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Published in:
Environmental Research: Infrastructure and Sustainability

DOI (link to publication from Publisher):
10.1088/2634-4505/ad2153

Publication date:
2024

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Meyer, F., Elliot, T., Craig, S., & Goldstein, B. (2024). The carbon footprint of future engineered wood construction in Montreal. *Environmental Research: Infrastructure and Sustainability*, *4*(1), Article 015012. https://doi.org/10.1088/2634-4505/ad2153

ENVIRONMENTAL RESEARCH
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To cite this article: Felicity Meyer *et al* 2024 *Environ. Res.: Infrastruct. Sustain.* **4** 015012

IOP Publishing Environ. Res.: Infrastruct. Sustain. 4 (2024) 015012 https://doi.org/10.1088/2634-4505/ad2153

ENVIRONMENTAL RESEARCH
INFRASTRUCTURE AND SUSTAINABILITY

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OPEN ACCESS

RECEIVED
2 August 2023

REVISED
1 January 2024

ACCEPTED FOR PUBLICATION
22 January 2024

PUBLISHED
14 March 2024

PAPER

The carbon footprint of future engineered wood construction in Montreal

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Keywords: building material stock, embodied carbon, life cycle assessment, engineered wood, mass timber, concrete

Supplementary material for this article is available online

Abstract

Engineered wood (EW) has the potential to reduce global carbon emissions from the building sector by substituting carbon-intensive concrete and steel for carbon-sequestering wood. However, studies accounting for material use and embodied carbon in buildings rarely analyse the city-scale or capture connections between the city and supplying hinterlands. This limits our knowledge of the effectiveness of decarbonising cities using EW and its potential adverse effects, such as deforestation. We address this gap by combining bottom-up material accounting of construction materials with life cycle assessment to analyse the carbon emissions and land occupation from future residential construction in Montreal, Canada. We compare material demand and environmental impacts of recent construction using concrete and steel to future construction using EW at the neighbourhood, urban scales under high- and low-density growth scenarios. We estimate that baseline embodied carbon per capita across the Agglomeration of Montreal is 3.2 tonnes per carbon dioxide equivalents (CO_2eq.), but this ranges from 8.2 tonnes CO_2eq. per capita in areas with large single-family housing to 2.0 tonnes CO_2eq. per capita where smaller homes predominate. A Montreal-wide transition to EW may increase carbon footprint by up to 25% under certain scenarios, but this varies widely across the city and is tempered through urban densification. Likewise, a transition to EW results in less than 0.1% land transformation across Quebec's timbershed. Moreover, sustainable logging practices that sequester carbon can actually produce a carbon-negative building stock in the future if carbon in the wood is not re-emitted when buildings are demolished or repurposed. To decarbonise future residential construction, Montreal should enact policies to simultaneously promote EW and denser settlement patterns in future construction and work with construction firms to ensure they source timber sustainably.

1. Introduction

Constructing and operating buildings directly and indirectly produces 40% of global greenhouse gas (GHG) emissions [1]. Much of this activity is in cities where most people and economic activity reside. This makes cities key nodes in decarbonising the building sector globally. Decisions surrounding the construction of new buildings and neighbourhoods in cities are critical to this effort as they heavily influence both the GHG emissions embodied in construction and shape future patterns of energy use and emissions for decades or longer [2]. Urban designers, policy makers, and researchers urgently require guidance on how to both assess [3] and reduce embodied emissions and to avoid carbon lock-in in future urban construction [4].

Modern construction has been dominated by a handful of building materials, including concrete, steel, and wood, among others. Concrete has been a default choice within the building construction industry for its affordability and mechanical properties (e.g. fire resistance, durability, compressive strength, workability) [5] and is widely used throughout commercial, industrial, and residential buildings for both structural (e.g.

foundations, slabs, load bearing walls, etc) and aesthetic purposes [6]. Concrete accounts for 8% of global GHGs due to the release of carbon dioxide during calcination and energy use during production [7, 8]. Recent studies estimate that global concrete production alone generated 1.5–2.6 Gt of carbon dioxide equivalents (CO_2eq.) [5, 9, 10].

After concrete, steel is the most used material in construction. Steel represents <1%–25% of residential building mass and provides framing and structural stability, particularly in high rises [11–16]. Approximately 1.5 Gt of steel are produced annually, accounting for 9% of global CO_2 emissions [17]. Primary steel is produced mainly using the basic oxygen furnace method, followed by the electric arc furnace method. The only large producers to utilise the open-hearth method as part of their operations included Russia and India, which produce 22.1% and 2.4% of global steel, respectively [11–16].

Recently, there has been a broad push in the construction sector to use wood as a low-GHG substitute for concrete and steel [18–20]. Substitution typically occurs in the form of engineered wood (EW) products that have structural, fire, acoustic and thermal properties suitable for tall buildings (i.e. $\geqslant$5 stories). Unlike steel and concrete, producing wood sequesters carbon via photosynthesis [21]. If harvested in a way that maintains soil and ecosystem health, wood can be very-low carbon or even act as a carbon sink if carbon captured by photosynthesis is mostly kept out of the atmosphere. By some estimates, replacing conventional materials with wood decreases embodied carbon by 216 kg CO_2eq. m^{-2} building [22]. Likewise, Churkina *et al* found that a timber structured five story residential building may store up to 186 kg of carbon m^{-2} [23], with other groups noting a three-times savings in emissions when substituting EW for other materials [24]. Others have found that one tonne of wood replaces 0.59 and 4.54 tonne of steel and concrete [25], respectively with considerable reductions in carbon, even when considering increased mass requirements compared to steel.

Despite some findings pointing towards the low-GHG emission potential of wood in future urban construction, knowledge gaps remain. For example, a bevy of recent studies examine existing material stocks of cities and emissions embodied in construction, but few consider the future material needs of cities using EW at scale [11, 13, 15, 16, 26–30]. Thus, we do not know how much wood future cities need to substitute for steel and concrete nor how much this will shift embodied carbon emissions from business-as-usual (BAU) construction. Moreover, there has been a tendency in the literature to focus on the carbon capture benefits of EW, with limited consideration of knock-on effects [31–33], such as land use impacts, impaired ecosystems functioning to supply massive volumes of timber, or improving forest ecosystem resilience by specifying functional traits and alternative species in EW [34]. Importantly, how life cycle assessment (LCA) accounts for biogenic carbon sis contested among researchers. Nonetheless, LCA can provide a useful insights into the potential benefits of storing carbon within the built environment [35]. These considerations as a whole result in a complex landscape of pros and cons when it comes to building with EW.

Here, we begin addressing these knowledge gaps through a case study of Montreal, Canada. We perform a bottom-up material accounting of Montreal's existing modern residential construction (post-1960). We then model future material demands under different development scenarios. Our scenarios consider both construction materials used (BAU vs. EW) and the settlement patterns of future urban growth (current patterns vs. strategic densification). We combine material accounting with LCA to estimate the carbon footprint of our scenarios (accounting for all relevant GHGs). To understand how the assumption that wood sequesters carbon influences the results, we perform our analysis with and without biogenic carbon. Lastly, we consider the land requirements to supply timber, gauging the viability of EW to support urban growth in a large city.

Montreal, and Canada broadly, provide an interesting backdrop to study widespread EW. Canada is home to the planet's second largest Boreal forest and a productive forestry sector. The Province of Quebec, where Montreal is located, has an immense logging industry and large EW producers. The use of EW in Canada is on the rise, with nearly 700 recent projects ongoing or completed, many in Quebec. Montreal has also committed to reducing the embodied GHGs of new buildings through the use of renewable building materials [36]. Given the continuing shift towards EW and the tendency for local wood supply in Quebec, it is essential to appraise the effectiveness of this shift in achieving the city's sustainable construction goals and to understand how it effects the landscapes that supply construction materials [37].

Our model suggests that as Montreal grows over the next two decades, a transition to EW construction would require a relatively small area of Quebec's total forestland (<1%) and could help reduce embodied emissions from construction of some neighbourhoods across the Montreal Agglomeration. Emissions reductions, however, depend on sustainable forestry practices, underscoring the need for researchers to better understand forest GHG dynamics [38] and the relationship between EW species selection and ecosystem resilience [34]. Urban densification (UD) can further reduce emissions under most scenarios including when concrete and steel use remain significant. Prioritising UD and building smaller homes using EW that are designed to fit the existing built form can work synergistically to abate emissions from the construction sector and help Montreal achieve its decarbonisation goals.

