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Growing greener cities – The potential for engineered wood construction to lower Montreal's environmental impact

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Abstract

Deep decarbonization of buildings and construction is required to reduce the 40% of global carbon emissions produced by this sector. Mass-timber construction that substitutes carbon-capturing wood for carbon intensive materials like steel and concrete can assist in this transition. However, most studies of material use and embodied carbon in the built environment are deficient in that they rarely analyze the city-scale, and they seldom capture connections between the city and hinterlands that supply most construction materials.

As such, we lack knowledge to effectively decarbonize new construction in cities and do not know the potential impacts, such as deforestation, of large-scale mass-timber construction in cities. We address these knowledge gaps through a city-wide assessment of three key construction materials - steel, concrete, and wood - in the city of Montreal, Canada. We combine bottom-up material accounting of the building stock with life cycle assessment to analyze the carbon emissions and land change implications of future development scenarios in the city. We compare the “status quo” construction reliant on concrete and steel to the use of renewable, regionally available materials, such as mass timber at the neighborhood and city scales.

This thesis provides much-needed insights to aid the construction sector in strategically implementing low-carbon development that decreases the environmental impacts of urbanization both in cities and in their hinterlands. We find the average embodied carbon impact of modern residential housing on the Montreal Agglomeration to be 2.7 T CO_2eq./capita. We estimate that agglomeration wide transition to engineered wood construction and/or increased settlement density does not necessarily decrease this footprint across each individual municipality/*arrondisement*. We do find that scale up of engineered wood construction could be supported by Quebec’s harvestable forests.

Résumé

La décarbonisation profonde des bâtiments et de la construction est nécessaire pour réduire 40% des émissions mondiales de carbone produites par ce secteur. La construction en bois massif, qui remplace le bois capturant le carbone par des matériaux intensifs en carbone tels que l'acier et le béton, peut contribuer à cette transition. Cependant, la plupart des études sur l'utilisation des matériaux et le carbone incorporé dans les immeubles présentent des lacunes, car elles analysent rarement l'échelle de la ville et capturent rarement les liens entre la ville et les régions environnantes qui fournissent la plupart des matériaux de construction.

En conséquence, nous manquons de connaissances pour décarboniser efficacement les nouvelles constructions dans les villes et nous ne connaissons pas les impacts potentiels, tels que la déforestation, la construction en bois massif à grande échelle dans les villes. Nous comblons ces lacunes en effectuant une évaluation au niveau de la ville de trois matériaux de construction clés - l'acier, le béton et le bois - dans la ville de Montréal, Canada. Nous combinons une comptabilité détaillée des matériaux du stock de bâtiments avec une évaluation du cycle de vie pour analyser les émissions de carbone et les implications des changements d'utilisation des terres de potentiels développement dans la ville. Nous comparons la construction du "statu quo" qui dépend du béton et de l'acier avec l'utilisation de matériaux renouvelables disponibles localement, tels que le bois massif, à l'échelle du quartier et de la ville.

Cette thèse fournit des perspectives nécessaires pour aider le secteur de la construction à mettre en œuvre stratégiquement un développement à faible teneur en carbone qui réduit les impacts environnementaux de l'urbanisation à la fois dans les villes et dans leurs régions environnantes. Nous constatons que l'impact carbone moyen incorporé des habitations résidentielles modernes dans l'agglomération de Montréal s'élève à 2,7 T CO_2eq./capita. Nous estimons que la transition vers la construction en bois d'ingénierie et/ou l'augmentation de la densité d'implantation ne réduit pas cette empreinte carbone dans chaque municipalité/arrondissement individuel. Toutefois, nous constatons que l'expansion de la construction en bois d'ingénierie pourrait être soutenue par les forêts exploitables du Québec.

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Contribution of Authors

The contribution of authors to this thesis is as follows (1) Felicity Meyer – who planned and subsequently conducted experiments, collected data on various academic, industrial, and governmental sources, and presented her findings; (2) Dr. Benjamin Goldstein – who supervised experimental design, provided project guidance and subject matter expertise, and reviewed results and conclusions made in thesis; (3) Dr. Salmaan Craig – who supervised throughout the duration of the project, contributed subject matter expertise, as well as reviewed this thesis; and (4) Dr. Thomas Elliot – who contributed methodological support throughout the duration of this project and reviewed results throughout the iterative research process.

Publications Related to This Thesis

Submitted for review:

Meyer F, Elliot T, Craig S, Goldstein B G 2023 A multi-scale model of the environmental impacts of low-carbon construction on the Island of Montreal *Environmental Research: Infrastructure and Sustainability special issue Carbon Storage in the Built Environment*

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Acronyms and Abbreviations

BOM	Bill of materials
BAU	Business as usual
CLT	Cross-laminated timber
CO_2	Carbon dioxide
CO_2eq.	Carbon dioxide equivalents
EAF	Electric arc furnace
EOL	End-of-life
EU	Europe
EW	Engineered wood
EWP	Engineered wood product
GHG	Greenhouse gas
GIS	Global information system(s)
GLT	Glue-laminated timber / Glulam ©
GWP	Global warming potential
IE	Industrial ecology
k	Thousand
kg	Kilogram
km	Kilometer
LCA	Life cycle assessment
LCIA	Life cycle inventory
m	Meter
M	Million
MT	Mass timber
MFA	Material flow analysis
NLT	Nail-laminated timber
RoW	Rest of the world
t*km	Ton per kilometer
UD	Urban densification
UM	Urban Metabolism

Chapter 1. Introduction

Society, much like a living organism, requires an input of energy and resources, while outputting both waste as a by-product. Using the metaphorical framework of a humanity's societal metabolism, researchers can study the intricacies and impacts of anthropogenic resource consumption and resulting effects on global, national, and subnational levels [1-8]. Krausmann et al. found that this metabolism increased by about a factor of 12 to 89 Gt/year between 1900-2015 and could potentially increase to 218 Gt/year by 2050, if left unchecked [6]. In later studies, Krausmann et al. similarly found that material inputs to global material stocks (i.e., buildings, infrastructure, operational machinery) increased year over year by 3% in the 21st century, driven primarily by construction, which accounts for 75% of material stock (62 Gt/year) [9].

While rural areas produce the bulk of our resources, most resource use takes place within urban centers. Continued urbanization is predicted to heighten this trend [2]. Cities are nodes of material consumption – and emissions –and are therefore key to slowing climate change and reducing humanity's environmental footprints. By first measuring and mapping as built material use across a city, such as Montreal, we can begin to understand key levers to pull in this fight. As such, we can then begin to see future possibilities of responsible – and irresponsible – material consumption within the urban framework.

Global quantities of construction materials tripled between 2000-2017, the highest of which was concrete driven primarily by rapid urbanization in China [10]. The costs of material usage in the construction sector are multifaceted. Likewise, raw material extraction processes are often connected to destructive environmental consequences. In particular, extraction and production of materials including metals and concrete are directly linked to environmental impacts including land use, terrestrial and freshwater ecotoxicity, and of course, climate change [11].

The construction sector emits 38% [12] of global greenhouse (GHG) emissions and is expected to continue growing in the coming decades. While there is increased attention to material stock analysis at a building or national level, there exists few studies focused on the neighborhood and urban scales. Of these studies, few trace connections of urban material usage to the rural hinterlands, which produce most global resources, while also bearing the brunt of resulting environmental consequences. Canada's built environment alone comprises 13% of the country's direct GHGs [13].

