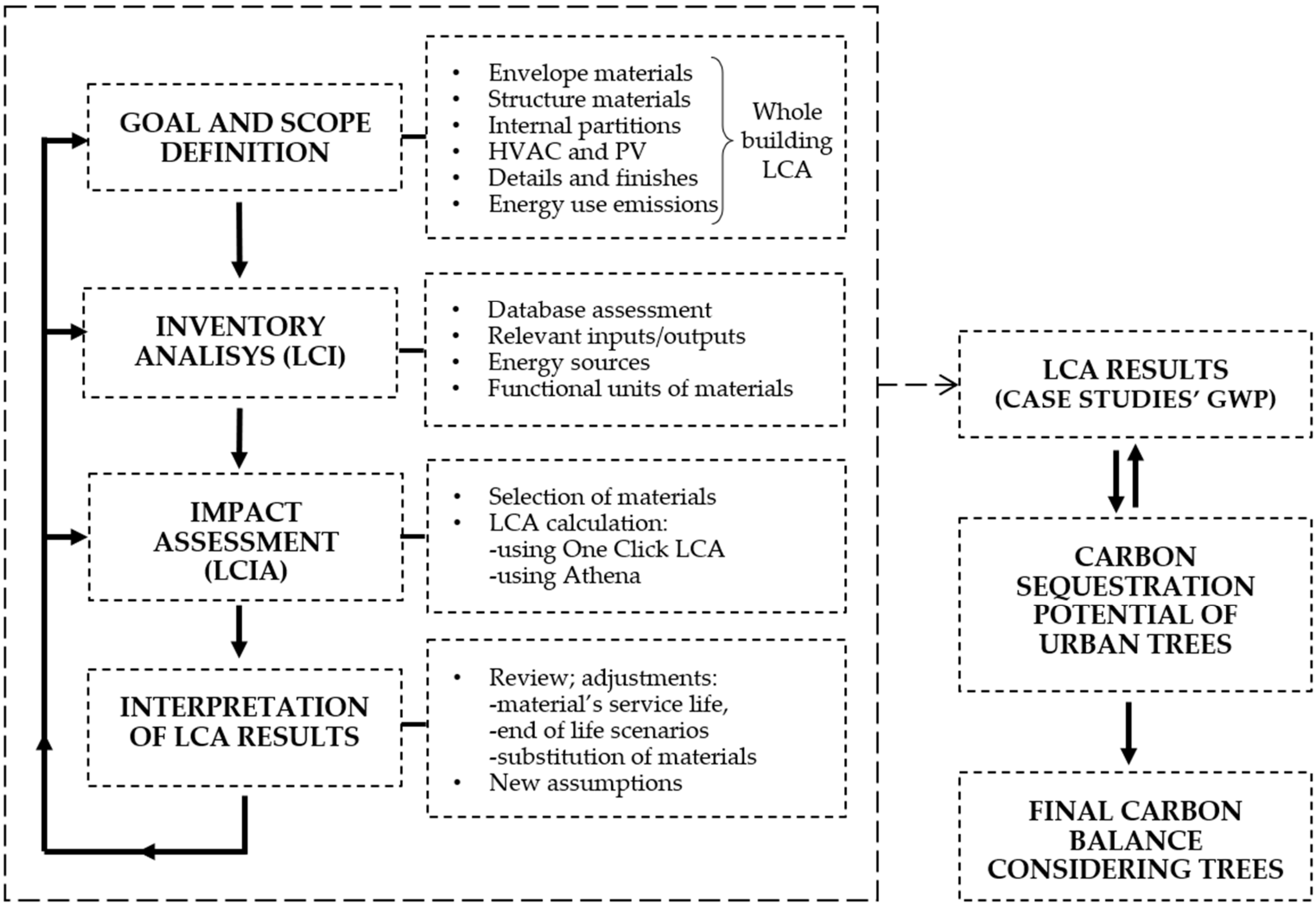

Figure 1. Research framework overview.

3.2. Estimation of Building's Environmental Impacts

The impact assessment started with the list of materials for each case study, according to their respective design specifications. This list, organized by building assembly, was mapped within the LCA software where each designed material was linked to an inventory data point. When necessary, information about thickness, density, and other material properties was also provided. The second input was the annual energy consumption, that was estimated by energy simulation. The GWP results, expressed in kgCO_2eq, are presented for each life-cycle stage, considering a 60-year calculation period.

3.3. Carbon Sequestration Potential of Urban Trees

This section presents an overview of the estimation of annual carbon sequestration rates of urban trees by Nowak et al. [53–55] for USA context, and adapted by Pasher et al. [52] to the Canadian climate. These papers include items such as countrywide conditions, size and types of urban trees, as concluded into a unique value of annual potential carbon sequestration rate per unit of tree cover area (kgC/m^{2}TC.year). This procedure is followed to estimate the carbon sequestration potential of the garden areas of the two case studies (410 m^2 for FBL, and 505 m^2 for single-detached house), and quantify the maximum offset of the corresponding life cycle emissions.

In the USA context, Nowak et al. [55] provided field data collection, high resolution photointerpretation, and computer models to determine the country's urban forest structure. Twenty-eight cities in six different states were randomly sampled in plots of 0.04 and 0.067 ha, and each tree inside the sampled boundary was analyzed in terms of species, stem diameter at 1.37 m above the ground (DBH), tree cover area, tree height, crown height, crown width, light exposure, leaf area, and crown's general state of life. The tree dry weight biomass for each measured tree (with a minimum size of 2.54 cm diameter at DBH) was calculated using different allometric equations from literature [56–59], as shown by Equations (1) and (2):

$$\mathrm{Y} = \mathrm{a} \times (\mathrm{DBH})^{\mathrm{b}} \tag{1}$$

$$\mathrm{Y} = \mathrm{Exp}^{(\mathrm{a}+(\mathrm{b}\ln \mathrm{DBH}))} \tag{2}$$

where Y is the tree biomass (kg dry weight), a and b are regression factors varying with the species and dependent on tree height and age, and DBH is the stem diameter at 1.37 m above the ground. Equations predicting only the aboveground biomass were converted to whole tree biomass based on a root-to-shoot ratio of 0.26 [60]. Carbon accounts for approximately 50% of whole tree dry weight biomass [61].

Once the total biomass of each sampled area was calculated, the next step was to estimate how much this biomass would increase in one year. To do that, measured growth rates for street, park, and forest trees from Frelich [62], De Vries [63], and Smith and Shifley [64] were standardized to the length of growing season for each sample location, based on Equation (3):

$$\mathrm{SG} = \frac{\text{measured growth rate } \times 153}{(\text{days of growing season of sample}'\text{s location})} \tag{3}$$

where SG is the standardized growth rate (cm per year) at the DBH, and 153 days is the minimum length of the growing season (frost-free days) from the measured data—and therefore it was used as the reference length [55]. This calculation is made for different species and different growing locations (street, park, forest). For different species of street trees, the average SG was equal to 0.83 cm/year [54].