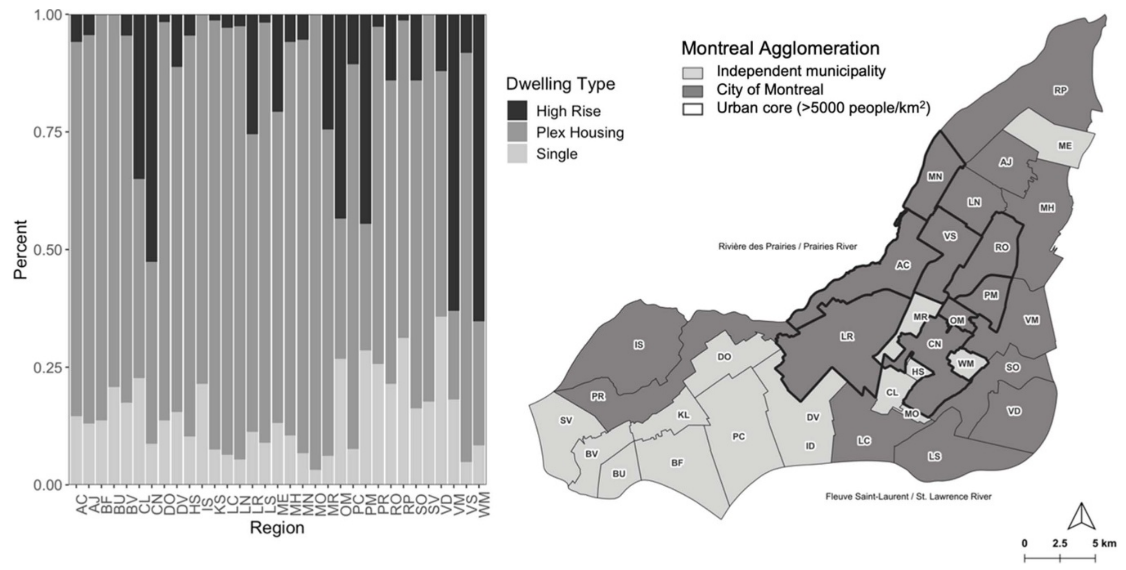

Figure 1. Administrative limits across the Montreal Agglomeration floor area distribution of housing typologies (left) and floor area per capita (FAC) of post-1960 dwellings (right). Municipalities and arrondissements are abbreviated as: Ahuntsic-Cartierville (AC), Anjou (AJ), Baie-D'Urfé (BU), Beaconsfield (BF), Côte-des-Neiges-Notre-Dame-de-Grâce (CN), Côte-Saint-Luc (CL), Dollard-Des Ormeaux (DO), Dorval (DV), Hampstead (HS), Kirkland (KL), L'Île-Bizard-Sainte-Geneviève (IS), Lachine (LC), LaSalle (LS), Le Plateau-Mt-Royal (PM), Le Sud-Ouest (SO), Mercier-Hochelaga-Maisonneuve (MH), Mont-Royal (MR), Montréal-Est (ME), Montréal-Nord (MN), Montréal-Ouest (MO), Outremont (OM), Pierrefonds-Roxboro (PR), Pointe-Claire (PC), Rivière-des-Prairies-Pointe-aux-Trembles (RP), Rosemont-La Petite-Patrie (RO), Saint-Laurent (LN), Saint-Léonard (LR), Senneville (BV), St-Anne-de-Bellevue (SV), Verdun (VD), Ville-Marie (VM), Villeray-Saint-Michel-Parc-Extension (VS), Westmount (WM).

2. Methods

Our model estimates trends in concrete, steel, and wood use in recent residential construction in Montreal. We use these estimates in scenarios to forecast the mass of materials needed to satisfy new construction to the year 2040 and the GHG emitted from producing and transporting those materials. Below we detail our case city, Montreal, our data sources, and modelling framework.

2.1. Case city: Montreal

Montreal is the second largest city in Canada with 3.7 million people living in the metropolitan area [39]. Our analysis focuses on the Montreal Agglomeration (figure 1) which has 2.0 million inhabitants on an island nestled between the St. Lawrence and Prairie Rivers. The agglomeration contains the City of Montreal (pop. 1.8 million) which is comprised of 19 *arrondissements* (i.e. municipalities/neighbourhoods), along with 14 independent municipalities spread across the rest of the agglomeration [40, 41].

The Montreal Agglomeration contains a diverse range of development patterns with a distinct urban core and swathes of suburban housing in the periphery. The urban core is dominated by duplex and triplex multi-family units from the 19th and early 20th century, and apartment blocks of varying ages including dense clusters of modern high-rises in Ville-Marie, Westmount, and Côte-des-Neiges-Notre-Dame-de-Grâce. Single-family households are most common in the surrounding suburbs. We focus on post-1960 residential housing in Montreal in our model to capture fundamental alterations to the urban form that occurred after automobiles proliferated and to have material inventories after the widespread adoption of concrete. The proportion of the population in post-1960 housing ranges from 100% in suburban Kirkland to 16% in Montreal-Ouest. Figure 1 shows the existing breakdown of housing types in post-1960 housing across the agglomeration's municipalities and arrondissements, their geographical distribution across the agglomeration, as well as high-density areas (>5 000 people km^{-2}). There is a clear tendency towards single family homes and larger floor area per capita outside the urban core with the exception of wealthy enclaves (e.g. Westmount).

2.2. Montreal building data

Our model analyses each residential building constructed after 1960 in the Montreal Agglomeration to estimate the concrete, steel, and wood stocks in these buildings. We use tax assessments pulled from the Montreal Property Assessment Database [42] to gather data on each building on the agglomeration for the year 2021. These data contain the age, use (e.g. residential, commercial, etc), floor area, building type (e.g.

residential, industrial, commercial, cultural etc), and other information relevant to estimating building material stocks. Duplicate entries and pre-1960 buildings are removed in R statistical software. Entries lacking data on year built (2.1% of entries) are not included except for reporting agglomeration-wide statistics. To isolate residential buildings, we filter for 'logements' (residential) uses, and remove dorms, nursing homes, and other non-traditional dwellings which account for a negligible share of housing.

Some tax entries have extremely large floor-areas (>5 000 m^2). Most of these entries are multi-unit buildings. To check for accuracy, we divide the total floor area by the number of units across the entire dataset. We remove entries with floor area greater than 1 500 m^2 $unit^{-1}$ or below 10 m^2 $unit^{-1}$. These thresholds align with the realistic range of floor areas one would find for homes and apartments in Montreal, and with legal requirements for minimum floor area [43]. Spot checks using Google Streetview were used to validate this assumption. After removing outliers, our final dataset contains 148 640 residential units across the agglomeration (see [41] for the distribution across the agglomeration).

2.3. Estimating concrete, steel, wood, and floor area per capita

To estimate tonnes of concrete, steel, and wood for each entry, we combine floor area and building type from publicly available tax-assessor data with a construction classification database that provides material intensity per square metre for different housing typologies [9]. Each entry was classified as one of three typologies: single detached, semi-detached housing (single through quadruplex), and high-rise apartments five stories and higher. Building typologies were developed based on previous work by Guven *et al* [9] assessing buildings in Toronto, Canada. As no published studies exist for Montreal, modern construction in Toronto is deemed an appropriate substitute. We note that although historic construction differs between the two cities (Montreal's iconic duplex style housing prevalent in neighbourhoods such as Le Plateau, for example), but post-1960 construction in both cities is similar in form and materials.

Guven *et al* scored data quality from 1 to 5. We use only top two tiers (1 and 2), though sensitivity analysis showed that excluding lower tier data had minimal effect on results. Materials in single-family homes are estimated based on the average material density/square metre of detached houses and renovated detached houses in the dataset ($N = 40$). Plex housing material estimates are based on the average of semidetached, renovated semidetached, townhouses, and laneway houses in the model ($N = 13$). No adjustments are made for high-rise apartment buildings compared to the model ($N = 8$), though it should be noted that all buildings taller than five stories are considered 'high-rise' which introduced some variability within this building typology. Each entry in construction database includes material contributions throughout the entire building, including underground parking and foundation. While buildings contain other materials (e.g. glass, masonry, etc) concrete, steel, and wood are the most significant by mass and provides an appropriate scope for assessing embodied emissions. Materials are reported in tonnes m^{-2} to compare material intensity across building types, though we recognise that household sizes may vary across both buildings and arrondissements, thus affecting per capita material and GHG impacts, which we believe more accurately capture the Montreal Agglomerations impact at the neighbourhood scale. The average number of residents was also estimated and are accounted for in densification scenarios (i.e. no change to floor area per capita (FAC) for BAU and decreased FAC for UD scenarios).

The number of people living in post-1960 construction in each neighbourhood is estimated as the product of the average number of inhabitants/dwelling times the number of post-1960 dwellings. The FAC is taken as the total square metres of floor area of post-1960 divided by our estimate of people living in post-1960 construction. The FAC in post-1960 construction is 10% lower than FAC for all buildings, indicating a decrease in floor area in newer construction. To adjust for the population living in post-1960 dwellings, we estimate the number of inhabitants per dwelling and then calculate the ratio of pre- and post-1960 housing (see supplementary information (SI) calculations). These calculations are made at the arrondissement level. Adjusted population is used in all relevant per capita calculations below (e.g. tonnes of CO_2eq. per capita).