Much of our modern built environment is composed of materials such as concrete, steel, wood, brick, aluminum, and polymers [14]. These materials are engrained in both our societal perception of "standard" building materials, as well as into the modern supply chain. Using alternative materials can address issues such as affordability, as well as environmental impact, of status quo construction.

Engineered wood (EW) construction has gained popularity in recent years, as an alternative to standard concrete and steel construction [15]. Many argue that a transition to a wood based built environment has the potential to decrease urban footprints by replacing high-carbon materials like concrete and steel with carbon storing wood. However, without assessing the spatial and temporal contexts of building with wood, we could inadvertently deploy wood in regions where it does not improve environmental outcomes.

This study is a necessary first step to provide detailed insight to the built environment of Montreal. As no similar studies have been carried out in Montreal or Quebec (QC), and few in Canada as a whole, the authors aim to provide a framework for assessing material flows and environment impacts of Canadian cities, and provide decision support to policy makers, urban planners, the construction industry, as well as urban stakeholders, across various population and urban growth scenarios. In recent years plans have been made to address both the growing concern around climate change, as well as expanding urbanization and housing needs within the urban context. Montreal's Master Plan [16], Quebec's 2030 Plan for a Green Economy [17], and Canada's Green Building Strategy [18], as serve as prime examples of these initiatives.

While these three initiatives address how, and with what materials, building are constructed, a gap in spatially contextualized information makes these programs difficult to properly execute.

In assessing the environmental impacts of increased urbanization, governments of Montreal, QC, and Canada will be able to make nuanced decisions to stay on track for both domestic and international decarbonization goals, which in the current climate trajectory, are vital.

1.1 Research Objectives, Questions, and Methods

We propose addressing knowledge gaps via a city-wide assessment of construction materials, using Montreal as a model city within the Greater Lakes Megalopolis. On a broad scale, we aim to contribute new knowledge to the field of Industrial Ecology to provide a more nuanced view of how Montreal has been developed to date, and specific levers to pull to develop the city between 2021 and 2040. On a more granular level, the goals of this research are as follows:

- Estimate the distribution of construction materials across Montreal using a bottom-up approach, for both residential and non-residential buildings.
- Quantify the environmental impacts of substitution of non-renewable materials (i.e., steel and/or concrete) with renewable materials (i.e., EW), on a neighborhood scale.
- Compare the substitution results with potentials for sustainability harvesting or mapping production (e.g., within Canada or within QC) to support this change.

Based on the knowledge gaps identified in my literature review, the scope of our study is potentially very broad. We have chosen to hone in on four key areas of investigation. Per our literature findings and research objectives, our research questions for this project include the following:

1. What is the embodied carbon in recent residential construction in the Montreal Agglomeration?
2. How does shifting from historically used materials and urban densification influence embodied carbon in future residential construction through 2040?
3. How much land is required to scale up EW construction in future Montreal?

To answer these questions, we did used bottom-up accounting of the Montreal building stock paired with a building typology database to determine the quantity in tons of concrete, steel, and wood currently used in modern residential buildings across the Montreal Agglomeration. We then paired performed carbon and land use impact metrics for concrete, steel, and wood to determine the carbon and land use inventory footprints per capita in each municipality/*arrondissement.*

Using population growth projections and home sizes we estimated the amount of new construction that will be built between 2021 through 2040. We then created various scenarios which highlighted material shifts from standard practice (i.e., concrete and steel) to a scenario that prioritizes wood-based construction through a mix of light frame timber and EW. Other scenarios optimized housing density across the Agglomeration. Using this matrix, we compare which levers can be pulled to decrease the carbon and land use footprints of Montrealers.

1.2 Thesis Outline

This thesis includes a literature review of the topics studied, a manuscript submitted for review, and a deeper discussion section, all of which relate to the objectives of this master's thesis. **Chapter 1** introduces our study topic, our research questions and objectives and outlines the cadence of this manuscript.

Chapter 2 encompasses a review of the existing body of literature on Urban Metabolism, Industrial Ecology, both areas of which focus primarily of the built environment in an urban context. We also discuss historical information about our case city – Montreal – and the motivations behind this work in measuring and mapping construction materials in today's built environment and for future development.

The literature review is followed by **Chapter 3** which contains one manuscript submitted to a special issue on Carbon Storage in the Built Environment in the Institute of Physics (IOP) journal *Environmental Research: Infrastructure and Sustainability*.

Finally, a broader discussion of findings made throughout the duration of this research are explored in **Chapter 4**. Lastly, conclusions and contributions to the knowledge base in our field of study are summarized in **Chapter 5**.

Connecting Text to Chapter 2

Chapter 1 provided a high-level overview of the environmental impacts of the global construction industry and how these impacts stem primarily from activities in urban areas. Wood was then introduced as a low-carbon substitute for steel and concrete, which are both heavily used in urban construction and environmentally intensive. I then laid out the overarching goals of this thesis and specific research questions and hypotheses. **Chapter 2** provides a more extensive review of recent literature in the fields of Industrial Ecology and Urban Metabolism. We also discuss material production and supply chain dynamics from a global perspective, and then specifically within QC, Canada.

Chapter 2. Literature Review

Early studies of humanity's environmental impact dates back to the 1970's when researchers sought to understand energy use [19]. Today thousands of life cycle assessment (LCA) researchers globally aim to measure and map our environmental footprints using increasingly sophisticated methods, as well as influence relevant policy and societal procedure based on these findings. A targeted search on GoogleScholar for relevant areas of study yields millions of results, from "Urban Metabolism" (~1,930,000 results), "Industrial Ecology" (~3,830,000 results), "Life Cycle Assessment AND Building" (~4,550,000 results), and "Material Stock Analysis" (~5,550,000 results).

The knowledge base from which we pull is both vast and profound. Here we aim to summarize high-level trends within our research topic to build a foundation for our study. We then identify key knowledge gaps that thesis aims to address.

2.1 Societal and Urban Metabolism

The United Nations estimates that 60% of the human population will reside in cities by 2030, and up to 66% by 2050. Globally, it is estimated that 12.5% of people who live in cities reside in megacities (i.e., cities with greater than 10 million inhabitants), while 50% live in smaller, though rapidly growing, medium-sized cities with populations less than one million [20]. Today, 81% of the Canadian population resides in urban centers, which make up less than 0.5% of the country's footprint (4,992,335 of 9,984,670 km^2) [21, 22]. Accordingly, urbanization is expected to continue in Canada, in line with global trends.

Population alone does not make a city; resources such as water, energy, and materials are required to support city-wide infrastructure and function. Given their concentrations of population and economic activity, cities are loci of global material and energy use. This resource use drives attendant environmental change where resources are sourced, and urban waste is deposited. For instance, in Canada, direct and indirect energy consumption by cities produced 42% of Canadian territorial greenhouse gas (GHG) emissions in 2015 [21]. While urban centers generate over 80% of global gross domestic product [23], they produce little of their own resources, which are often extracted and manufactured, to some extent, in rural regions [2]. Because of this, cities are, by nature, inextricable from their hinterlands, which serve a variety of purposes, be they agricultural, industrial, or other natural services [24].

As of 2015, a combination of construction and building operations accounted for 38% of global CO_2 emissions. This trend continued an upward trajectory to a peak in 2019 (13.4 gigatons CO_2) [12]. Similarly, energy, water, and land-use are all inextricably linked to the city's metabolism, and consequently its environmental footprint, the material configuration alone of a city is a substantial contributor. The heaviness of a city is directly connected to both the types of buildings, as well as the types and volumes of material use in those buildings [3].