Then, standardized growth rates (SG) of trees of the same species were compared to determine the average difference between standardized growth rates for street trees (0.83 cm/year) and standardized growth for park and forest trees. The difference between a 'street' tree from a 'park' or 'forest' tree is related to the number of sides/top exposed to sunlight: 0–1 sides/top to represent forest growth condition, 2–3 sides/top to represent park tree, 4–5 sides/top to represent street tree. This information is used to calculate the local base growth rates (BG), which is defined in Equation (4):

$$\mathrm{BG} = \begin{cases} \mathrm{SG} \div 2.29 \rightarrow \text{Forest trees} \\ \mathrm{SG} \div 1.78 \rightarrow \text{Park trees} \\ \mathrm{SG} \div 1.00 \rightarrow \text{Street trees} \end{cases} \tag{4}$$

The local base growth rate (BG) is adjusted with Equation (5), according to the trees' state of life condition (which takes into account the color of leaves and other appearance/disease factors) in order to determine the final growth rate. Base growth (BG) rates were multiplied by 1 (no adjustment) for trees in fair to excellent conditions, representing no dieback. For trees in poor conditions, base growth rates were multiplied by 0.62 (26–50% dieback); trees in critical conditions by 0.37 (51–75% dieback); dying trees by 0.13 (76–99% dieback); and dead trees by 0 (100% dieback) [54].

$$\mathrm{BG_{adjusted}} = \begin{cases} \mathrm{BG} \times 1.00 \text{ fair to excellent conditions (no adjustment)} \\ \mathrm{BG} \times 0.62 \text{ trees in poor conditions (26 to 50\% dieback)} \\ \mathrm{BG} \times 0.37 \text{ trees in critical conditions (51 to 75\% dieback)} \\ \mathrm{BG} \times 0.13 \text{ trees in daying conditions (79 to 99\% dieback)} \\ \mathrm{BG} \times 0.00 \text{ for those trees that are dead (100\% dieback)} \end{cases} \quad (5)$$

It is important to point out that SG, local BG, and adjusted local BG are related to growth rates (size increase of tree DBH from year (x) to year (x+1), in centimeters). After estimating the final base growth rates of each tree within each sampled area, it is possible to calculate the increase of biomass from year (x) to year (x+1) for each tree sampled, by using again the biomass equations aforementioned. In a sample level, total biomass of year (x+1) minus total biomass of year (x) is equal to gross annual biomass increase in the sample [55].

Gross annual increase of biomass is translated to carbon contents, and represents the annual carbon that was sequestrated in each sampled area over one year. The samples' total variation of carbon is divided by the total samples' tree cover area, estimated using photo-interpretation and i-Tree methodology (www.itreetools.org/, accessed on 13 August 2022), in order to provide the average gross sequestration rate in units of kgC/m^2 of tree cover per year.

Once this procedure was applied for all sampled trees, the overall average annual value for USA gross carbon sequestration rate was found to be 0.277 kgC/m^2 of tree cover, and for net sequestration, 0.205 kgC/m^2 of tree cover. The net sequestration rate considers the dieback of trees, which incurs GHG emissions due to decomposition of organic matter. Therefore, net sequestration rate averages 74% of the gross sequestration rate [55]. To convert a quantity of carbon (C) into an equivalent quantity of carbon dioxide (CO_2), we multiplied the values of C by 3.67, which represents the ratio of the atomic mass of a CO_2 molecule to the atomic mass of a C atom (44:12) [65]. The converted values for USA gross and net CO_2 sequestration are 1.015 $kgCO_2eq/m^2TC$ year and 0.751 $kgCO_2eq/m^2TC$ year, respectively.

While a Canadian specific standardized growth rate did not exist, Pasher et al. [52] assumed that information derived from USA datasets was consistent for Canadian cities, as long as the average value of annual gross carbon sequestration from Nowak (0.277 kgC/m^2TC) was adjusted for a shorter length of growing season in Canada (133 frost-free days). As a result, the annual gross carbon sequestration rate of Canadian urban trees is equal to 0.212 kg C/m^2TC. To calculate net sequestration rates, Pasher et al. [52] also considered the 74% of gross carbon sequestration from Nowak's works, which resulted in 0.156 kg C/m^2TC year. In terms of CO_2eq, the converted values are 0.777 $kgCO_2eq/m^2TC$ year for gross sequestration and 0.575 $kgCO_2eq\ /m^2TC$ per year for net sequestration.

In conclusion, a net carbon sequestration potential of 0.575 $kgCO_2eq/m^2$ of tree cover area per year is used in this paper.

3.4. Case Study 1: Future Buildings Laboratory

Opened in 2021, the Future Buildings Laboratory (FBL) is a research facility located at Concordia University's Loyola Campus, in Montreal. The 125 m^2 all-electric lab was designed with a focus on the development of advanced concepts for carbon neutral buildings. The facility is prepared for testing building-integrated photovoltaics (BIPV), motorized shading devices, urban wind energy, and many other technologies. Its envelope incorporates large removable parts, allowing the replacement of approximately 60% of the exterior walls for the assessment of performance of various types of wall assemblies, their hygrothermal performance, effects on indoor environmental conditions, interaction with mechanical systems, and renewable energy.

The building is composed of a concrete slab-on-grade foundation, engineered wood structure made of glued laminated timber, metallic system for the roof, insulated wood frame walls with wood cedar painted cladding, plywood sheathing, insulation, gypsum boards, and finishes. The HVAC system is an air-source heat pump, air-handling unit (with heat recovery), including humidifier and electric heater. Currently the four test cells on the south façade have building-integrated photovoltaic/thermal (BIPV/T) and semi-transparent PV curtain wall systems installed, but the systems have been used just for research purpose, and not yet to generate electricity for the operation of the facility. Thus, its potential to displace carbon emissions from grid-purchased electricity is not considered in this work. Further information about the building is provided in Figures 2–4.

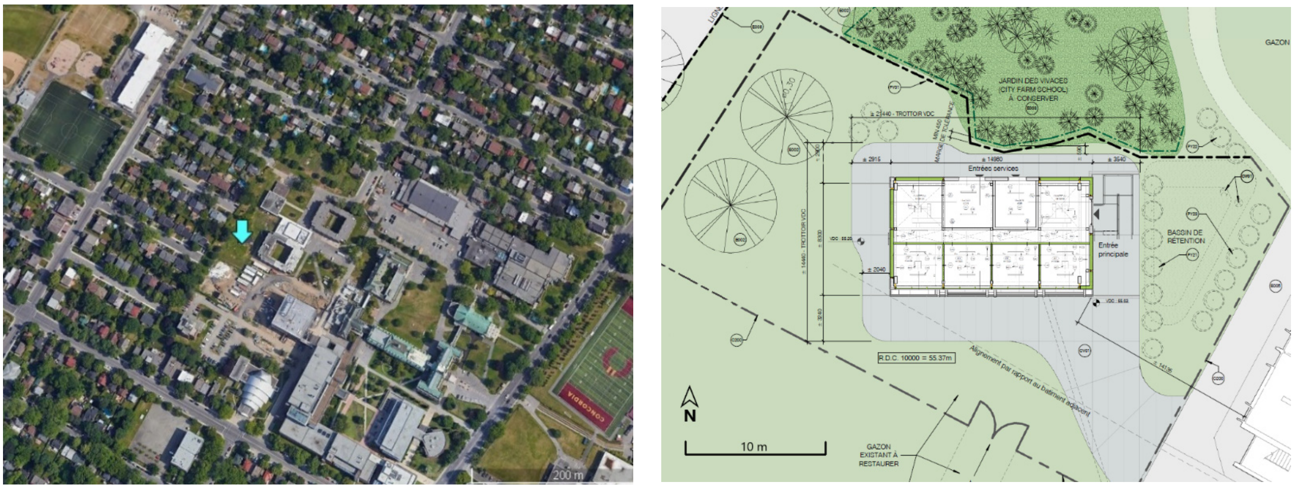

Figure 2. Situation/location plan, and landscape boundaries/floor plan.