2.4. Embodied GHG estimation

GHG intensity for concrete, steel, and wood are taken from the ecoinvent 3.8 database (www.ecoinvent.org) in openLCA (www.openlca.org) using the cut-off modelling framework [44, 45] and economic allocation between co-products. Cut-off models exclude the secondary impacts of recycled goods, which are accounted for in their initial production. We use the IPCC 100a method to estimate global warming potential (GWP) in kg CO_2eq. We also run a scenario using IPCC 100a method with biogenic carbon uptake to assess the implications of this inclusion the carbon calculus. Relevant GHG flows used for total GHG equivalent can be found in SI calculations. GHG emissions factors for different building materials are shown in table 1 (see table S1 in SI for full list of factors and ecoinvent processes). We assume materials are produced in Quebec.

Table 1. Upstream emission factors for primary construction materials calculated from ecoinvent [44].

Material	ecoinvent process	GWP100 (CO_2eq. kg^{-1})	GWP100 including biogenic (CO_2eq. kg^{-1})
Concrete	Concrete, average all densities, CA-QC	0.12	0.13
Steel	Steel, low-alloy, CA-QC	0.81	0.81
Wood	Softwood beam, average of kiln and air dried, CA-QC	0.18	−3.08
EW	Glue laminated timber (GLT), CA-QC	0.30	−2.56

This is a reasonable assumption given that concrete is often produced close to construction sites, and because Quebec is a significant producer of steel and wood [46].

Transport distance is determined using a distance matrix function in QGIS (www.QGIS.org) from the last point of material production to a centroid point of the agglomeration of Montreal. For instance, the ArcelorMittal mine at Fire Lake sits approximately 900 km from Montreal; likewise, end stage EW producer Nordic Structures is 500 km away. Distances were determined without road network analysis. Where the amounts of a material produced at different sites are known (e.g. tonne of steel/producer), weighted average distances are used, otherwise, we use unweighted averages. For concrete and steel, we identify where quarries are located through the Government of Canada's Principal Mineral Areas, Producing Mines, and Oil and Gas Fields dataset [46]. Production quantities are obtained through industry reports [47], press releases [48–51], and global steel tracking databases [52, 53]. Forestry activity was reported in Canadian governmental reports [54]. EW producers and project data is collected using the Canadian State of Mass Timber map and report [55].

Specific end-of-life scenarios are not included in the model due to the long lifespan of buildings. While there is increasing interest in the circular construction economy both by academics [56–58] and practitioners [59], future waste treatment options are highly uncertain. End-of-life assumptions built into this model, both positive and negative, would be strictly conjecture, though potential waste management possibilities and costs and benefits of the materials included in this study are discussed. Emission factors for the upstream primary building materials is shown in table 1.

2.5. Biogenic GHG estimation

While GHG emissions, such as those from burning fossil fuels, are the primary focus of this study, biogenic scenarios are also assessed as a prospective scenario, as carbon uptake is particularly important for wood product life cycle considerations. To account for biogenic carbon, we include the biogenic carbon inventories in the ecoinvent processes in our model.

Over the long-term, biogenic carbon in construction is often considered GWP-neutral if a simplistic view of forest carbon stocks is taken (e.g., ignoring post-harvest changes to belowground carbon stocks). This is because the carbon dioxide sequestered and stored in timber materials is eventually released back to the atmosphere. This release can happen due to incineration or decomposition, or a combination of these through transformation processes [60]. The fate of timber products can have an important effect on the GWP of their life cycles. For example, if the timber decomposes and is released as methane, thereby having a stronger GWP at end-of-life than that of the CO_2eq. which was sequestered during the forest growth stage. Alternatively, the timber may be incinerated to substitute fossil energy or repurposed for feedstock in other energy transition sectors [61], thereby offsetting GHG emissions. While these factors make the end-of-life stage critical to understanding the net biogenic contribution to the GWP of forest-based building materials, there are multiple unknowns pertaining to future recycling, reuse, and circularity of building materials. As such, the biogenic carbon estimation in this study does not account for end-of-life flows.

2.6. Land impacts

Land impact (taken as the sum of transformation and use inventories) for concrete, steel, and wood are taken from the ecoinvent 3.8 database (www.ecoinvent.org) in openLCA (www.openlca.org) using the cut-off modelling framework [44, 45] and economic allocation between co-products. Land inventory data for each material are found in table 1 (SI calculations). Again, we assume materials are produced in Quebec and report both land use and land transformation in km^2. We also report the per cent of land transformed based on the total area of Quebec's third-party certified forested land.

2.7. Scenarios of future construction in Montreal

Using four scenarios, we forecast how changing materials and urban form impact embodied carbon and land transformation to the year 2040.

Table 2 details each scenario. BAU models current building material profiles for dwellings typologies and settlement patterns (i.e. distribution of housing types and FAC) for each arrondissement or independent

Table 2. Material and settlement patterns for four Montreal development scenarios through 2040.

Scenario	Models	Material profile and settlement pattern	ecoinvent processes
BAU–BAU	Embodied GHG Biogenic GHG Land Use	• Material usage remains BAU • Settlement pattern remains BAU	• Concrete, average all densities, CA-QC • Steel, CA-QC • Softwood beam, average of kiln and air dried, CA-QC • Freight lorry, EURO6
BAU–UD	Embodied GHG Biogenic GHG Land Use	• Material usage remains BAU • Settlement pattern transitions to UD	
EW-BAU	Embodied GHG Biogenic GHG Land Use	• Material usage transitions to EW • Settlement pattern remains BAU	• Concrete, average all densities, CA-QC • Steel, CA-QC • Softwood beam, average of kiln and air dried, CA-QC • Glue laminated timber (GLT), CA-QC • Freight lorry, EURO6
EW-UD	Embodied GHG Biogenic GHG Land Use	• Material usage transitions to EW • Settlement pattern transitions to UD	

municipality. For EW material scenarios, bills of materials m^{-2} (gross floor area) are developed based on literature which tracked cross-laminated timber and glue-laminated timber (Glulam/GLT) EW based apartment/high-rise style buildings [11, 13–16]. Changes in material use are reported for the entire building and do not clarify specific modifications. This allows us to estimate changes on a square metre basis but precludes deeper analysis of what design decisions led to replacement of steel and concrete with EW. Data was primarily reported in total m^3 of EW, though kg or tonnes material was also reported. All quantities are converted from m^3 to total tonne. The average material tonne m^{-2} of EW quantities are applied to apartments five stories and higher. For our model, we use Quebec produced GLT as our standard EW material substitute. Single family homes and plexes (i.e. duplex, triplex, etc) are constructed largely of wood and concrete in Montreal; these are estimated to be built using current light frame timber methods which utilises very little steel. EW low-rise and single-family construction exists but is uncommon and not considered here.

For UD scenarios, we identify *high-density* areas of the city and use these as a template for future development in Montreal. We define high-density as areas above 5 000 person km^{-2}, which corresponds to thresholds for supporting transit-oriented development, walkability, and other urban synergies. For existing high-density neighbourhoods, we assume development as is. For *low-density* areas, the average FAC and built form (taken as mix of housing types) in the high-density areas are used for future growth. See the SI for details on material intensities for the EW scenarios and the morphological characteristics for the UD scenarios across the agglomeration.

Additional floor area needs by housing type are determined using population projections published by the Government of Quebec [40] and average FAC needs based on development scenarios. Population projections for independent municipalities across the agglomeration are reported individually, however, the City of Montreal is reported as a whole. Some areas of the Montreal Agglomeration are projected to lose population between 2021 and 2040 (i.e. Baie-D'Urfé, Dollard-Des Ormeaux, Dorval, L'Île-Bizard-Sainte-Geneviève, and Westmount) [40]; in these cases, additional floor area requirements are assumed zero.

3. Results

The material impacts of developing Montreal are significant and substantial. Our model of material stock embodied carbon in Montreal's residential building stocks shows that both material and GHG intensity varies significantly between different building types. These differences translate into significant spatial variation in embodied emissions across Montreal Agglomeration. In general, material scenarios which increased densification had the lowest total impact when biogenic carbon is excluded. Development scenarios which prioritised densification resulted in lower intensity per capita across many of the agglomerations neighbourhoods and municipalities than BAU. Changes to baseline impacts are lowest in neighbourhoods that already fit ideal material and/or density scenarios. For BAU, the carbon footprint of Montreal is 3.2 tonnes CO_2eq. per capita. For BAU–UD this decreases to 2.7 tonne CO_2eq. per capita but increases to 8.8 and 5.8 tonnes CO_2eq. per capita when considering EW-BAU and EW-UD scenarios, respectively. Below we discuss these findings in detail and how supplanting wood for steel and concrete would affect the environmental impacts of future construction in the city. Calculations and results for all scenarios can be found in the SI.