Understanding current and projected materials use is needed to create ecologically leaner cities of the future, particularly because of the environmental impacts associated with producing and transporting resources *to* cities. Although there have been some studies abroad [2-5, 8, 25-30], few have focused on current urban material stocks of Canadian cities [23, 27], and to the author's knowledge no studies have been carried out in Montreal, QC. Consequently, researchers and policy makers lack insight on the weight of Canadian cities and material stocks might change in the future.

On top of this, GHGs associated with materials used within Canadian city limits are inevitably decoupled from the regions in which they are produced, providing further hurdles in meeting international and domestic carbon reduction goals, such as Sustainable Development Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable [31, 32]. While effort has been made to retroactively improve energy efficiency of existing buildings or target energy efficiency in new construction, the carbon cost of construction materials themselves must be addressed to achieve the Paris Agreements goals of decarbonization of the construction and building operations industry by 2050 [12]. In high efficiency buildings, the construction phase can contribute over 50% of the energy outputs over a building's lifespan as compared with operational phases due to high inputs at material production stages, as well as a decreased share in construction-related inputs [29].

While a reduction in all construction material use is the simplest solution to decreasing the impact of the construction sector, population increase, and more specifically urban population increase, render such an outcome implausible. Raw material extraction processes are often drivers of negative environmental consequences such as GHG emissions and land use. With current low rates of construction material recycling, material usage and raw material extraction go hand in hand. Current usage projections through 2060 ultimately result in a failure to meeting Paris Agreement goals [11].

Canada is one of the world's most urban countries and urban growth is expected out outpace population increases in other regions. Canada is already seeing the effect of urban migration: in the time between the 2016 and 2021 census metropolitan areas made up 5.2% of total population growth [33].

2.2 Materials in the Built Form

Modern buildings are made of hundreds of materials such as metals, stone and brick, polymers, composites, various types of wood [34-36]. For our BAU case study, we focus on three materials widely used in urban settings: concrete, steel, and light frame timber. These materials are both ubiquitous and used in high quantities across the urban built environment, regardless of housing typology. While other material may add to the environmental footprint of the residential built environment, concrete, steel, and wood, weigh heavily on that value.

2.2.1 Concrete

Concrete has been ubiquitous is construction since the early- to mid-1900's as a successor of cement, which has been produced and widely utilized in England and France throughout the 1800's, and to a lesser extent, back to antiquity [37]. Modern concrete is a complex material, comprised of clicker (i.e., cement as a binder), water, and aggregate, which is typically crushed stone or, more commonly in Europe, blended fly ash [38].

Concrete has been a clear choice within the building construction industry for its low price point and ideal mechanical specifications (e.g., fire resistance, durability, compressive strength, workability, etc.) [39]. As in much of the world, concrete production in Canada is highly dependent non-renewable energy sources regardless of mix type. Much of this energy input is devoted to clinker production. While efforts to reduce clinker percentage in concrete mixes have shown some improvement to water usage and energy requirements, they make up only a portion of the inputs of concrete production and therefore have a limited capacity to reduce GHG in the construction sector [40].

Concrete production can be broken down into several phases: extraction of raw materials needed for cement and aggregate, followed by processing of the limestone via grinding and heating (1400-1500°C). Concrete is then produced upon mixture of the processed dry calcium trisilicate (Ca_3SiO_5) with water and aggregate, which hardens in a matter of hours depending on environmental conditions, and continues to cure and strengthen over time [41].

Cement alone, which typically makes up 95% of concrete by mass is estimated to account for 8% of global GHG emissions on a yearly basis due to the release of carbon during limestone processing, as well as the energy input required for processing [41, 42]. Portland cement is the most widely used type of cement. For every 1 kg of Portland cement produced, approximately 0.5 kg of CO_2 are emitted [43]. As of 2014, global concrete consumption was estimated to be 25 Gt per year, equating to 2.6 Gt of CO_2 emissions from cement, alone [39].

Volatile organic compounds, benzene, heavy metals, hydrofluoric acid, and hydrochloric acid are common emissions associated with Portland cement production and are regularly reported as part of environmental analyses across the industry. Additional pollution may occur post use stage during concrete mixer cleaning, which some studies have indicated results in hydrocarbon excretion. Water and energy consumption, particulate matter, as well as other toxic emissions to local industrial regions continue to be areas of concerns despite years of apparent advancement in the industry [39, 44]. **Figure 1** illustrates a simplified overview of concrete production from a life cycle thinking perspective.

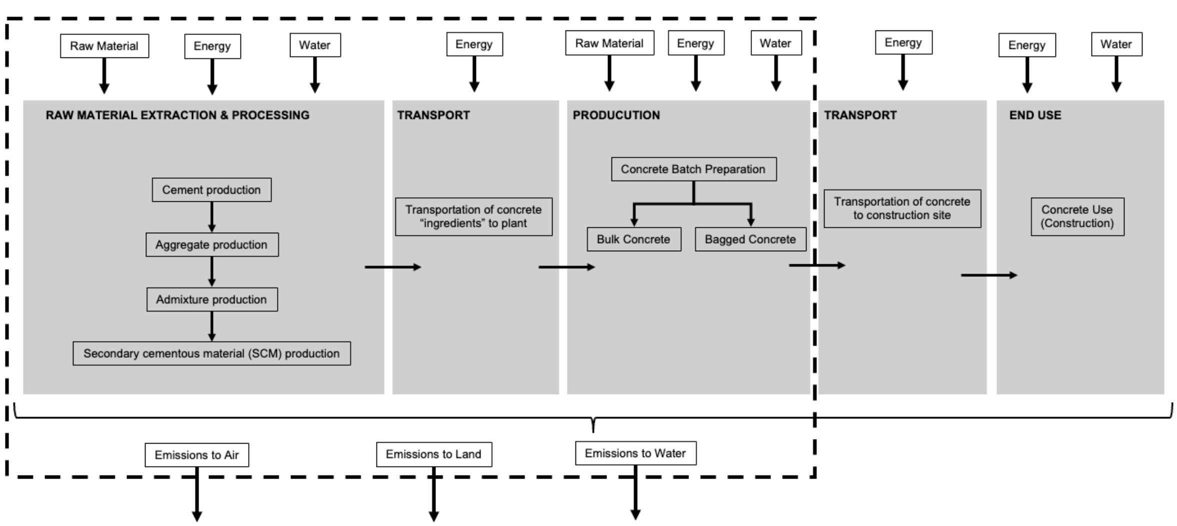

Figure 1 Simplified Concrete Production and Supply Chain

2.2.2 Steel

It is estimated that 1,500 M tonnes of steel are produced annually, accounting for 9% of global CO_2 emissions due to high material and energy requirements [45]. GHGs are naturally an important consideration in steel production, but often overshadow other environmental consequences of iron ore extraction and primary steel production. For example, high quantities are arsenic and other contributors to ecotoxicity were detected near Chinese steel producing facilities [46].

Steel is an alloy of iron and carbon. Iron is highly abundant in the Earth's crust and naturally occurs as iron ore, which encompasses a class of several solid iron oxide compounds. During smelting (i.e., heating) metallic oxygen is released from the iron ore, resulting in primarily metallic iron, along with slag. Upon exposure to extreme heat or electricity, the iron begins to react with carbon. Steel comprises approximately 0.2-1.5% carbon, which imbibes high strength without making it brittle, and therefore, renders an excellent building material. While low carbon iron materials have been used since about 2000 BCE, affordable steel was not produced until the mid 1800's [47].