Figure 3. Future Buildings Laboratory.

To simulate the annual electricity consumption related to HVAC system, equipment, and interior lighting, the building was modeled in Design Builder (Energy Plus) (v7.0.2.004, 2022) following the design specifications (Tables 2 and 3).

Table 2. U-values (W/m^2.K) for FBL.

Building Elements	U-Value
Slab-on-grade foundations	0.13
Exterior walls	0.22
Roof	0.14
Windows	1.30
Doors	1.40

Table 3. Energy simulation inputs for FBL.

Inputs	Value	Unit
Occupancy	20.0	m^2/person
Lighting power density	5.0	W/m^2
Appliances and plug loads	8.0	W/m^2
Heating setpoint	22.0	°C
Heating setback	18.0	°C
Cooling setpoint	23.0	°C
Coefficient of performance (summer)	3.5	-
Coefficient of performance (winter)	2.0	-
Ventilation rate (per person)	5.0	L/sec/person
Ventilation rate (per area)	0.9	L/sec/m^2
Air change rate (per hour, at 50 Pa)	0.8	ACH

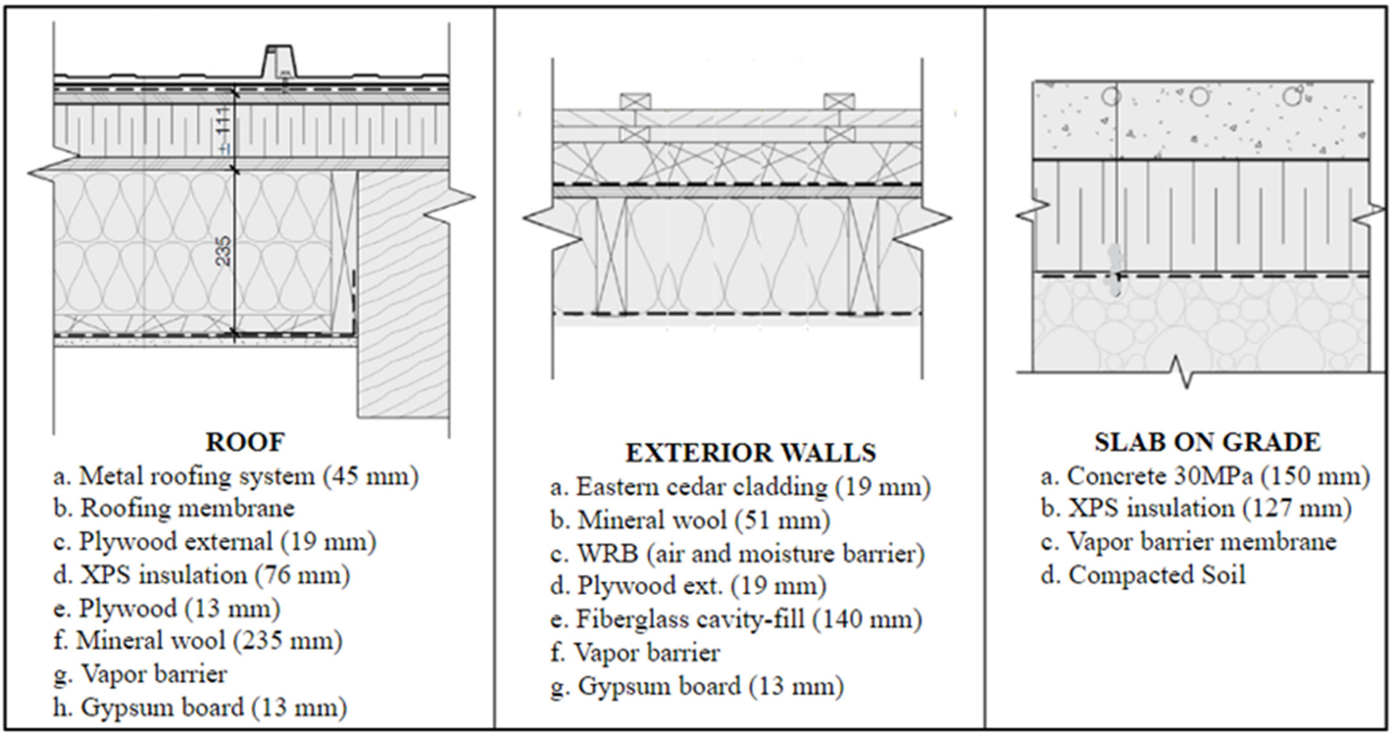

Figure 4. Typical sections of the envelope assemblies.

The simulated annual 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/^{3} of heated internal volume per year.

Table 4 lists the bill of materials used in each LCA software for the calculation of environmental impacts related to FBL. The specifications were retrieved from project drawings, and total quantities are related to the construction of the building (software inputs). Additional replacement of materials throughout the buildings' life cycle is automatically calculated by the software based on material's service life defined in these programs, as will be discussed in results section.

3.5. Case Study 2: Single-Detached House

The second case study is a single-detached house built in 1967, not energy-efficient, located in Dollard-des-Ormeaux (near Montreal). The information about the house was retrieved from Baouendi [66]. The house has 258 m^2 of heated floor area, and encompasses 14 rooms that are distributed on one main floor and a basement. It has a typical wood frame envelope, with brick veneer in the above ground exterior walls, reinforced concrete in the basement walls and foundations and double-glazed aluminum frame windows. The annual energy consumption was simulated using the HOT2000 software [66]. Natural gas is used for space heating and domestic hot water (DHW) (3561.3 m^3, equivalent to 13.8^3 gas/m^2/year), and electricity is used for lighting and electric appliances (9725 kWh, equivalent to 37.7 kWh/m^2/year). No air conditioning is used. The basic simulation inputs are presented in Table 5.

Table 4. Bill of materials according to Future Buildings Lab's design specs, and correspondent material option chosen in One Click LCA and Athena.