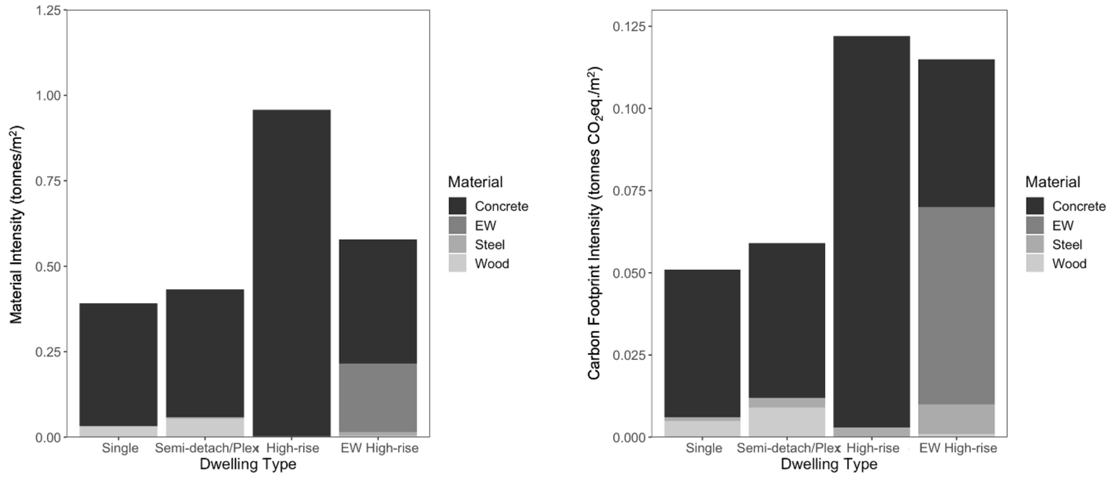

Figure 2. Total material quantity in tonnes m^{-2} across housing typologies (left). Embodied GHG intensity in tonnes m^{-2} across housing typologies (right).

3.1. Material and embodied carbon impact across building types

Figure 2 shows the tonne of different materials m^{-2} and tonnes of CO_2eq. m^{-2} of each dwelling type (excluding biogenic uptake). High-rise apartments (i.e. ^{3}5 stories) are the most material and GHG intensive of the building typologies. They require 0.96 tonnes m^{-2} of material, almost entirely in the form of concrete (99.7% by mass). Material intensity is much lower for both plex (0.43 tonnes m^{-2}) and single-family (0.39 tonnes m^{-2}) dwellings relative to high-rises. The material composition is also different for these housing forms; wood accounts for 12.5% of materials in plexes and 7.9% in single-family homes, though concrete still accounts for nearly 90% in both types (86.6% and 91.2% in plex and single-family structures, respectively). For high-rises, switching to EW reduces total material intensity by 60.5% to 0.58 gross tonnes m^{-2} and cuts the share of concrete to 62.7% of the EW building's mass. The primary material difference is the quantity of concrete required when switching to EW high-rise construction, which required 62% less concrete and 77% less steel than a standard high-rise. For light frame timber in standard to EW high-rises, a 14% increase was observed.

The high GHG intensity of concrete translates directly into high GHG footprints for high-rises. This housing type has 0.121 tonnes CO_2eq. m^{-2}, twice as carbon intensive of semi-detached (0.06 tonnes CO_2eq. m^{-2}) and single-family dwellings (0.05 tonnes CO_2eq m^{-2}). Interestingly, while current high-rise apartments require more concrete and steel/unit area compared to EW construction, their GHG intensity is only marginally higher than EW alternatives due to the high embodied carbon of EW products (0.115 tonnes CO_2eq. m^{-2}). Strikingly, while the material mass is greatly reduced with EW, this does not translate into significant GHG savings when biogenic emissions are not considered. Though EW construction reduces material needs by about 25% compared to standard concrete and steel construction, minimal GHG savings are observed, as shown below in figure 2.

While switching the EW materials may appear an obvious solution to GHG intensive construction materials like concrete and steel, high-rise construction requires inherently large quantities of materials for structural integrity on floor area m^{-2} basis. Thus, investigation into housing typology is a necessary second step to optimise low-carbon development in the urban context.

3.2. Material intensity across the agglomeration

Figure 3 shows the tonnes per capita of concrete (top left), steel (top right), and wood (bottom) across the agglomeration. In terms of combined material intensity, the top three areas of the agglomeration are Senneville (49.2 tonnes per capita), Hampstead (38.9 tonnes per capita), and Westmount (32.5 tonnes per capita). These areas are typified by high rates of single, followed by duplex style housing, low total population, low rates of new construction, high FAC, as well as high relative pre-tax income on the agglomeration.

When considering individual materials, concrete is the largest component of recent residential construction in Montreal. Average use across the agglomeration is 21.9 tonne per capita, but this ranges from 12.5 tonne per capita in Montreal-Est to 42.7 tonne per capita in Senneville. Per capita concrete is highest in wealthy inner-city enclaves, such as Westmount, and suburban regions (i.e. Senneville), as see in figure 3. Again, high FAC is the main driver of concrete use across the agglomeration. Steel and wood follow much the

Figure 3. Material density (2021) in tonnes per capita across the Agglomeration of Montreal's neighbourhoods and municipalities for concrete (top left), steel (top right), and wood (bottom).

same spatial pattern as concrete with clusters on the west of the agglomeration and in affluent enclaves. Wood is present across much of the agglomeration as it is used in timber-framed construction for plexes and single-family homes. Notably, the use of wood is lowest in the inner core where concrete high-rises dominate and in Montreal-Est where 71% of housing predates 1960. Steel deviates slightly from patterns of concrete and wood in that 70% of municipalities or arrondissements on the agglomeration use 0.1 tonnes per capita or less. Again, Senneville, with its large suburban homes, has the highest per capita steel use (0.4 tonnes per capita).

3.3. Embodied carbon in recent construction

Average carbon equivalent emissions across the agglomeration were estimated to be 2.8 tonnes CO_2eq. per capita ranging from 2.0 tonnes CO_2eq. per capita Montreal-Est up to 8.2 tonnes CO_2eq. per capita BV. The highest rates of embodied carbon across the Agglomeration of Montreal are primarily concentrated in areas of low-density housing typology, both in terms of FAC (m^2 per capita) and land area per capita. Unsurprisingly, low-density suburban regions beyond the urban core exhibit the highest per capita impacts, namely Senneville (8.2 tonnes CO_2eq. per capita), Hampstead (6.41 tonnes CO_2eq. per capita), and Baie-D'Urfé (5.3 tonnes CO_2eq. per capita). Interestingly, none of these regions are incorporated within the City of Montreal, though it is unclear whether this correlation is based on development policy in those independent municipalities versus the City of Montreal or simply a preference of suburban inhabitants living near the city for less dense, and therefore generally more impactful, housing.

Both FAC and built form are drivers of GHG impact across the agglomeration. Low population density regions showed elevated impact across the board, as they generally also had higher FAC compared to high density areas. On the other hand, regions with high rates of high-rise housing, despite being dense and having

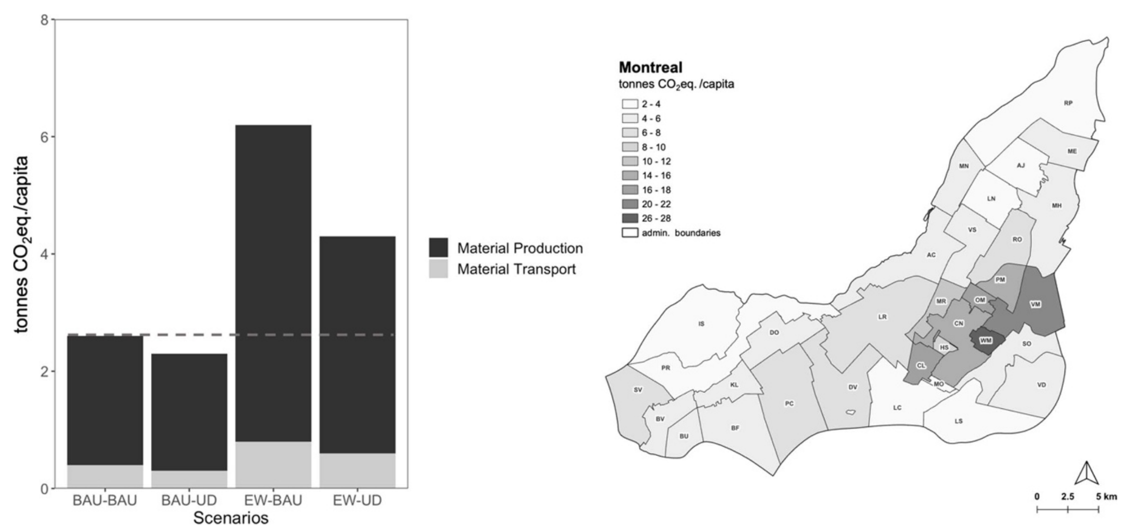

Figure 4. Weighted average CO_2eq. per capita across building scenarios (left). Tonnes CO_2eq. per capita on the Agglomeration of Montreal for EW-BAU development (right).

generally lower FAC, also had elevated impact, primarily due to an increased need for concrete and steel in construction. There was little correlation between pre-tax income, housing types across neighbourhoods, or per cent of new construction with BAU–BAU embodied GHG impact per capita. Likewise, while there was some correlation between high FAC and low population density, they are not interlinked (see SI).