Primary steel production methods lean heavily towards the basic oxygen furnace (BOF) method, followed by the electric arc furnace (EAF) method; the only top producers to utilize the open-hearth method as part of their operations included Russia (22.07%) and India (2.45%). Shifts is processing methods have led to significant decreases in energy consumption when it reached a peak in 1950 (63 gigajoules/tonne crude steel) and then began significantly declining (1990, 31 GJ/tonne crude steel; 1998, 21GJ/tonne crude steel). Energy consumption in steel production is projected to continue decreasing through 2030, despite increasing production [48]. Canada does not rank in the top steel producing countries, but as of 2020 was the 8th highest producer of iron ore globally [49], of which 40% is exported [46].

Secondary steel production refers to recycled steel. While steel is entirely recyclable, it is highly dependent on the availability of both quantity and quality of available scrap supplies and high recycled content can only be processed through EAF [43]. Utilizing both more recycled steel and less total steel is becoming increasingly important. A 2008 United States Geological survey estimated that at current extraction rates and unextracted quantities, iron ore mining could continue, on average, for just 79 additional years; heavy extractors such as China are estimated to run out of production volumes within 35 years [48]. **Figure 2** illustrates a simplified overview of steel processing, from a LCA perspective.

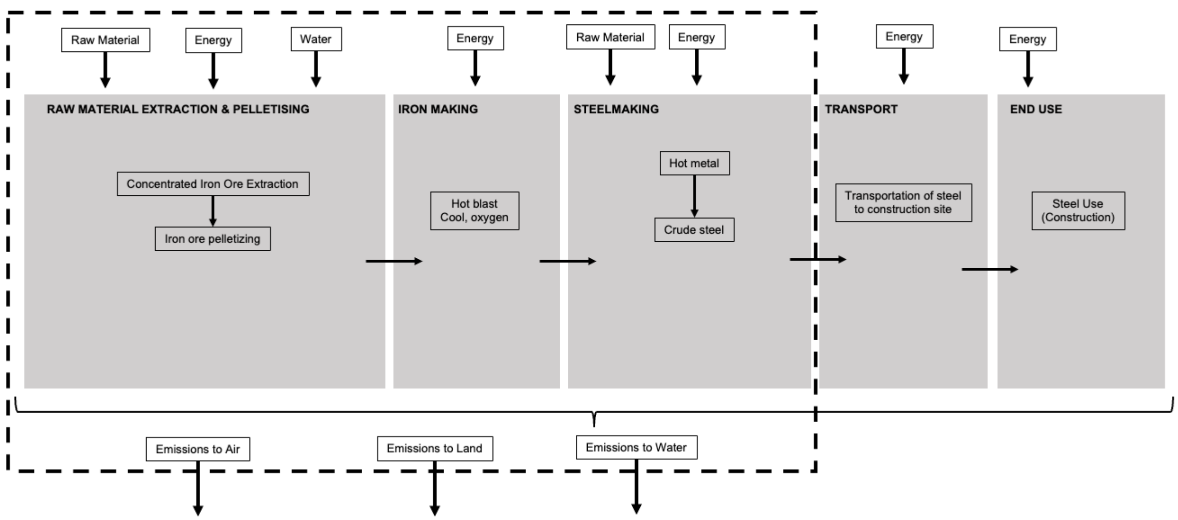

Figure 2 Simplified Steel Production (Blast Furnace) and Supply Chain

2.3 Wood for Low Carbon Construction

Since the 2015 Paris Agreement the focus on the built environment within the framework of sustainability has increased, notably with a 54.6% increase of Nationally Determined Contributions (NDC) which discuss building goals (88 to 136) and a 39.5% increase in investment in the building sector (129B USD to 180B USD) [12]. Wood, which utilizes CO_2 during growth through photosynthesis, is considered one of the most environmentally friendly construction materials due to its low embodied energy compared to other traditional construction materials, such as concrete and steel, which require significantly higher energy inputs to extract, manufacture, and ship [50]. On a percent mass basis, North American hard and softwood species range from 46.3-49.6% and 47.6-55.5% carbon, respectively [51].

Carbon uptake during growth: **sunlight + $6CO_2$ + $6H_20$ → $C_6H_{12}O_6$ + O_2**

Carbon release during decay: **$C_6H_{12}O_6$ + O_2 → $6CO_2$ + $6H_20$**

For simplicity, wood is generally characterized into two categories: hardwood and softwood. Hardwoods (angiosperms) are most easily distinguished for their branching forms, whereas softwoods (gymnosperms/conifers) are typically straight stemmed. Softwoods are considered more “workable” than hardwoods, though not necessarily the “softer” of the two [52]. Hardwoods such as oak and maple are commonly used for applications such as flooring and paneling. Conversely, softwoods such as cedar and pine are more often used for framing, scaffolding, or cabinetry; both hardwood and softwood species are available throughout North America and continue to be widely used in construction [53].

2.3.1 Engineered Wood Products and Mass Timber

Engineered wood (EW) was developed in the early 1990’s in Germany and Austria and became popular throughout Northern Europe in the proceeding decades [54]. Mass timber encompasses a group of engineered wood products, typically panels and beams, comprised of bonded solid wood in varying directional configurations, resulting in good structural, fire, acoustic and thermal properties, often used in tall wood buildings. Examples of current mass timber products include cross-laminated timber (CLT), glue-laminated timber (GLT/Glulam), nail-laminated timber (NLT), and dowel-laminated timber (DLT), among others [55, 56] (see **Figure 3**).

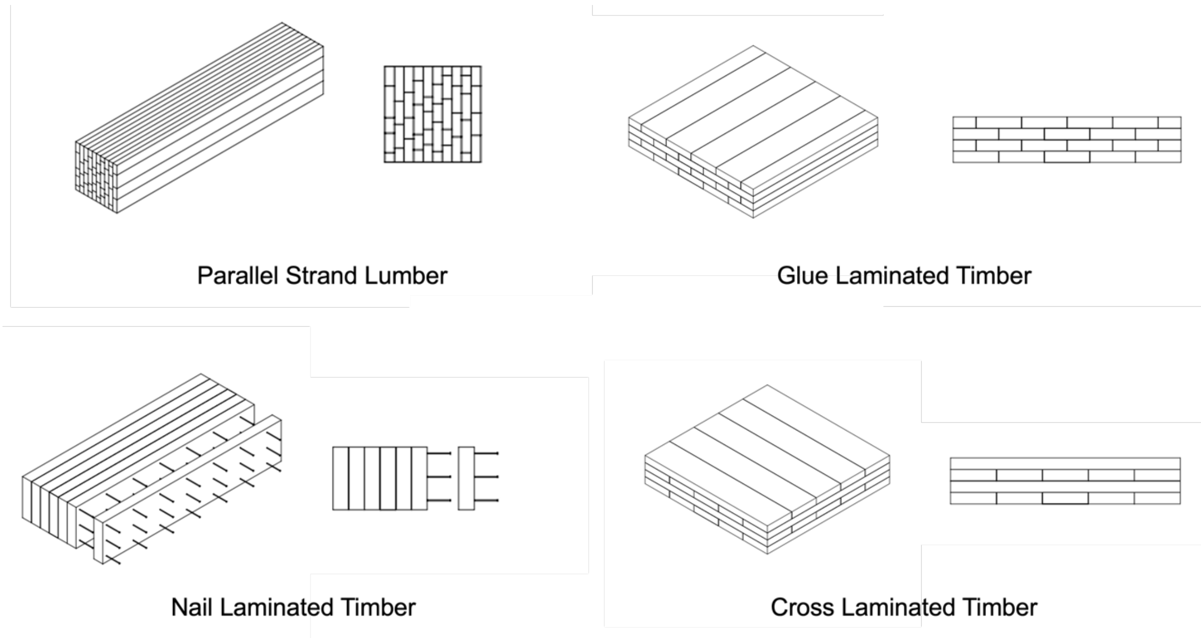

Figure 3 Examples of common types of engineered wood used in mass timber building; models created by author using SolidWorks 2021