		Project Specification	**One Click LCA**	**Athena**
m^3	26.04	Concrete 30 MPa—15 cm slab + borders	Ready-mix concrete, 30 Mpa Industry Average Benchmark (CRMCA)	Concrete Benchmark CAN 30 MPa
kg	1953.6	Steel bars (mesh) d = 10 mm, 10 × 10 cm	Reinforcement steel (rebar), 7850 kg/m^3 (Gerdau, Whitby plant)	Rebar, Rod, Light Sections
m^2	198.40	Insulation, RSI-3.42, rigid, XPS, 127 mm	XPS insulation, 15 psi, R-10, 50.8 mm, Foamular XPS (Owens Corning)	Extruded Polystyrene
m^2	156.75	Insulation, RSI-2.59, rigid, XPS, 76 mm		
m^2	197.90	Insulation, RSI-4.29 cavity fill, FG, 140 mm	Glass wool insulation panels, unfaced, generic, L = 0.031 W/mK, R = 3.23 m^2 K/W	FG LF Cavity Fill R22
m^2	197.90	Insulation, RSI-1.41, semi-rigid, MW, 51 mm	Rock wool insulation board, R = 8.6, 50.8 mm, 88 kg/m^2, (Rockboard 60)	MW Batt R11-15
m^2	119.22	Insulation, RSI-1.41, semi-rigid, MW, 89 mm		
m^2	156.75	Insulation, RSI-5.64, semi-rigid, MW, 235 mm	Mineral fiber batt insulation, 6.89 in	MW Batt R30
m^2	124.10	Gypsum board, fire resistant, 13 mm	Glass-mat gypsum boards, fire/moisture., 12.7 mm, 10.15 kg/m^2 (AGC)	1/2″ Fire- Type X Gypsum Board
m^2	395.19	Gypsum board, regular, 13 mm	Gypsum plaster board, regular, generic, 6.5–25 mm, 10.725 kg/m^2 for 12.5 mm	1/2″ Regular Gypsum Board
m^2	400.89	Gypsum board, fiber-board, 16 mm	Gypsum plaster board, regular, generic, 6.5–25 mm, 10.725 kg/m^2 for 12.5 mm	5/8″ Gypsum Fibre Gypsum Board
m^2	197.90	Plywood board, 13 mm	Softwood plywood, 477.33 kg/m^3 (Canadian Wood Council)	Softwood Plywood
m^2	156.75	Plywood board, external, 19 mm	Softwood plywood, 709.79 kg/m^3 (American/Can. Wood Council)	
m^2	23.12	Plywood board, 19 mm	Softwood plywood, 477.33 kg/m^3 (Canadian Wood Council)	
m^3	16.33	Glued Laminated Timber	Glue laminated timber (Glulam), 467.3 kg/m^3 (Canadian Wood Council)	GluLam Sections
m^3	8.16	Wood joists, glulam, 5 × 25 cm, 300 mm sp	I-joist, wood (FPInnovations)	
m^3	1.34	Wood joints cover for cladding, 2 × 4 cm	Softwood lumber, kiln-dried, 19 mm, 460 kg/m^3 (Can. Wood Council)	Small Dim. Softwood Lumb, kiln-dried
m^3	6.84	Wood studs, 5 × 20 cm, 400 mm spacing		
m^2	197.90	Eastern cedar cladding, painted, 19 mm	Western red cedar bevel siding, painted, 1 × 6 in (W Red Cedar Lumber Assoc.)	Cedar Wood Shiplap Siding
m^2	532.34	Air/water barrier 6 mil	Air and water barrier system, mechanically fastened, 0.11 kg/m^2, Tyvek (DuPont)	Air Barrier
m^2	396.65	Vapor barrier, dynamic, 6 mil		Polypropylene Scrim Kraft Vap. Ret. Cl
m^2	156.75	Metal roofing syst (45 mm w/membrane)	Hot-dip galvanized steel sheets, 0.4–3.0 mm, zinc coating, 0.28 kg/m^2	Metal Roof Cladding—Resident. 30 Ga
m^2	156.75	Impermeable membrane (roof)	SPPR PVC roofing membrane, single-ply, 40 mil (Chemic.Fab. Film Assoc.)	#30 Organic Felt
kg	200.00	Bolts, Fasteners, Clips	Structural steel profiles, generic, 40% recycled content	Bolts, Fasteners, Clips
m^2	26.00	Windows aluminum frame	Aluminum frame windows, 37 kg/m^2—30% Alum., 61% Glazing (AluQuébec)	Aluminum Window Frame
m^2	26.00	Double Glazed Hard Coated Argon		Double Glazed Hard Coated Argon
m^3	0.20	Doors/steel doors	Galvanized steel door w/ polystyrene, 44.5 mm, 41 kg/unit (De La Fontaine)	Rough Lumber SFWP

Table 4. *Cont.*

		Project Specification	One Click LCA	Athena
m	75.00	Steel structure on roof to support BIPV/T	Stainless steel crash rails with tube brackets, 10.84 kg/m (Constr.Specialties)	Steel Tubing
m^2	120.00	Industrial floor paint—Epoxy or similar	Water-based epoxy floor and wall coating, 2.31 kg/m^2 (SherWilliams)	Solvent Based Alkyd Paint
				Solvent Based Varnish
m^2	698.31	Paint intern	Recycled latex paints, interior, 12 m^2/L, 1.23 kg/L, 0.205 kg/m^2, (Laurentide)	Water Based Latex Paint
m^2	23.12	Vinyl cover, 12pprox. 3 mm	Vinyl tile flooring, 2.4–3.2 mm, 6.4–6.9 kg/m^2 (Armstrong, Tarkett)	Vinyl Siding
unit	1.00	HVAC (air src heat pump, 2.5 kW output, 47.5 MJ/h) + air handling unit	Ground source heat pump (excluding ground tubes), per 1 kW max output	N/A—One Click's results adopted
			Air hand. Unit, w/ heat recovery, indirect liq. Circulation, 1000 m^3/h, 92 kg/unit	N/A—One Click's results adopted
m^2	15.00	PV system 1.63 kWp (BIPV on south façade)	PV polycrystalline panel, per m^2, 14.5 kg/m^2, 210 Wp (One Click LCA)	N/A—One Click's results adopted

Obs.: For insulation materials, software' default thicknesses (provided in terms of functional unit) were adjusted to match the R-values defined in project specifications.

Table 5. Energy simulation inputs and parameters for the single-detached house.

Energy Simulation Inputs	Value	Unit	Envelope Assemblies	U-Value ($W/m^2.K$)
Occupancy	60.0	m^2/person	Basement floor	1.00
Temperature setpoint for heating	19.0	°C	Basement walls	0.48
Temperature domestic hot water	55.0	°C	Above ground walls	0.45
Forced-air natural gas furnace heating	80	MJ/h	Roof and ceiling	0.18
Volumetric air flow rate	210.0	L/s		
Air change rate (measured, at 50 Pa)	7.76	ACH		

Obs.: U-values of walls include windows and doors.

In order to highlight the high environmental impact of natural gas, an alternative setup was proposed by converting the energy provided by natural gas to an energy equivalent value of electricity. 1^3 of natural gas is equivalent to 10.7330 kWh [67]. Thus, for this alternative setup, the total electricity consumption (general use, plus heating and DHW) is 47,950 kWh/year (equivalent to 185 kWh/m^2/year).

The garden area of 505 m^2 represents the typical landscape of single-detached houses in Dollard-des-Ormeuax, as shown in Figure 5. The bill of materials inputted in the LCA softwares to calculate the life cycle GWP is presented in Table 6.

Figure 5. Typical landscape and garden of single-detached house in Dollard-des-Ormeaux. Source: Google Earth, 2022.

Table 6. Bill of materials according to single-detached house design specs, and correspondent material option chosen in One Click and Athena.