Areas with the lowest impact were found to be those with high rates of new construction and a mix of housing types. Montreal-Est (2.0 tonnes CO_2eq. per capita), Le Sud-Ouest (2.1 tonnes CO_2eq. per capita), and Verdun (2.1 tonnes CO_2eq. per capita) had the three lowest per capita impacts and fell well below the agglomeration-wide average. In total, 42% of regions fall below average per capita emissions, with the agglomeration nearly split between dense, materially lean areas and suburbs with high FAC, high material use. Regions within the City of Montreal with per capita intensities above this average were those with increased rates of high-rise housing (e.g. Ville Montreal, 3.9 tonnes CO_2eq. per capita) and low rates of post-1960 construction (e.g. Outremont, 4.0 tonnes CO_2eq. per capita).

3.4. Embodied GHG in future scenarios

For potential development scenarios, densification reduced embodied carbon equivalents per capita emissions the most, with reductions of 44%–100% for high baseline neighbourhoods. However, only 53% of neighbourhoods saw improved impact values for BAU–UD. Neighbourhoods in the lowest quartile of baseline impacts increased their GHG intensity by 100%–135%, mainly because of increased high-rise construction compared to their current building mix. Few neighbourhoods showed beneficial embodied carbon effects of switching to EW for both BAU and UD development scenarios, with only Beaconsfield and Saint-Anne-de-Bellevue experiencing reduced impacts in either scenario. An average of 276% and 183% increase in embodied carbon was observed in EW-BAU and EW-UD, respectively.

Figure 4 shows embodied emissions per capita across the entire Agglomeration for the four scenarios. Montreal can reduce embodied carbon in future construction by 14% relative to baseline using current materials and denser settlement patterns. Both EW scenarios resulted in increased carbon impact of approximately 2.8 and 1.8 times the baseline scenario for EW-BAU and EW-UD, respectively. The reason for this is the minimal embodied carbon savings when switching to EW construction.

Transport impacts were stable for all scenarios, as distances and masses did not vary significantly across material types, all of which can be produced in QC. The greatest impacts were driven by material production based on housing typology needs. While wood is generally considered a low GHG building material, materially intense building typologies played a significant role in driving the embodied carbon impact across scenarios which showed that EW construction alone did not necessarily translate to lower m^{-2} impact, primarily because of materially intense high-rises in our model. The embodied carbon reduction was minimal in EW high-rise buildings compared to standard high-rises due to the continued need for concrete and steel in these structures, as well as the high embodied carbon of EW products themselves. Glue production for glulam specifically contributed heavily to the EW material's embodied carbon, followed by diesel use; while switching to an adhesive-free EW could potentially improve these results, they were not

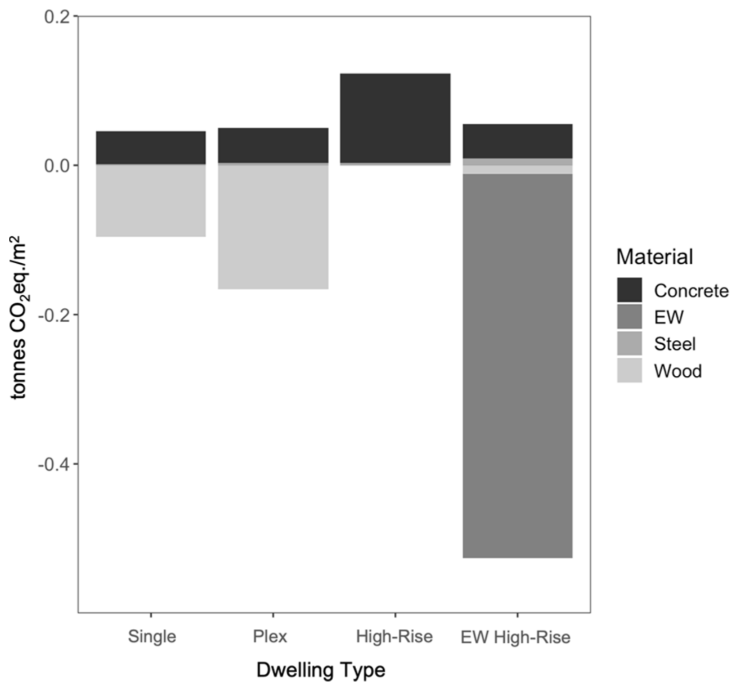

Figure 5. Tonnes CO_2eq. m^{-2} of building area (including biogenic carbon).

explored here. Additional impacts drivers come from underground parking in the high-rise buildings for both standard and EW buildings, where concrete was used.

City-wide metrics mask how different areas of the agglomeration perform under our scenarios. Figure 4 (right) maps per capita emissions across the agglomeration for the shift to EW construction with the current urban form. We focus on this scenario because it has the most dramatic shifts from baseline (see SI for maps of other scenarios). Nearly all neighbourhoods had a significant increase in embodied carbon impact relative to the BAU–BAU scenario, excluding Rivière-des-Prairies-Pointe-aux-Trembles (RP), which both decreased marginally by 0.02 tonnes per capita. Notably, Côte-Saint-Luc, Westmount, Outremount, Ville Marie, Le Plateau-Mont-Royal, and Côte-des-Neiges-Notre-Dame-de-Grâce, saw the highest impact increase (3–5 times increase) with material profile shifts, despite optimising for housing typology (i.e. moving towards medium density plex housing rather than high-rise construction) in those regions, which generally helped reduce per capita impact in other areas of the city.

Compared to BAU–BAU, both construction with current materials and EW would increase impacts, though to a lesser extent than EW-BAU, due to the high embodied carbon content of both glulam EW. While concrete and steel quantities are reduced when shifting to EW, impact values for EW high-rises ultimately exceeded BAU–BAU and BAU—UD scenarios. Of note is that these adverse outcomes with EW only occur when biogenic uptake is not included. However, given current uncertainties in forest GHG accounting, our findings underscore that if popular assumptions that timber is carbon negative or neutral are wrong, then wholesale transitions to wood may exacerbate emission of construction and work counter to urban decarbonisation goals.

3.5. Biogenic GHG in future scenarios

Including carbon uptake during sequestration using the IPCC GWP 100a carbon equivalent accounting method with biogenic carbon (both uptake and emissions) yields vastly different values from our original results. Assuming best case end-of-life scenarios (i.e. efficient reclamation via reuse or recycling after usable period), construction in Montreal yields future scenarios which sequester carbon and store it within the city's built environment. Figure 5 shows the tonnes of GHGs m^{-2} across housing typologies under biogenic carbon accounting. Standard high-rise construction, which uses little wood showed no changes compared to IPCC GWP 100a accounting methods. Conversely, single and plex style housing showed carbon sequestration due to the high quantity of light-frame timber. Most notably, EW high-rise construction has the potential to store 0.5 tonnes CO_2 m^{-2} of floor space, significantly reducing the carbon burden of high-rise construction for Montreal's development (a 30-fold decrease).

All development and material scenarios are GHG negative when biogenic carbon uptake is considered (Figure 6). These changes are most pronounced in the EW-BAU scenario, where significant amounts of