An attractive distinction between utilizing wood and steel or concrete are a tree's ability to sequester carbon from the atmosphere during growth. Harvested timber then locks in the carbon and theoretically allows room for a new tree to grow, continuing the process, rather than releasing carbon during the raw material extraction phase [57]. Comparatives studies have illustrated the substitutability of mass timber construction in place of steel or wood, particularly in tall buildings (i.e., greater that 5 storeys) [54]. Common uses for EW in tall buildings include beams and columns (e.g., GLT/Glulam and DLT), flooring, walls, roofing (e.g., CLT and NLT), as well as in both stair and elevator shafts (e.g., NLT).

Table 1 outlines an overview of EWP produced in Canada, high-level specifications, and other key characteristics. While it is important to note that Northern Europe has a much longer history and output capacity of EWPs compared to North America, the focus of this project is on the North American market.

Table 1 Overview of common Engineered Wood Products, their construction uses, typical species used, and design considerations

Product	Uses	Species Used	Design Notes	Ref
Cross-laminated timber (CLT)	Floors, walls, roofs	Most common: Spruce-fir-pine, (NA) Norway spruce (EU) Others also used: Norway spruce White fir Scots pine European larch Douglas fir Western larch	• Unlimited size panels	[58], [59]
Glued-laminated timber (GLT, Glulam©)	Beams, columns	Most common: Spruce-fir-pine (NA) Norway spruce (EU) Others also used: Norway spruce White fir Maritime Pine Scots pine Sugar maple European larch Douglas fir	• Maximum dimensions: • 14000 mm L x 1200 mm W x 284 mm D • Higher compressive force resistance than CLT, but less ductility and prone to snaping/energy absorption	
Dowel-laminated timber (DLT)	Beams, columns, flooring, walls	Lamella-dowel UK larch-Beech Sugar maple Yellow birch Maritime pine- Beech Spruce-Beech Beech-Beech Irish spruce-Beech	• Does not require adhesive or adhesive requirement significantly reduced • Potential for dimensional changes with changes in ambient humidity	[60]

Product	Uses	Species Used	Design Notes	Ref
Nail-laminated timber (NLT)	Floor, decking, roof, walls, elevator shafts, stair shafts	Spruce Beech Any	• Unlimited size panels/products • Cannot be altered post manufacturing due to nails within product • Any species, grade, and size wood depending on intended use and design considerations	[59],[61], [62]

By some estimates, using wood as a replacement for conventional materials could decrease GHGs by 216 kg CO_2eq. per m^2 building floor footprint [63]. Likewise, Churkina et al. found that could store 186 kg of carbon per m^2 [64], with other groups noting a 3x savings in emissions when switching to engineered wood over conventional building materials [65]. Other research found that, on average, 1 tonne of wood used for building could replace 0.59 and 4.54 tonnes of steel and concrete, respectively. While the input of wood to steel substitution seems high on a per weight basis, the authors noted that the outsized environmental consequences of primary steel production resulted in environmentally beneficial emission outcomes (i.e., avoidance of 5.0×10^5 CO_2 eq. in 2017) which increased over the studied time horizon (out to 2050). Further benefits of utilizing mass timber as a replacement for traditional steel and concrete structures include decreased project timeline (4 days/10ft vertical versus 28 days/10ft vertical, respectively) while maintaining comparable cost for high-storey buildings [66].

2.4 Implications of Replacing Steel and Concrete with Wood

Responsible utilization of wood comes with several key considerations. Some studies have explored the possibility of compounding renewable resource use with a local-based economy, such as with case studies performed in Brussels and Montreal, assessing the feasibility of utilizing urban-grown wood [67]. However, while there be may positive aspects of utilizing locally grown materials, urban wood can hardly be expected to meet high throughout requirements for neighborhood, let alone, city level, construction needs.

Natural climate solutions related to timber that could have significant effects in Canada include improving forest management practicing, avoiding forest conversion into nanoforest land, and general restoration of forest cover. Forest management and restoration alone could mitigate an estimated 7.9×10^6 T CO_2 e/year by 2030. While restoration is estimated to have a minimal effect on a 2030-time horizon, further benefits are realized when the viewed out to 2050, at which point an estimated 2.5×10^7 T CO_2 equivalents could be mitigated annually. Based on these practices, in addition to other similar natural climate solutions, a reduction of 7.8×10^7 T CO_2 eq (i.e., the value of total Canadian emissions in 2018) could be met and at a price point below $50 CAD per Mg CO_2 eq [68].

Likewise, it is important to include rural stakeholders in the planning and forest management to ensure that the complexity for rural systems is adequately considered, as has been an issue historically in the field of planning theory. Canadian logging regions, such as Hautes Laurentides, have already shifted to a multistakeholder approach to managing forests, particularly with groups that have traditionally been considered local "non-experts" [69].

A map of concrete, steel, wood, and engine wood producers in QC can be found in **Figure 4**.