		Project Specification	One Click LCA	Athena
m^3	36.77	Concrete 30 Mpa	Ready-mix concrete, 30 MPa Industry Average Benchmark (CRMCA)	Concrete Benchmark CAN 30 MPa
kg	3991.24	Steel rebars (double mesh)	Reinforcement steel (rebar), generic, 80% recycled content, A615	Rebar, Rod, Light Sections
m^3	12.55	Brick veneer, 10.9 mm thickness	Clay brick, 2120 kg/m^3 (several manufacturers)	Ontario (Standard) Brick
m^3	3.46	Mortar (0.03 ^{3} per m^2 of brickwork)	Lightweight mortar, single component, 3.625 kg/m^2 (Mapei)	Mortar
m^2	107.62	Insulation RSI-4.94, FG, cavity fill, 89 mm	Insulation, glass wool, loose, 30 m^2 K/W, Industry average US (NAIMA)	FG LF Cavity Fill R30
m^2	137.55	Insulation RSI-3.53, FG, cavity fill, 152 mm	Glass wool insulation panels, unfaced, generic, L = 0.031 W/mK, R = 3.23 m^2 K/W	FG LF Open Blow R13-20
m^2	137.55	Insulation RSI-3.53 FG, continuous, 152 mm		
m^2	958.57	Gypsum board, 13 mm	Gypsum plaster board, regular, generic, 12.5 mm, 10.725 kg/m^2	1/2" Regular Gypsum Board
m^2	594.63	Plywood board, 13 mm	Softwood plywood, 477.33 kg/m^3 (Canadian Wood Council)	Softwood Plywood
m^2	497.88	Polyethylene sheet, 6 mil	PVC-polyester waterproofing membrane (Chemical Fabrics and Film Association)	6 mil Polyethylene
m^2	275.10	Wood flooring	Solid hardwood flooring, 19 mm, 12.35 kg/m^2 (Wickham)	Spruce Wood tongue/groove (closest option)
m^3	6.88	Wood studs 5 × 15 cm	Softwood lumber, kiln-dried, 460 kg/m^3, (Canadian Wood Council)	Small Dimension Softwood Lumber, kiln-dried
m^3	8.80	Wood studs 5 × 10 cm		
m^3	1.70	Wood joists 5 × 10 cm		GluLam Sections
m^3	0.76	Wood Doors	Hardwood lumber (Quebec Wood Export Bureau)	Rough Lumber SFWP
m^2	17.00	Windows aluminum frame	Aluminum frame windows, 37 kg/m^2, 30% Alum., 61% Glazing (AluQuébec)	Aluminum Window Frame
m^2	17.00	Double glazed units		Double Glazed Soft Coated Air
m^2	958.56	Paint intern	Recycled latex paints, interior, colored, 0.205 kg/m^2 (Laurentide re/sources)	Water Based Latex Paint
m^2	204.36	Asphalt shingle	Fiberglass asphalt shingle roofing system, 12.7 kg/m^2 (ARMA)	Organic Felt shingles 30 yr
m^2	204.36	Organic felt	SPPR PVC roofing membrane, 60 mil (Chemical Fabrics and Film Association)	6 mil Polyethylene
kg	200.00	Bolts, Fasteners, Clips	Structural steel profiles, generic, 40% recycled content, I, H, U, L, and T sections	Bolts, Fasteners, Clips
unit	1.00	HVAC (forced-air nat gas furnace, 80 MJ/h)	Air handling unit, w/ heat recovery, liquid circulation, 1000 m^3/h, 92 kg/unit	N/A—One Click results adopted

Obs.: For insulation materials, softwares' default thicknesses (provided in terms of functional unit) were adjusted to match the R-values defined in project specifications.

4. Results and Discussion

4.1. LCA Results: Future Buildings Laboratory

The life cycle CO_2eq emissions for the FBL are presented in Table 7, as obtained from the two softwares, One Click LCA and Athena Impact Estimator, considering a 60-years' time horizon. The baseline scenario considers all life cycle stages (A1–A5, B4–B6, C1–C4), except for module D (biogenic carbon in wood products). For the baseline scenario, the total GWP, without considering the carbon sequestration potential of trees, is equal to 83,521 kgCO_2eq (calculated using One Click LCA) and 82,666 kgCO_2eq (using Athena). The share of emissions from each life cycle stage for this scenario is presented in Figure 6. In terms of annual CO_2eq emissions per heated floor area (125 m^2), the results are 11.13 kgCO_2eq/m^2 (using One Click) and 11.02 kgCO_2eq/m^2 (using Athena).

Table 7. LCA results for Future Buildings Laboratory: Global warming potential (without contribution of trees).

Modules	Life Cycle Stages	One Click LCA kgCO_2eq over 60 yr	Athena kgCO_2eq over 60 yr
A1–A3	Material manufacturing processes	55,715.76	51,692.01
A4	Transportation to site	2131.45	1793.95
A5	Construction process	2633.84	1647.87
B4–B5	Replacement; Refurbishment	14,282.14	14,320.24
B6	Operational energy use	5445.38	9737.97
C1–C4	End-of-life (demolition; disposal; waste processing)	3313.14	3473.99
D	Benefits beyond building's life (biogenic carbon in wood products)	−35,885.45	−27,553.12
Scenario 1	**Total Emissions—Modules A to C—baseline scenario**	**83,521.71 (11.13)**	**82,666.02 (11.02)**
Scenario 2	**Total Emissions—Modules A to D**	**47,636.26 (6.31)**	**55,112.90 (7.34)**

Obs. 1: HVAC and PV are not available in Athena database. Thus, for these two items, the values from One Click were considered for Athena; Obs. 2: Values between parenthesis (e.g., (9,28)) refers to the equivalent CO_2eq emissions results per m^2 of heated floor area per year.

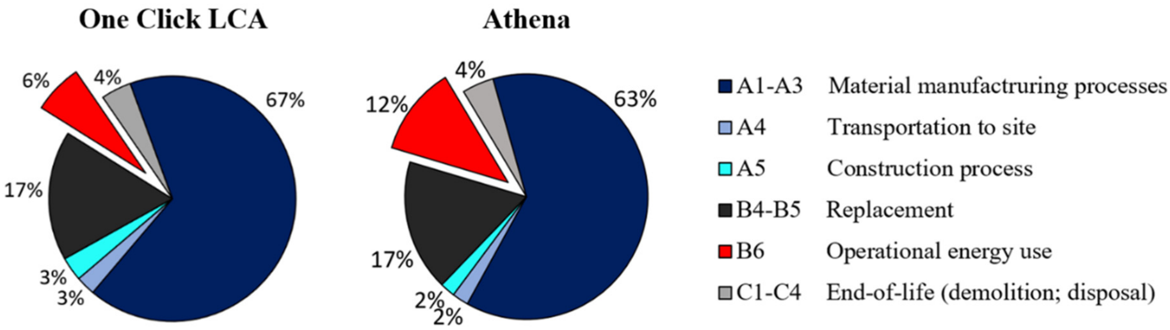

Figure 6. Emissions contribution of each life cycle stage for FBL's baseline scenario (A to C), using One Click LCA and Athena.

The second scenario includes module D, which is not mandatory in the cradle-to-grave approach according to EN 15978 [50]. The GWP estimated for this scenario, without vegetation contribution, is equal to 47,363 kgCO_2eq (calculated using One Click LCA) and 55,112 kgCO_2eq (using Athena). In terms of annual CO_2eq emissions per heated floor area, the results are 6.31 kgCO_2eq/m^2 (using One Click LCA) and 7.34 kgCO_2eq/m^2 (using Athena).