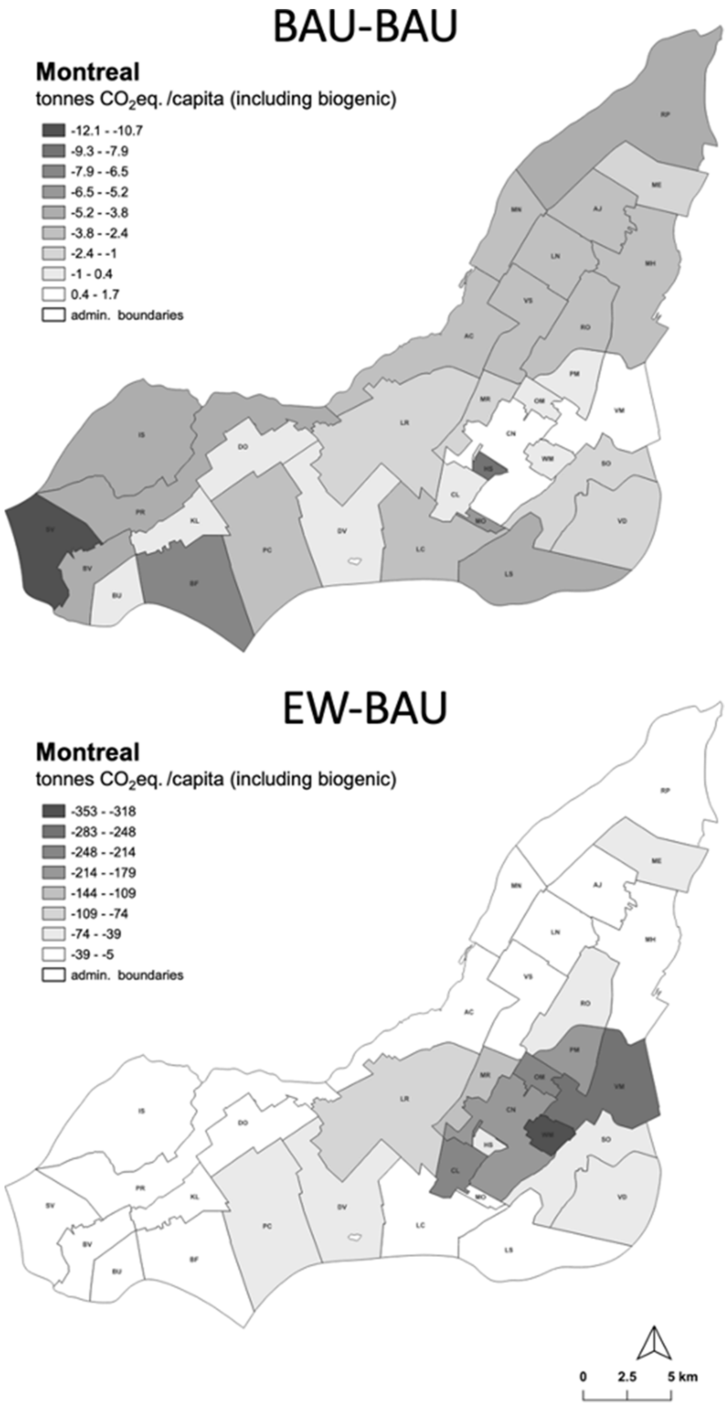

Figure 6. Tonnes CO_2eq. per capita on the Agglomeration of Montreal (including biogenic carbon) with material shift for business-as-usual (top) and EW material shift-business-as-usual development (bottom).

carbon would be stored in EW throughout neighbourhoods with significant high-rise construction. Neighbourhoods characterised by low-densities benefited less from the transfer to EW construction, as they already have the potential to store wood in their housing stock. Predictably, low rates of population growth appear to also contribute significantly to decreased GHG impact, though shifts towards less dense housing need to be examined further. It is worth noting that these findings are contingent on forestry practices that maintain forest ecosystems functioning and carbon stocks, as well as the long-stem storage of carbon in the wood after building demolition. As such, they represent an optimistic scenario of the potential of EW to cut carbon emissions of the urban building stock.

3.6. Land use

Land transformation and use are important considerations when it comes to assessing a city's impact on the hinterlands which supply most materials and are particularly salient for scaling up EW construction. As

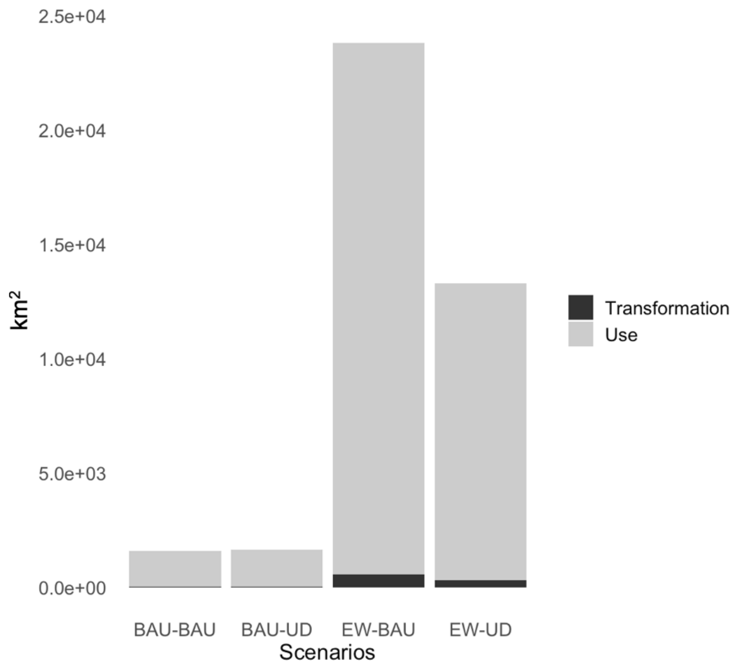

Figure 7. Inventory of land use (i.e. occupation) and transformation across future scenarios.

shown in figure 7, both EW-BAU and EW-UD scenarios result in higher land transformation and use impacts than BAU–BAU and BAU–UD. BAU–BAU scenarios resulted in the least amount of land transformation at approximately 42 km^2 conversion, while the EW-BAU and EW-UD scenarios resulted in the highest increases at 575 km^2 and 323 km^2 of land transformed, respectively, due to the need for a marginal uptick in forested land in these scenarios.

BAU–BAU and BAU–UD did not result in additional transformation. All scenarios comprised less than 0.1% of QC's forested area, equivalent to a small percentage of the 900 000 km^2 of third-party certified forests in the province. Land use numbers were considerably higher than transformation impacts. BAU scenarios required 1600 and 1660 km^2 of total land use for BAU–BAU and BAU–UD, respectively. For EW material profiles, land occupation increased to 23 800 and 13 300 km^2 of land for EW-BAU and EW-UD, respectively, highlighting the quantity of land needed to support EW supply as opposed to traditional building methods.

4. Discussion

4.1. FAC and built form

It is clear from our findings that Montreal's carbon equivalent impact is not solely due to materials used in construction, but also the types of dwellings we build. For example, high FAC contributes directly to increased material needs and related impact. While building typology can technically be decoupled from high FAC, Montreal's built form generally leans in two distinct directions: high FAC, single family dwellings, and low FAC plex and high-rise construction. While new construction has shifted towards smaller floor footprints, these buildings are almost exclusively high-rise, which require significant concrete, which exacerbates the city's carbon footprint. Materials cannot be replaced without considering the effects of high-FAC housing, as optimisation of both material usage with housing typology is required to effectively decarbonise.

The City of Montreal has already begun to consider how sustainability can be meshed into the city's built form [62, 63]. Programmes such as Partenariat Climate MTL (The Climate Montreal Partnership) [64] aim to educate and support all stakeholders on what it will take to reach decarbonisation by 2050. Likewise, work such as our aims to contribute to the larger conversation and knowledge base for decision making.

Further, it appears that an agglomeration wide development plan may not be best suited for decreasing per capita impacts, but rather a concerted, yet tailored, plan for each municipality to optimise urban density, housing typology, and FAC, as they continue to develop. Based on estimates by the Government of Quebec, Montreal's growth rate is generally low, and a reduction in new construction in general may help in keeping per capita impact steady, so long as new residences that are built are do not repeat the same high impact practices observed here.

4.2. Land use considerations

Even if EW at scale can reduce GHG emissions, there is a concern that an increase demand for wood products could result in a shift away from sustainable forest management [65], which has already been a hurdle for stakeholders in areas of high production and/or demand. Canada's forested land stores an abundance of carbon, with 5 987 million tonnes stored in non-Boreal forests, and another 10 453 million tonnes in the Boreal [66]. As of 2021, Quebec forestry contributed 22% of Canadian national wood supply across approximately 318 600 km^2 of public land (provincial and federal). Understanding how local production rates can support local building projections will be a key factor in the overall sustainability of shifting away from steel and concrete.

It is equally important to recognise that neither the Montreal Agglomeration, nor Quebec's forests, exist within a vacuum. Increased demand for Canadian wood products both in and outside Canada could drastically affect land use and transformation metrics beyond what is estimated here.

Transboundary impacts of material production should be considered as the construction material supply chain spans the province. While this means relatively short transportation distances compared to regions that must source materials from abroad, understanding how local environments are potentially impacted is key. Even though the land use is within the capacity of QC forestry sector, a nuanced evaluation of the indirect land impacts much be considered. These externalities have not been quantified here, though carbon imbalances with indirect land use change for palm oil [67], corn ethanol, as well as many other biofuel feedstocks [68–70] are just some examples of significant land use changes resulting from sustainability-motivated initiatives.

When it comes to forested land, Natural Resource Canada estimates that less than 0.5% of Canada's 362 million hectares of forested land has been converted for non-forest use in the past 30 years. [54]. Nonetheless, deforestation rates should be closely monitored to ensure a stable and healthy forest supply. One recent study has shown how to improve the ecosystem health and resilience of Quebec forests by selectively harvesting and growing tree species that are not normally used in construction but can nevertheless fulfil construction requirements with innovative EW products [34].

4.3. Limitations and future work

This study is a first attempt to account for the material and embodied carbon impacts of Montreal's built form. Future studies should refine building typologies more specific to Montreal and provide more precise material compositions and environmental impact metrics. The addition of other building materials, such as brick, glass, aluminium, or more refined estimations of the broad categories studied here (i.e. wooden doors versus wooden window frames) will improve model completeness. Likewise, inclusion of pre-1960 construction may provide more nuanced detail, especially as research comparing the impact of new construction with renovation of the existing built environment may yield useful insights in Montreal. While this study only accounts for new construction, many have shown the importance of considering refurbishment of the built environment [71, 72]. Further investigation into the turnover rate of Montreal's current built form and dwellings more suitable to refurbishment than replacing may yield variations in the results shown here. Likewise, a sizeable portion of unreliable datapoints were removed, accounting for a potentially underreporting of materials and per capita emissions.