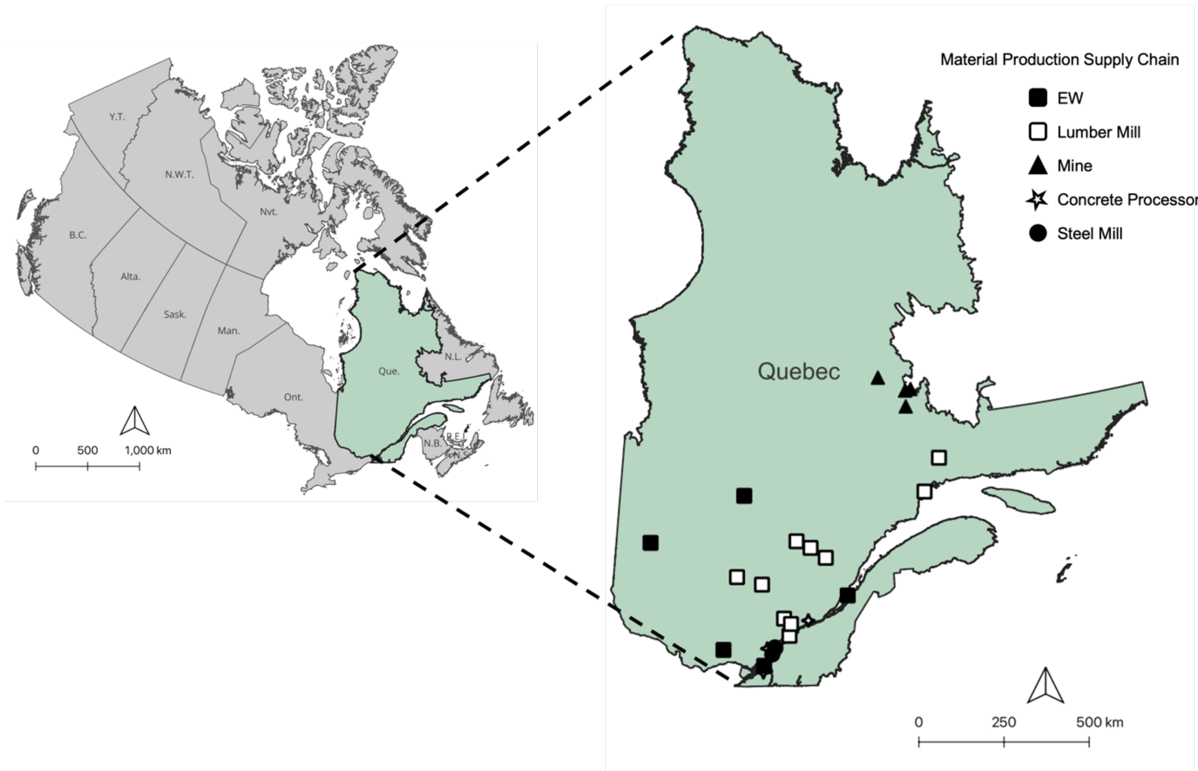

Figure 4 Material producers within the concrete, steel, wood, and EW supply chain across QC, Canada

2.4.1 Knowledge Gaps

It is important to determine if current assumptions on carbon neutrality for EW are correct. EW requires additional processing compared to light frame timber, and thus could exhibit a higher embodied carbon footprint. While EW allows for increased density through tall buildings, grounding our study in Montreal provides a clearer picture of its suitability in a city such as Montreal. Knowledge gaps exist on the potential costs and benefits of EW, both pertaining to Montreal, but also globally.

First, there is a lack of studies at the city scale since most are at building level. Assessing buildings one to one leaves out key factors in assessing the fuller picture how density and building typology interplay across the urban landscape. Evaluating the sustainability of upscaling can therefore be quite powerful since there are limits to the quantity of development that sustainable forest production cam support.

2.5 Review of Current Methods

To understand Montreal's urban metabolism (UM) a combination of Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) methodologies can be utilized. Here we use methods common in Industrial Ecology to measure and contextualize where and how materials are produced, where and how materials are used, and ultimately how these synergies impact the environment at both the rural and urban level.

Below we discuss frameworks of thinking about and modeling urban systems and their interconnectedness to the hinterlands from which they source the vast majority of resources, and how resource stocks are accounted for.

2.5.1 Life Cycle Assessment of the Built Environment

LCA is the framework by which the environmental impact of any process or product can be quantified using prescribed protocols It is important to note that LCAs cannot answer the question: *Is this sustainable?* but rather provide tool to compare processes for decision making. On a high level, LCAs comprise of several key factors: an inventory of the product(s) of interest, the impacts of related processes, and the boundary of the system being observed, among others [70, 71]

While guidelines exist to support LCA practitioners, variations in specific methods are used within LCA research to measure a process or systems impact across the built environment [72]. While many studies are the built environment exist, they often provide dissimilar functional units or study scopes, and are therefore difficult to compare against one another. This can be especially challenging when assessing sustainability within the built environment. Through a targeted literature review, Andersen et al. found that of 226 relevant journal articles, approximately 40% reported cradle-to-gate results, with options, while 50% reported impacts from cradle-to-grave, though chose to exclude the recycling potential which includes impacts beyond the buildings life cycle. Further, only 9% of studies reported biogenic carbon separately, a gap in knowledge that the authors here will address subsequently. Regarding impacts, 32% reported only final GHGs, while just 4% included land use and transformation in their impact assessment [19].

Table 2 is a non-exhaustive summary of recent literature on comparing EW and buildings to their standard concrete, steel, and wood counterparts. Here we focus primarily on recent studies in similar geographies to Montreal, QC. Most notable is the variation in accounting methods, system boundaries, and functional units used across the published literature. While a breadth of information is available, comparing results is notably difficult.

Table 2 LCA of built environment across various system boundaries for both whole building LCA and whole city per capita impacts

Unit	Notes	Boundary	Region	Year	GWP (kg CO_2eq.)	Ref
m^2 of building	CLT building	Cradle to site, w/o transport	Portland, OR	2020	193	[73]
	Concrete building				237	
m^2 of building	Light timber frame building	Cradle to gate	Växjö, Sweden	2022	151	[74]
	CLT coulometric module building		Nykvarn, Sweden		150	
	CLT building		Växjö, Sweden		203	
	Prefabricated RC building		Växjö, Sweden		390	
Whole building	Steel building - 5 story	Cradle to gate	PNW, US	2021	1213	[75]
	Mass Timber building - 5 story				826	
	Steel building - 12 story				4112	
	Mass Timber building - 12 story				2596	
m^2 of building	CLT building (base scenario)	Cradle to grave	Scandinavia	2021	0.0569	[76]
	CLT building (embodied)				0.0361	
	Concrete building (base scenario)				0.112	
	Concrete building (embodied)				0.112	
	CLT m2 (biogenic)				-102.953	
	Concrete building (biogenic)				449.885	
m^2 of building	CLT building - Fossil CO_2	Cradle to grave	Portland, OR	2021	193	[77]
m^2 of building	CLT building - Biogenic CO_2				81	
m^2 of building	CLT building - Stored CO_2				-276	
Whole building	8 story building	Cradle to gate	New Haven, CT	2016	-4.60E+04	[78]
Per capita	Whole city, residential housing	Cradle to grave	Toronto, CA	2006	3.3	[79]
Per capita	Whole city, residential housing	Cradle to grave	Hammarby Sjostad, Sweden	2003	2.8	[80]
Per capita	Whole city, residential housing	Cradle to grave	La Rochelle, France	2005	0.6	[81]

2.5.2 Urban Metabolism

Urban Metabolism is the research field by which industrial systems are modeled as natural cities are represented as living organisms, due to their inherent ability to consume inputs and produce waste outputs. In likening the city to an organism, it is an obvious next step to study their metabolism. Kennedy et al. describe the UM as "the sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste" [1].

Industrial Ecology is the study of industrial processes as if there were natural ecosystems to understand how materials flow through that locale. This high-level understanding of local ecosystems can be disseminated across a variety of interdisciplinary perspectives, namely engineering (i.e., simple resource accounting), economic (i.e., effect of politics on resource and pollution flows), or ecological (i.e., the effect of pollution, resource access, and urban form on the city ecosystem) [82, 83].

Opening the "black box" of metabolic flows has been explored by multiple groups regarding both the city [2] and its hinterlands [84, 85]. While urban locales were once considered only on a local basis, the increasing threat of climate change, as well as the growing rate to which urban populations are growing, has underlined the need to examine the footprint of cities, especially in relation to resource-producing rural regions [82]. Industrial ecologists utilize tools such as LCA to quantify the accounts and/or impacts of materials and processes across a variety of industrial processes [71].