There are a few aspects related to software calculations and material inventory options that need to be discussed regarding the FBL's LCA results:

1. Although the operational emissions (module B6) are only dependent on two inputs (building location and annual energy consumption by type of fuel), the result provided by Athena for this module (9737 kgCO_2eq) is almost 80% higher than the results from One Click LCA (5445 kgCO_2eq). The reason is that Athena contains highly

specific data for North American regions, which means that city-level geographic relevance is critical, especially for operational emissions. According to Athena's Transparency Document [68] and customer support service, starting with version v.5.4, the source data for electricity profiles for Canadian provinces has been changed to Ecoinvent 3.4-2017, which is very likely to include factors for biogenic decay in hydro reservoirs (rotting vegetation emitting CO_2 and methane (CH_4)), and other impacts related to transmission processes, which results in a multiplier factor of 0.018302 kgCO_2eq per kWh. For One Click LCA, the operational electricity use emissions are calculated considering a factor of 0.010234 kgCO_2eq per kWh of electricity. Based on the information presented from reading data-cards available in the One Click LCA browser, the calculation is done according to an internally verified LCA study for country-specific electricity mixes (Quebec/Canada) based on the International Energy Agency (IEA) and Ecoinvent databases from 2020.

2. There is a high environmental impact due to the use of Extruded Polystyrene (XPS) insulation materials, which is the type of insulation specified for the FBL's foundation and roof. The impact of XPS exceeds any other materials, carrying a GWP of around 20,700 kgCO_2eq, which represents 25% of the total life cycle emissions for the baseline scenario (modules A to C). Both softwares use data from publicly available Environmental Product Declarations (EPDs) from Owens Corning and Dupont to estimate life cycle CO_2eq emissions impacts. The raw material extraction and manufacturing processes of XPS are the highest contributing modules, including emissions from electricity, natural gas and liquefied petroleum gas combustion, as well as blowing agent emissions from the trimming, cutting, and profiling of the XPS boards. The chart presented in Figure 7 adapted from One Click LCA to demonstrate the total GWP contribution related to the most impactful materials considered in this case study.

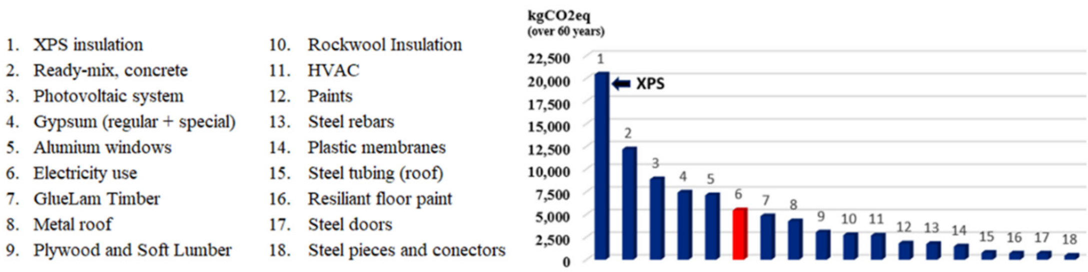

Figure 7. Life Cycle GWP contribution by material type (and energy use, in red), for baseline scenario, using One Click LCA.

3. The life cycle stage "replacement; refurbishment" (modules B4 and B5) also represents a relevant burden on the final LCA results. It contributes around 14,300 kgCO_2eq, representing 17% of the FBL's emissions, calculated using both softwares. The service life determines how long the product is in use before it is replaced. Foundation materials, for example, are never replaced. Insulation materials usually have a service life of 75 years, as defined in different EPDs, which is longer than the 60-years' service life assumed for the case studies in this paper. Equipment such as HVAC and PV have a shorter service life (20 to 25 year); taking the PVs as example, it carries embodied emission of around 3000 kgCO_2eq due to manufacturing processes (A1–A5), and 6000 kgCO_2eq more due to two events of replacement (at building age of 20 years and 40 years).
4. Default scenarios are assumed for End-of-Life stages. The default inputs are based on the processing chain defined in EPDs, or local common practice. In One Click LCA, it is possible to alternate those scenarios that impact the results for modules C2 to C4, and also for module D, if applicable. Examples of end-of-life treatments are landfill (for inert materials), wood incineration, plastic-based material incineration,

steel recycling, gypsum recycling, and glass-containing and metal-containing product recycling.

4.2. LCA Results: Single-Detached House

Following the same approach adopted in the first case study, the baseline scenario for the single-detached house also considers a 60-years' service life, and includes all life cycle stages, except for module D. As presented in Table 8, the total GWP calculated using One Click LCA is equal to 544,907 kgCO_2eq, and using Athena is equal to 566,856 kgCO_2eq. In terms of annual CO_2eq emissions per heated floor area (258 m^2), the results are 35.20 kgCO_2eq/m^2 (using One Click LCA) and 36.62 kgCO_2eq/m^2 (using Athena).

Table 8. LCA results for the single-detached house: Global warming potential (without contribution of trees).

Modules	Life Cycle Stages	One Click LCA kgCO_2eq over 60yr	Athena kgCO_2eq over 60yr
A1–A3	Material manufacturing processes	36,404.74	28,419.32
A4	Transportation to site	2845.62	2142.13
A5	Construction process	1968.34	1213.91
B4–B5	Replacement; Refurbishment	9812.94	9378.59
B6	Operational energy use	491,894/29,443 *	523,812/52,654 *
C1–C4	End-of-life (demolition; disposal; waste processing)	1981.08	1889.72
D	Benefits beyond building life (biogenic carbon in wood products)	−26,084.30	−25,736.74
Scenario 1	**Total Emissions (Modules A to C)—baseline scenario**	**544,907.34 (35.20)**	**566,856.35 (36.62)**
Scenario 2	**Total Emissions (Modules A to D)**	**518,823.04 (33.51)**	**541,119.61 (34.95)**
Scenario 3	**Total Emissions (Modules A to C)—natural gas converted to electricity**	**82,456.32 (5.32)**	**95,697.69 (6.18)**

* Emissions from module B6 (operational energy use) considering the setup where natural gas was converted to electricity.
Obs. 1: HVAC and Boiler are not available in Athena's database. Thus, for these two items, the values from One Click LCA were considered for Athena;
Obs. 2: Values between parenthesis (e.g., (35.20)) refers to the equivalent CO_2eq emissions results per m^2 of heated floor area per year.

The second scenario includes module D, benefits beyond a building's life, which brings benefits from the biogenic carbon stored in wood products. For this scenario, the GWP results are 518,823 kgCO_2eq with One Click LCA, and 541,119 kgCO_2eq with Athena. In terms of annual CO_2eq emissions per heated floor area, the results are 33.51 kgCO_2eq/m^2 (using One Click LCA) and 34.95 kgCO_2eq/m^2 (using Athena).

This case study house uses natural gas for heating and domestic hot water supply, which results in a high GWP related to the operational use stage (module B6), accounting for about 90% of total LCA carbon emissions, as shown in Figure 8. If we consider a gas-free setup (scenario 03, A to C), where the natural gas has been converted to an energy equivalent value for electricity, the house's total life cycle GWP calculated using One Click LCA results in 82,456 kgCO_2eq (5.32 kgCO_2eq/m^2.year), and using Athena, it results in 95,697 kgCO_2eq (6.18 kgCO_2eq/m^2.year).

Regarding the individual result of module B6 (operational energy use emissions) for this gas-free scenario, it drops from 491,894 kgCO_2eq to 29,443 kgCO_2eq (One Click LCA), and from 523,812 kgCO_2eq to 52,654 kgCO_2eq (Athena). Table 9 presents information about the calculation of operational emissions, and Figure 8 presents a comparison between the share of embodied and operational emissions for this situation.