Additionally, assessment of embodied carbon and land impacts of Montreal's built environment including pre-1960's housing under refurbishment could shed light on additional areas of impact or savings. Furthermore, though the scope of this study was bound by the geographical limits of the Agglomeration of Montreal, which ignored substantial suburban development off the island. A broader investigation into increased urbanisation off-agglomeration is vital to measure the impact of urban sprawl in the greater-Montreal, and subsequently throughout Quebec and broader the Greater Lakes Megalopolis.

Further limitations of the study include the variability and incompleteness of currently available process data for construction materials. Complementing process data with input-output data in a hybrid approach could overcome this shortcoming. Studies show that hybrid methods can capture 10%–50% more life cycle GHG emissions [73, 74]. For example, Crawford *et al* report and utilise the hybrid-LCA EPiC database to fill in gaps. For concrete, steel, and wood, the EPiC database hybrid method showed an average coefficient of GHG emissions 71.4%, 59.1%, and 39.3%, respectively in an Australian context [73] with other researchers, such as Lausselet *et al*, have included both hybrid approaches with an expanded system boundary to include modes of transportation and energy mix, which resulted in up to a 191% reduction in GHGs for optimal scenarios [75]. For our first look into Montreal's emissions, we believe a process-based approach is a valid estimation that can be improved upon with emerging databases in the future. We also assume no changes in how Montreal interacts with an EW-focused built environment beyond material replacement. Future work should aim to refine and reduce potential areas that are particularly sensitive (i.e. light frame and EW products).

Next, inclusion of various end-of-life scenarios would further elucidate the true GHG footprint of Montreal's built environment. Carbon that is sequestered during forest growth may be released back to the atmosphere when buildings are demolished. Wood would not be carbon neutral such instances. End-of-life scenarios for this study were assumed as landfill (i.e. worst case scenario) though we acknowledge that Quebec is engaging in initiatives to reduce the quantity of construction materials sent to landfill [76]. While interst in emerging technologies and repurposing construction materials is increasing [56, 57, 77, 78] it is difficult to assume these will be the future norm. We acknowledge that this presents a wide knowledge gap and should be addressed. However, given the long lifespan of residential buildings (e.g. 60–100 years), accurate representations of future end-of-life scenarios are not necessary to gain an initial understanding of the city's material impacts. Future research may look deeper into emerging waste management technologies for concrete, steel, light frame timber, and EW, as well as further accessing policy shifts both throughout QC and Canada.

Operational energy is another major consideration that should be explored further, as it contributes heavily to its GHG impact [79]. Research has shown that there are benefits to EW building [80–82] which could improve total embodied carbon across a building's lifespan. Further, UD scenarios could have added benefits of lowered per capita energy use (reduced need for lighting, heating, cooling, etc.) which could reduce impact across those scenarios.

5. Conclusion

This study was a first attempt to assess the GHG and land use impact of construction across Montreal. When it comes to construction, Montreal benefits heavily form Quebec's industrious and diverse supply chain across all materials. While the embodied carbon impact of Montreal's neighbourhoods varies greatly amongst themselves, the impact of the average Montrealer has much room for improvement if the city is to be a global leader low/GHG urbanism.

As developers consider the benefits and costs of switching the EW construction, it will be vital to consider housing typology to minimise the environmental footprint of the housing sector. Careful evaluation should be undertaken to consider alternatives to EW (i.e. readily available light-frame construction), as well as density needs of Montreal's inhabitants. Quebec in particular holds an abundance of natural resources. Ensuring that development in the region is undertaken in a manner that is both beneficial to the urban and rural inhabitants, alike, is of utmost importance.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

Acknowledgments

The authors gratefully acknowledge the financial support of this work by the Natural Sciences and Engineering Research Council of Canada through the Discovery Grant Program (Grant Number: RGPIN/03440-2021). We are grateful for the expertise and support of Naomi Keena in Montreal's building typology, Bryant Serre for sharing his expertise in GIS, as well as editing support.

Conflict of interest

The authors declare no conflicts of interest in regard to this research. Felicity Meyer is an employee of BoxOne Ventures (Montreal, QC, Canada).

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References

[1] German Sustainable Building Council 2020 *Building for a Better World: How Buildings Contribute to the UN Sustainable Development Goals*

[2] Seto K C, Davis S J, Mitchell R B, Stokes E C, Unruh G and Ürge-Vorsatz D 2016 Carbon lock-in: types, causes, and policy implications *Annu. Rev. Environ. Resour.* **41** 425–52

[3] Saxe S *et al* 2020 Taxonomy of uncertainty in environmental life cycle assessment of infrastructure projects *Environ. Res. Lett.* **15** 083003

[4] Elliot T and Levasseur A 2022 System dynamics life cycle-based carbon model for consumption changes in urban metabolism *Ecol. Modelling* **473** 110010

[5] Petek Gursel A, Masanet E, Horvath A and Stadel A 2014 Life-cycle inventory analysis of concrete production: a critical review *Cem. Concr. Compos.* **51** 38–48

[6] Nawy E G (ed) 2008 *Concrete Construction Engineering Handbook* 2nd edn (CRC Press)

[7] Nature 2021 Concrete needs to lose its colossal carbon footprint *Nature* **597** 593–4

[8] Fennell P S, Davis S J and Mohammed A 2021 Decarbonizing cement production *Joule* **5** 1305–11

[9] Guven G, Arceo A, Bennett A, Tham M, Olanrewaju B, McGrail M, Isin K, Olson A W and Saxe S 2022 A construction classification system database for understanding resource use in building construction *Sci. Data* **9** 42

[10] Andrew R M 2019 Global CO_2 emissions from cement production, 1928–2018 *Earth Syst. Sci. Data* **11** 1675–710

[11] Gu H, Liang S and Bergman R 2020 Comparison of building construction and life-cycle cost for a high-rise mass timber building with its concrete alternative *For. Prod. J.* **70** 482–92

[12] Liang S, Gu H and Bergman R 2021 Environmental life-cycle assessment and life-cycle cost analysis of a high-rise mass timber building: a case study in Pacific Northwestern United States *Sustainability* **13** 7831

[13] Liang S, Gu H, Bergman R and Kelley S S 2020 Comparative life-cycle assessment of a mass timber building and concrete alternative *Wood Fiber Sci.* **52** 217–29

[14] Andersen J H, Rasmussen N L and Ryberg M W 2022 Comparative life cycle assessment of cross laminated timber building and concrete building with special focus on biogenic carbon *Energy Build.* **254** 111604

[15] Felmer G, Morales-Vera R, Astroza R, González I, Puettmann M and Wishnie M 2022 A lifecycle assessment of a low-energy mass-timber building and mainstream concrete alternative in Central Chile *Sustainability* **14** 1249

[16] Allan K and Phillips A R 2021 Comparative cradle-to-grave life cycle assessment of low and mid-rise mass timber buildings with equivalent structural steel alternatives *Sustainability* **13** 3401

[17] Moynihan M C and Allwood J M 2014 Utilization of structural steel in buildings *Proc. Math. Phys. Eng. Sci.* **470** 20140170

[18] D'Amico B, Pomponi F and Hart J 2021 Global potential for material substitution in building construction: the case of cross laminated timber *J. Clean. Prod.* **279** 123487

[19] Harte A M 2017 Mass timber—the emergence of a modern construction material *J. Struct. Integr. Maint.* **2** 121–32

[20] Svatoš-Ražnjević H, Orozco L and Menges A 2022 Advanced timber construction industry: a review of 350 multi-storey timber projects from 2000–2021 *Buildings* **12** 404

[21] Moe K 2019 *Carbon and Timber Building, in Wood Urbanism: From the Molecula Rto the Territorial* ed J H Daniel Ibañez and K Moe (Actar Publishers)

[22] Himes A and Busby G 2020 Wood buildings as a climate solution *Dev. Built Environ.* **4** 100030

[23] Churkina G, Organschi A, Reyer C P O, Ruff A, Vinke K, Liu Z, Reck B K, Graedel T E and Schellnhuber H J 2020 Buildings as a global carbon sink *Nat. Sustain.* **3** 269–76

[24] Mishra A, Humpenöder F, Churkina G, Reyer C P O, Beier F, Bodirsky B L, Schellnhuber H J, Lotze-Campen H and Popp A 2022 Land use change and carbon emissions of a transformation to timber cities *Nat. Commun.* **13** 4889

[25] Cordier S, Robichaud F, Blanchet P and Amor B 2021 Regional environmental life cycle consequences of material substitutions: the case of increasing wood structures for non-residential buildings *J. Clean. Prod.* **328** 129671

[26] Ahmed S and Arocho I 2021 Analysis of cost comparison and effects of change orders during construction: study of a mass timber and a concrete building project *J. Build. Eng.* **33** 101856

[27] Anna Esbjörnsson P M 2014 Urban timber—a resilient timber architecture in the city and a vision of mass customization *Architecture* (Chalmers University of Technology)

[28] Cappellazzi J, Konkler M J, Sinha A and Morrell J J 2020 Potential for decay in mass timber elements: a review of the risks and identifying possible solutions *Wood Mater. Sci. Eng.* **15** 351–60