2.5.3 Material Stock Analysis

Material stock studies have been carried out extensively on both the urban and national level across the world using a variety of approaches. Breaking down the city into its parts is necessary to not only understand the current landscape (i.e., physical, political, etc.) but to also determine the characteristics related to growth, expansion, population, land-use, etc. It is imperative to link material use and environmental impacts to the built form and urban morphology to support materially “lean” and climate-friendly urban growth in Canada and beyond. While increasing effort has been made to integrate the impacts of construction to urban planning exercises (e.g., using MFA), studies by governments remains disjointed or underutilized. For example, in Toronto, studies have been limited by the scope of publicly maintained and/or available data on both new and rehabilitated infrastructure [86]. Thus, researchers have called for increased attention paid to further develop and share Bills of Materials (BOMs) – master lists of all the materials and their quantities used in a buildings construction – in order to close knowledge gaps on the environmental impact by the built environment [7, 87].

Coupling standard archetype methodologies with geographic information system (GIS) data helps to minimise the inherent uncertainty of current building stock models and has been utilized by a variety of researchers. Coupling an archetype/GIS method with real-time data tracking could help improve models even further [7]. Comprehensive overviews of modeling best practices has been outlined by several groups, with ongoing studies in process [2, 71],[88].

While studies of UM around the world have increased in recent years, political and planning decisions based on these findings have lagged. This indicates a gap where better policy could be explored based on empirical data, rather than happenstance and unplanned urban growth. This is particularly evident on the municipal, rather than national or global, scale, with a focus on regions undergoing rapid development [89]. Maintaining detail rich inventories of secondary materials for the built environment would also allow for more input into the circular economy and then reducing material waste [25]. Of course, a lack of reliable data can render material stock models highly variable [89], and highlight the importance of meticulous, albeit bureaucratic, data reporting to feed into planning policy.

To alleviate pain points commonly experienced in MFA practitioners such as Stephan et al. proposed an in-depth take on the bottom-up approach which assesses individual BOMs rather than building archetypes at the city level using Melbourne, Australia as a case study [30]. While this method provides a high level of specificity related to the as-built environment, intrinsic uncertainty associated with this method must be addressed according to data quality. It should be noted that non-residential buildings are typically closer approximations of the BOM [30]. Additionally, it has been shown that bottom-up estimation of materials stocks is characterization by generating spatially explicit data which quantifies materials at the building level, allowing for better specificity than top-level approaches (i.e., national, global level estimations), and up to 10 m spatial resolution [28].

2.6 Case study

Given these unknowns I am eager to contribute to our collective understanding of what currently exists at the urban scale and how future shifts in material use or settlement patterns could potentially affect change at the city scale. Moreover, there are not many studies at urban scale and none in Montreal (see **Table 2**). As discussed, enthusiasm over the potential for EW construction has increased in recent years. While there appears to be some preliminary findings on the benefits on EW, we aim to look beyond the hype and consider potential impacts of Agglomeration-wide adoption of EW in Montreal.

Montreal makes a good testbed for trying to understand the implications of upscaling EW. Montreal is in QC which contains an active timber industry and growing EW producer presence. Urban-rural linkages are prominent between QC and Montreal for both wood and other materials. Because of this, there is potential to stay within the province to develop urban centers in QC, such as Montreal. Avoiding assumptions that local production can or even should be pursued is important for rural and urban stakeholders, alike.

The Montreal Agglomeration is also broken into distinct *arrondissements* and independent municipalities, which all have their own settle patterns and unique histories. Comparing how EW performs on a city-wide basis, but also on a neighborhood scale could provide ample information for future urban decision making.

2.6.1 Montreal

According to a 2016 study, Montreal is the second densest city in Canada with a population density of 4,916 inhabitants/km^2 across 346 km^2 [90]. The boundaries of the city of Montreal are geographically constrained by the Fleuve St-Laurent (St. Lawrence River) on the south and east and the Rivière des Prairies (Prairies River) to the north-west. Access to the St. Lawrence provided an economic boom for Montreal during its establishment as a key manufacturing and economic hub [91]. The city limits of Montreal are largely developed, though room for growth in undeveloped land, or areas amenable to further development do still exist. **Figure 5** hows the skyline of Montreal, typified by high-rise construction and surrounded by plex-style housing and, to a smaller extent, mid-rise residential buildings and single family homes.

Figure 5 Skyline of Downtown Montreal, showing high-rise construction, plex-style housing, and mid-rise residential buildings (single family homes, not shown); photo taken by author

Population has increased in Montreal in the past half decade with Montreal and surrounding suburbs growing rapidly compared to other urban areas in Canada.

Population rates within downtown Montreal increased 24.2% from (21,340 residents) while the urban fringe increased by 2.1% (14,846 residents) from 2016-2021. Surrounding suburbs also experienced growth between 3.4-7%. [33].

The city of Montreal is currently assessing a strategic growth plan coined The 2050 Urban Design and Mobility Plan (PUM 2050, le Plan d'urbanisme et de mobilité 2050), which is set to go into effect in 2023 [92]. Since 2004, "The Master Plan" has served as a guide for all urban planning initiatives for residential, commercial, and industrial projects with zoning and by-laws specific to each borough. Notably, the Master Plan outlines the need to both "maintain the built form of established areas" while also ensuring "adequate building density on sites to be built for residential purposes…". The Master Plan has also targeted areas in Montreal to either be built or transformed [16].

An important consideration in Montreal's expanding urban development is gentrification, which remains a key issue for numerous transition districts, which have seen increases in development of high-rise condominiums [91] highlighting the need for strategic growth in high density housing that serves Montreal inhabitants. Overall, Montreal provides an interesting basis on which to perform such a study, due to the governmental emphasis on environmentalism and ongoing city planning initiatives.

2.6.2 Wood and EWP Production in Canada and QC

As of 2021, QC forestry contributed 22% of Canadian national wood supply across approximately 31.86 M hectares of publicly available (i.e., provincial and federal) land. As of 2019, the wood harvest in QC amounted to $275 M CAD in revenue [93]. Understanding how local production rates can support local building projections will be a key factor in pursuing innovative avenues of local material flow. Reasonably, there is concern that an increase demand for wood products could result in a shift away from sustainable forest management [94], which has already been a hurdle for stakeholders in areas of high production and/or demand. Canada contains both vast tracks of forested land and a variety tree species used within the construction material industry. Properties of various tree species prevalent throughout Canada have been studied extensively over the past century by forestry researchers. Distribution of all species across Canada, as well as density averages are summarized by Beaudoin [95, 96] and Gonzalez [97] and will therefore not be reproduced here in their entirety.

Table 3 highlights hardwood and softwood species throughout QC and Canada and their distribution volumes.

Table 3 Key Tree Species Across Canada Used in EW Manufacturing

Species	Type[1]	% Forest Distribution		
		Non-Boreal	**Boreal**	**All Canada**
Birch	H	6.9	3.0	3.9
Cedar & conifers	S	4.4	0.1	1.1
Douglas-fir	S	5.9	--	1.3
Fir	S	14.5	3.9	6.3
Hemlock	S	7.0	--	1.6
Larch	S	1.0	3.1	2.6
Maple	H	10.9	0.1	2.6
Other hardwoods	H	1.6	0.1	0.4
Pine	S	14.8	9.9	11.0
Poplar	H	9.1	11.3	10.8
Spruce	S	17.0	62.5	52.1
Unclassified	-	4.4	4.5	4.5
Unspec. conifers	S	1.4	1.2	1.2
Unspec. hardwood	H	1.2	0.3	0.5
Total	**-**	**22.8**	**77.2**	**100.0**

As of 2022, 593 mass timber projects were completed throughout Canada, with another 74 under construction, and 35 more in planning stages. Of these 664 completed and uncompleted projects (excluding bridges), the vast majority were between 1-7 storeys (94%), while 27 (4%) were between 8-12 storey buildings, and 8 (1%) will stand greater than 13 stories tall, though it is notable that only 3 (0.45%) of 13+ storey buildings are either completed or currently under construction. Producers of mass timber located in QC had a combined production capacity of 135.5k m^3 manufacturing capacity, about 12.5% of Canada's total current production capacity (1.1M m^3) despite

[1] Type refers to hardwood (H) or softwood (S)

making up a quarter of the production facilities in the country. Today there are nearly 20 major players in the mass timber sector, 5 of which are based on QC [98].