This situation illustrates the importance of shifting to all-electric buildings in places like Quebec, Canada, where the electricity grid is based on renewable sources (i.e., hydro power). In Table 9, if we divide the total life cycle operational emissions related to the use of natural gas in the real scenario 01 by its equivalent (converted) value of electricity consumption in the gas-free scenario 03 (38,225 kWh/year, over 60 years), the results are around 0.211 kgCO_2eq emitted per kWh consumed (with One Click), and 0.223 kgCO_2eq/kWh with Athena. Those values are 10 to 20 times higher than the CO_2eq emissions per kWh from electricity, which are equal to around 0.0102 kgCO_2eq/kWh (One Click) and 0.0183 kgCO_2/kWh (Athena) in the case of Montreal.

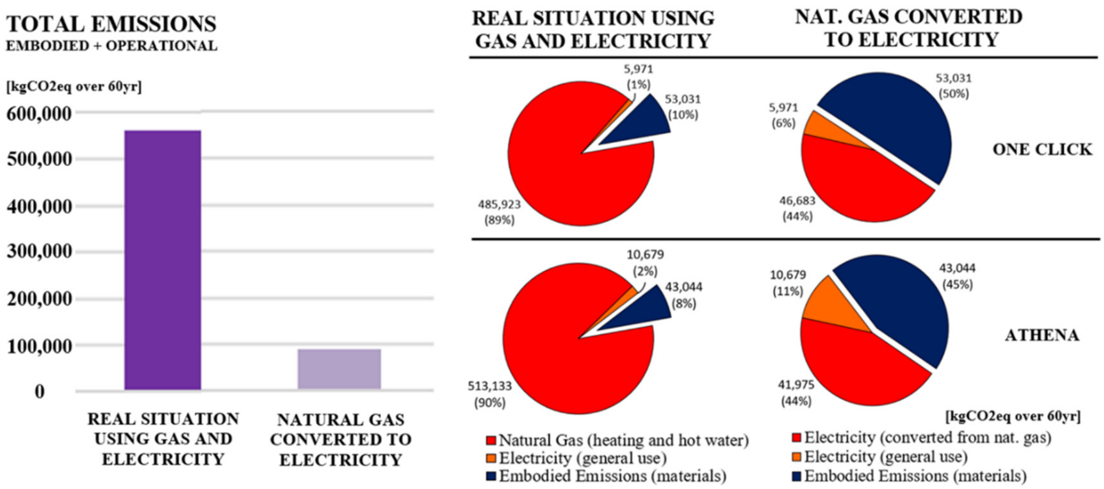

Figure 8. Comparison between real situation (scenario 1) and gas-free (scenario 3) for the single-detached house.

Table 9. Energy consumption and operational emissions for the Single-detached house (scenarios #01 and #03).

REAL SCENARIO 1 (electricity + natural gas)	Energy Consumption (Annual)	One Click LCA kgCO_2eq over 60yr	Athena kgCO_2eq over 60yr
Electricity	9725 kWh/year	5971	10,679
Natural gas	3561.3 m^3/year	485,923	513,133
Total Operational Emissions (module B6)		**491,894**	**523,812**
SCENARIO 3 (natural gas converted to electricity)			
Electricity	9725 kWh/year	5971	10,679
Electricity (from natural gas)	38,225 kWh/year	23,472	41,975
Total Operational Emissions (module B6)		**29,443**	**52,654**

Obs. 1: 1^3 of natural gas is equivalent to 10.7330 kW [67]
Obs. 2: Equivalent CO_2 emissions per kWh from electricity: 0.010234 kgCO_2eq/kWh (One Click) and 0.018302 kgCO_2eq/kWh (Athena)
Obs. 3: Equivalent CO_2 emissions per kWh from natural gas: 0.211869 kgCO_2eq/kWh (One Click) and 0.223734 kgCO_2eq/kWh (Athena)

4.3. Final Balance: Potential for Carbon Sequestration Using Urban Trees

Until this point, the results provided and discussed were about the LCA calculations, which did not include the potential of planting trees around the case study buildings to sequestrate CO_2 and reduce their carbon footprints.

The final balance is the difference between the total life cycle CO_2eq emissions (GWP) related to each building and the total CO_2eq captured by the trees in their respective gardens. If we consider that the garden areas (410 m^2 for the FBL, and 505 m^2 for the single-detached house) are fully covered by representative urban trees without canopy overlap, then the carbon sequestration potential at the FBL is equal to 235.7 $kgCO_2eq/year$ (annual sequestration rate of 0.575 $kgCO_2eq/m^2$ of tree cover area multiplied by 410 m^2 garden), and at the single-detached house is 290.3 $kgCO_2eq/year$ (0.575 $kgCO_2/m^2TC \times 505\ m^2$ of garden). Supposing that those trees will not grow or die, and that the annual sequestration rates will remain constant during the 60-years calculation period, the life cycle carbon sequestration potential of these gardens is equal to 14,145 $kgCO_2eq$ for the FBL, and 17,418 $kgCO_2eq$ for the single-detached house.

In the case of the FBL's baseline scenario 01 (modules A to C), the final balance resulted in
69,377 $kgCO_2eq$ (One Click) and 68,521 $kgCO_2eq$ (Athena). Therefore, this set of representative urban trees has the potential to offset 16.9% and 17.1% of the FBL's total life cycle emissions calculated using One Click LCA and Athena, respectively.

When we apply those potentials to the baseline scenario of the single-detached house (which has natural gas as part of its energy source), the CO_2 removals from the trees can offset only 3.2% of the total emissions (One Click LCA), and 3.1% (Athena). However, if we consider the alternative setup for the single-detached house (scenario 03) where natural gas is converted to an energy equivalent value of electricity, the carbon removals from the trees would have the potential to offset 21.1% of the total emissions (One Click LCA results), and 18.2% for Athena. The results for those and other scenarios are presented in Table 10.

Table 10. Summary of results and contribution of trees on reducing buildings' life cycle carbon emissions.

	Total Emissions (without trees) $kgCO_2eq$ over 60yr		Total CO_2 Sequestration * $kgCO_2eq$		Final Carbon Balance (with trees) $kgCO_2eq$ over 60yr		Trees Contribution [%]	
	OneClick	Athena	per year	over 60y	One Click	Athena	One Click	Athena
FUTURE BUILDINGS LAB								
Scenario 01 (A to C)-baseline	83,522	67,531	235.7	14,145	**69,377**	**68,521**	16.9%	17.1%
Scenario 02 (A to D)	47,636	39,977			**33,491**	**40,968**	29.7%	25.7%
SINGLE-DETACHED HOUSE								
Scenario 01 (A to C)-baseline	544,907	566,856	290.3	17,418	**527,489**	**549,438**	3.2%	3.1%
Scenario 02 (A to D)	518,823	541,120			**501,405**	**523,702**	3.4%	3.2%
Scenario 03 (A to C) - gas-free	82,456	95,698			**65,038**	**78,280**	21.1%	18.2%

* Calculated using annual CO_2 sequestration rate of 0.575 $kgCO_2eq/m^2TC$, garden areas of 410 m^2 (FBL) and 505 m^2 (Single-detached house), and 60-year time horizon.