[29] Chaggaris R, Pei S, Kingsley G and Feitel A 2021 Carbon impact and cost of mass timber beam–column gravity systems *Sustainability* **13** 12966

[30] Duan Z, Huang Q and Zhang Q 2022 Life cycle assessment of mass timber construction: a review *Build. Environ.* **221** 109320

[31] Nepal P, Johnston C M T and Ganguly I 2021 Effects on global forests and wood product markets of increased demand for mass timber *Sustainability* **13** 13943

[32] Pasternack R *et al* 2022 What is the impact of mass timber utilization on climate and forests? *Sustainability* **14** 758

[33] Syed M T 2020 Identifying mass timber research priorities, barriers to adoption and engineering, procurement and construction *John H. Daniels Faculty of Architecture, Landscape and Design* (University of Toronto)

[34] Osborne P, Aquilué N, Mina M, Moe K, Jemtrud M and Messier C 2023 A trait-based approach to both forestry and timber building can synchronize forest harvest and resilience *PNAS Nexus* **2** pgad254

[35] Hill C A S 2019 The environmental consequences concerning the use of timber in the built environment *Front. Built Environ.* **5**

[36] City of Montreal 2022 *Road Map for Zero-emissions Buildings by 2040*

[37] Pizzol M and Scotti M 2016 Identifying marginal supplying countries of wood products via trade network analysis *Int. J. Life Cycle Assess.* **22** 1146–58

[38] Kurz W A *et al* 2009 CBM-CFS3: a model of carbon-dynamics in forestry and land-use change implementing IPCC standards *Ecol. Modell.* **220** 480–504

[39] Statistics Canada 2022 *Census Profile, 2021 Census of Population*

[40] I.d.l.s.d. Québec (ed) 2022 Projection de la population des municipalités de 500 habitants1 et plus, scénario Référence A2022, Québec, 2021–2041

[41] Québec D (ed) 2016 Limite administrative de l'agglomération de Montréal

[42] S.d.l.é. foncière (ed) 2017 *Unités d'évaluation foncière* (Ville de Montréal)

[43] National Research Council of Canada 2022 *Quebec Construction Code: Chapter 1 Building, and National Building Code of Canada 2015 (Amended)*

[44] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E and Weidema B 2016 The ecoinvent database version 3 (part I): overview and methodology *Int. J. Life Cycle Assess.* **21** 1218–30

[45] Steubing B, Wernet G, Reinhard J, Bauer C and Moreno-Ruiz E 2016 The ecoinvent database version 3 (part II): analyzing LCA results and comparison to version 2 *Int. J. Life Cycle Assess.* **21** 1269–81
[46] Natural Resources Canada Canada's minerals and mining map 2022 (available at: https://atlas.gc.ca/mins/en/index.html)
[47] Natural Resources Canada 2009 Canadian cement industry energy benchmarking—summary report
[48] *Minerai de Fer Québec/Quebec Iron Ore* (available at: https://mineraiferquebec.com/our-iron/?lang=en)
[49] ArcelorMittal *Our Mines* (available at: https://mines-infrastructure-arcelormittal.com/en/nos-mines/#:~:text=We%20produce%20approximately%2026%20million,continue%20to%20increase%20this%20capacity)
[50] *Integrated Report 2021–2022* 2022 (available at: www.tatasteel.com/investors/integrated-report-2021-22/manufactured-capital.html#:~:text=Tata%20Steel%2C%20with%20an%20annual,most%20geographically%20diversified%20steel%20producers)
[51] TATA Steel Minerals Canada Ltd. 2015 *DSO Project Activities: Environmental Protection Plan*
[52] RTIT *Rio Tinto Fer et Titane* (available at: www.gem.wiki/Rio_Tinto_Fer_et_Titane) (Accessed 13 May 2023)
[53] Global Energy Monitor 2023 *Global Steel Plant Tracker*
[54] Natural Resources Canada *The State of Canada's Forests Annual Report* 2022
[55] Natural Resources Canada *The State of Mass Timber in Canada 2021 Mass Timber in Canada 2021* 2021
[56] Bilec R and Bilec M M 2022 Building material stock analysis is critical for effective circular economy strategies—a comprehensive review *Environ. Res.* **2** 032001
[57] Lanau M and Liu G 2020 Developing an urban resource cadaster for circular economy: a case of Odense, Denmark *Environ. Sci. Technol.* **54** 4675–85
[58] Lanau M, Liu G, Kral U, Wiedenhofer D, Keijzer E, Yu C and Ehlert C 2019 Taking stock of built environment stock studies: progress and prospects *Environ. Sci. Technol.* **53** 8499–515
[59] *Vers une feuille de route montréalaise en économie circulaire* 2023
[60] Babí Almenar J, Petucco C, Sonnemann G, Geneletti D, Elliot T and Rugani B 2023 Modelling the net environmental and economic impacts of urban nature-based solutions by combining ecosystem services, system dynamics and life cycle thinking: an application to urban forests *Ecosyst. Serv.* **60** 101506
[61] Kouchaki-Penchah H *et al* 2023 The Role of Hydrogen in a Net-zero Emission Economy under Alternative Policy Scenarios *Int. J. Hydrog. Energy* **49** 173–87
[62] City of Montreal 2020 *Montreal Climate Plan 2020–2030*
[63] En route vers une stratégie renouvelée pour le centre-ville 2022–2030 2022 (Ville de Montréal)
[64] Partenariat Climate MTL (available at: https://climatmontreal.com/en/) (Accessed 14 May 2023)
[65] Hoogstra-Klein M A and Meijboom K 2021 A qualitative exploration of the wood product supply chain—investigating the possibilities and desirability of an increased demand orientation *For. Policy Econ.* **133** 102606
[66] Beaudoin A, Bernier P Y, Guindon L, Villemaire P, Guo X J, Stinson G, Bergeron T, Magnussen S and Hall R J 2014 Mapping attributes of Canada's forests at moderate resolution through kNN and MODIS imagery *Can. J. For. Res.* **44** 521–32
[67] Hansen S B, Olsen S I and Ujang Z 2013 Carbon balance impacts of land use changes related to the life cycle of Malaysian palm oil-derived biodiesel *Int. J. Life Cycle Assess.* **19** 558–66
[68] Van Stappen F, Brose I and Schenkel Y 2011 Direct and indirect land use changes issues in European sustainability initiatives: state-of-the-art, open issues and future developments *Biomass Bioenergy* **35** 4824–34
[69] Kim S and Dale B E 2011 Indirect land use change for biofuels: testing predictions and improving analytical methodologies *Biomass Bioenergy* **35** 3235–40
[70] Kouchaki-Penchah H, Bahn O, Vaillancourt K, Moreau L, Thiffault E and Levasseur A 2023 Impact of biogenic carbon neutrality assumption for achieving a net-zero emission target: insights from a techno-economic analysis *Environ. Sci. Technol.* **57** 10615–28
[71] Slabik S *et al* 2023 Proposing an LCA methodology for the assessment of neighbourhood refurbishment measures *Environ. Res.* **3** 015009
[72] Pedinotti-Castelle M, Astudillo M F, Pineau P-O and Amor B 2019 Is the environmental opportunity of retrofitting the residential sector worth the life cycle cost? A consequential assessment of a typical house in Quebec *Renew. Sustain. Energy Rev.* **101** 428–39
[73] Crawford R H, Stephan A and Prideaux F 2022 The EPiC database: hybrid embodied environmental flow coefficients for construction materials *Resour. Conserv. Recycl.* **180** 106058
[74] Lenzen M 2000 Errors in conventional and input-output—based life—cycle inventories *J. Ind. Ecol.* **4** 127–48
[75] Lausselet C, Ellingsen L A-W, Strømman A H and Brattebø H 2019 A life-cycle assessment model for zero emission neighborhoods *J. Ind. Ecol.* **24** 500–16
[76] Grenier A 2023 *Circular Materials and Éco Entreprises Québec Join Forces to Advance Innovation and the Circular Economy* (Éco Entreprises Québec)
[77] Lederer J, Gassner A, Kleemann F and Fellner J 2020 Potentials for a circular economy of mineral construction materials and demolition waste in urban areas: a case study from Vienna *Resour. Conserv. Recycl.* **161** 104942
[78] Ghaffar S H, Burman M and Braimah N 2020 Pathways to circular construction: an integrated management of construction and demolition waste for resource recovery *J. Clean. Prod.* **244** 118710
[79] Correa Hackenhaar I, Babí Almenar J, Elliot T and Rugani B 2022 A spatiotemporally differentiated product system modelling framework for consequential life cycle assessment *J. Clean. Prod.* **333** 130127
[80] 2015 *Wood Products Other Building Materials Used in New Residential Construction in the United States, with Comparison to Previous Studies 2012* (USDA Forest Service) p 75
[81] Milner H R and Woodard A C 2016 Sustainability of engineered wood products *Sustainability of Construction Materials* pp 159–80
[82] Sotayo A *et al* 2020 Review of state of the art of dowel laminated timber members and densified wood materials as sustainable engineered wood products for construction and building applications *Dev. Built Environ.* **1** 100004