Alternatively, in a scenario where only the operational use stage is considered (module B6), the relative contribution provided by the trees would be much more effective applied to cases of all-electric buildings. For places like Quebec, with the energy grid generation based on renewable sources, it would be feasible to achieve carbon neutrality by including urban trees around buildings.

As shown in Table 11, in the FBL, the operational use stage is responsible for 5445 $kgCO_2eq$ emissions (calculated using One Click) and 9737 $kgCO_2eq$ (using Athena), while the total potential of the trees to sequestrate carbon is 14,145 $kgCO_2eq$. Therefore, carbon neutrality of the operational use stage would be achieved, resulting in a balance equal to –8700 $kgCO_2eq$ (One Click) and –4408 $kgCO_2eq$ (Athena).

For the detached house (gas-free scenario), the operational use stage is responsible forFor the detached house (gas-free scenario), the operational use stage is responsible for 29,443 kgCO_2eq emissions (One Click) and 52,654 kgCO_2eq (Athena), while the total carbon sequestration potential due to the garden full of trees is 17,418 kgCO_2eq. Therefore, the balance would be 12,025 kgCO_2eq (One Click) and 35,235 kgCO_2eq (Athena). Although this is not enough to offset 100% of the operational use stage emissions, it can contribute towards reducing 59% and 33% of operational emissions, considering One Click and Athena's results. It is important to remember that the FBL is a state-of-the-art construction, projected with a focus on energy performance, while the single-detached house is a typical construction from the 1960s with several issues of air leakage. Renovation strategies would be required to improve the final carbon balance. 29,443 kgCO_2eq emissions (One Click) and 52,654 kgCO_2eq (Athena), while the total carbon sequestration potential due to the garden full of trees is 17,418 kgCO_2eq. Therefore, the balance would be 12,025 kgCO_2eq (One Click) and 35,235 kgCO_2eq (Athena). Although this is not enough to offset 100% of the operational use stage emissions, it can contribute towards reducing 59% and 33% of operational emissions, considering One Click and Athena's results. It is important to remember that the FBL is a state-of-the-art construction, projected with a focus on energy performance, while the single-detached house is a typical construction from the 1960s with several issues of air leakage. Renovation strategies would be required to improve the final carbon balance.

Table 11. Carbon balance considering only operational use stage.

	Operational Emissions (Module B6) kgCO_2eq over 60yr		Total CO_2 Sequestration kgCO_2eq over 60yr	Carbon Balance (Operational Stage) net kgCO_2eq		Trees Contribution [%]	
	One Click	Athena	From Trees	One Click	Athena	One Click	Athena
Future Buildings Laboratory	5445	9737	14,145	**−8700**	**−4408**	260%	145%
Single-detached House *	29,443	52,654	17,418	**12,025**	**35,236**	59%	33%

* Considering the scenario where natural gas has been converted to energy equivalent value of electricity.

Although it might not be possible to reach a net-zero carbon balance by just considering the direct carbon sequestration potential of trees when accounting for total life cycle emissions (embodied and operational), our estimations disregarded many benefits related to the use of vegetation around buildings. For example, the effect of greeneries on moderating the local microclimate and their indirect contribution to reducing heating and cooling loads, and therefore providing energy savings, were out of the scope of this paper. Regarding the LCA calculations, several premises aiming at conservative results were adopted. The biogenic carbon stored in wood products and their benefits beyond building life (module D) were not accounted for in the baseline scenario; the environmental impact related to manufacture and replacements of the PV system in the FBL was included in the LCA calculations, but the system is currently used for research purposes only, and the electricity generation as a renewable energy source was not counted yet. There is also available space to install a green roof, providing additional direct carbon sequestration.

4.4. Aditional Scenarios and Directions for Future Work

As presented in Table 12, we used the LCA results from the FBL's baseline scenario (83,522 kgCO_2eq calculated with One Click) to demonstrate a complete set of strategies that could be considered in order to reach a net-zero carbon balance. The complete set includes biogenic carbon in wood products, urban trees planted around the building, on-site PV generation, and a green roof.

As discussed, in the FBL, the biogenic carbon in wood products could reduce the final GWP by 35,885 kgCO_2eq over 60 years (see Table 7). In addition to that, the carbon sequestration potential of a garden full of urban trees could offset an additional 14,145 kgCO_2eq over 60 years (see Table 10). In addition, we can roughly estimate the annual on-site electricity generation related to the PV system that is already installed on the façade, and calculate the respective CO_2eq emissions displaced from the energy grid. Based on solar data from NRC [69], the estimated photovoltaic potential (kWh/kWp) considering vertical panels under southern Quebec's climate conditions is equal to 873 kWh/kWp. The 15 m^2 PV system on FBL's façade has an installed capacity of 1.6320 kWp, which means that it can produce up to 1425 kWh/year. In One Click LCA, each kWh of electricity generated in Quebec incurs 0.010234 kgCO_2eq emissions; therefore, over 60 years, the PV system would be able to offset an additional 875 kgCO_2eq. Finally, if we also include in our approach a properly fertilized and irrigated green roof of 130 m^2 removing 25.8 kgCO_2eq/m^2 per year for 10 years, as reported by Luo et al. [32], this solution could offset an additional 33,540 kgCO_2eq.

Table 12. CO_2 offset from additional strategies in FBL (kgCO_2eq over life cycle).

Benefits beyond building's life (Biogenic carbon in wood products)			35,885		
Garden fully covered by urban trees			14,145		
1.63 kWp vertical PVs system electricity generation			875		
130 m^2 irrigated and fertilized green roof *			33,540		
Total emissions offset			**84,445**		
Final balance with addition solutions:	**** 83,522**	**–**	**84,445**	**=**	**– 893**

* For the green roof, a 10y calculation period was assumed, since this kind of vegetation may have a shorter life cycle.
** See Table 7.

Putting all these CO_2eq removals together, the total offset would be equal to 84,445 kgCO_2eq. Thus, the final carbon balance applied to the FBL's baseline scenario would result in (–) 893 kgCO_2eq, which means that carbon neutrality could be achieved for this scenario.

5. Conclusions

This paper presents a framework and general approach, applied to real case studies, to address the feasibility of planting trees around buildings as a nature-based solution to achieve carbon neutral buildings using life cycle carbon analysis. This work shows that, for those buildings that still consume fossil fuels (such as the single-detached house), or for those places where the electricity grid is not yet based on renewable sources, it is not feasible to reach carbon neutrality considering just the sequestration potential of trees. However, in the case of all-electric buildings (such as the FBL), it has been shown that this solution could mitigate 16.9% to 17.1% of the building's life cycle carbon emissions without considering on-site electricity generation.

Based on the analysis of the different scenarios and assumptions presented in this paper, it seems to be possible to achieve a carbon balance closer to net-zero when expanding the strategies with approaches including other types of green solutions and on-site electricity generation. Coupling those strategies with the indirect benefits of vegetation (i.e., energy savings), the use of nature-based materials, and the use of recyclable/reusable materials is definitely a consistent pathway towards the design and operation of carbon neutral buildings.

The analysis presented in this work has also shown that LCA studies can be very sensitive to decisions made during the calculation process, although LCA results are still very useful for indicating the relative importance of a process in the different life cycle stages, or for estimating the expected magnitude of the impacts related to a specific material. The framework developed in this paper will be applied to investigate the contribution of urban greeneries to carbon neutral buildings and neighborhoods including both new constructions and retrofits for various building types in our future work.

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