Respondents to a 2017 governmental survey in QC indicated that 72% of firms utilized engineered wood products for new residential and/or commercial buildings. 56% and 38% acknowledged the use of engineered wood in multiple-unit houses or in industrial buildings, respectively. Nearly half (46%) of sales of all QC wood products remained within the QC market, with another 33% moving into the US. The authors noted that the majority of these secondary manufacturing firms were located in southern QC, and benefitted from well-established supply infrastructure and were close to urban centers, as is highlighted in map ***Figure 4*** [99].

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 [96]. The Boreal forest, also known as Taiga, comprises approximately 33% of all global forested land, of which 27% is located within Canada [100]. While there is mounting concern surrounding protections for Canada's old growth forests, very little of the Canadian Boreal is older than 100 years. This has largely been due to a variety of natural (e.g., wildfire, insect infestation) and anthropogenic (e.g., agriculture, construction, wood products, mining, energy) disturbances [101]. Nonetheless, protections of this carbon rich environment are vital to both sustainably harvest wood while also maintaining the environmental integrity of the region.

Connecting Text to Chapter 3

In **Chapter 2** we conducted a literature review of key production and supply chain dynamics for construction materials, as well as their environmental impacts. We also delved into recent studies into the carbon impact across the built environment. We found there were gaps in whole city LCAs and per capita environmental metrics, as many studies focus on single buildings. We did a review of appropriate methods within the fields of Industrial Ecology and Urban Metabolism, and key considerations for applying LCA methodologies to our study city. **Chapter 3** is a manuscript submitted to Environmental Research: Infrastructure and Sustainability, special issue Carbon Storage in the Built Environment. The paper is currently under review. Felicity Meyer is lead author on the paper submitted for review on 03 August 2023. The manuscript provides a bottom-up accounting of Montreal to address the research questions posed.

The following manuscript contains edits not included in the initial journal submission. The edits include:

- Duplicated “s” removed from “high-rises s”
- “An estimated that 1.5 Gt of steel are produced annually…” replaced with “It is estimated that…”
- Cross reference error message resolved

Chapter 3. Submitted Manuscript

A multi-scale model of the environmental impacts of low-carbon construction on the Island of Montreal

Submitted for publication in the peer reviewed journal, Environmental Research: Infrastructure and Sustainability, special issue Carbon Storage in the Built Environment

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Abstract

Engineered wood (EW) can reduce the 40% of global carbon emissions from the building sector by substituting carbon-intensive concrete and steel for carbon-sequestering wood. However, studies accounting material use and embodied carbon in buildings rarely analyze the city-scale or capture connections between the city and supplying hinterlands. This limits our knowledge of the effectiveness of decarbonizing 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 analyze the carbon emissions and land occupation from future residential construction in Montreal, Canada. We compare material demand and environmenetal impacts of recent construction using concrete and steel to construction using EW at the neighborhood and city and agglomeration scales under high- and low-density urban growth scenarios. We estimate that baseline embodied carbon per capita across the Agglomeration of Montreal is 2.0 tons CO_2eq., but this ranges from 5.3 tons CO_2eq. in areas with large homes and mostly single family housing to 1.4 tons CO_2eq./capita where smaller homes and apartments predominate. Surprisingly, an Agglomeration-wide transition to EW may increase carbon footprint by 28% due to higher total material needs, but this varies widely across the city and is tempered through urban densification. Despite this, a transition to EW only requires 0.2% of Quebec's timbershed. Moreover, sustainable logging practices that sequester carbon can actually produce a carbon-negative building stock in the future. To decarbonize future residential construciton, Montreal should enact policies to simultaneouly promote EW and urban densification in future construction and work with construction firms to ensure they source timber sustainably.

Keywords: building material stock, embodied carbon, life cycle assessment, EW, concrete

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1. Introduction

Constructing and operating buildings directly and indirectly produces 40% of global carbon emissions [1]. Much of this activity is in cities where most people and economic activity reside. This makes cities key nodes in decarbonizing the building sector globally. Decisions surrounding the construction of new buildings and neighborhoods in cities are critical to this effort as they heavily influence both the carbon 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: concrete, steel, and wood. Two of these, concrete and steel, are very carbon intensive. 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 aesethic purposes [6]. Concrete, which is typically 95% cement by mass, accounts for 8% of global greenhouse gas emissions (GHGs) due to the release of carbon during calcination, as well as from energy inputs from other non-cementous material production [7, 8]. As of 2014, global concrete consumption was estimated to be 25 Gt per year, equating to 2.6 Gt of CO_2eq. alone [5, 9].

After concrete, steel is the most used material in construction. Steel represents <1% to 25% of residential building mass and is necessary for framing and structural stability, particularly in high-rises [10-15]. It is estimated that 1.5 Gt of steel are produced annually, accounting for 9% of global CO_2 emissions [16]. Primary steel is produced mainly using the basic oxygen furnace method, followed by the electric arc furnace method; the only top producers to utilize the open-hearth method as part of their operations included Russia and India, which produce 22.07% and 2.45% of global steel, respectively [10-15].

Recently, there has been a broad push in the construction sector to use wood as a low-carbon substitue for concrete and steel. 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., >5 stories). Unlike steel and concrete, producing wood sequesters carbon via photosynthesis [17]. If harvested in a way that maintains soil, wood can be very-low carbon or even act as a carbon sink. By some estimates, replacing conventional materials with wood decrases emboided carbon by 216 kg CO_2eq. per m^2 building [18]. Likewise, Churkina et al. found that wood sequesters 186 kg of carbon per m^2 [19], with other groups noting a three-times savings in emissions when switching to EW over conventional building materials [20]. Others have found that one ton of wood replaces 0.59 and 4.54 tons of steel and concrete, respectively with considerable reductions in carbon, even when considering increased mass requirements compared to steel.

Despite the low-carbon potential of wood in future urban construction, knowledge gaps remain. 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 [10, 12, 14, 15, 21-25]. Thus, we do not know how much wood future cities need to substitue for steel and concrete nor how much this will shift embodied carbon emissions from 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 [26-28], such as land use impacts and impaired ecosystems functioning to supply massive volumes of timber.

Here, we begin addressing these knowledge gaps through 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 life cycle assessment (LCA) to estimate the carbon footprint of our scenarios. 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 many major players in the EW industry. The use of EW in Canada is on the rise, with nearly 700 recent projects ongoing or completed, with many in Quebec. Montreal has also committted to reducing the carbon footprint of new buildings, including through the use of renewable building materials [29]. Given the continuing shift towards EW and the tendency for local wood supply in Quebec, it is essential to apraise 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.

We find 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 carbon dynamics [30]. Urban densification can further reduce emissions under most scenarios including when concrete and steel use remain signficant. Prioritizing urban densification and building smaller homes using EW that are designed in a locally sensitive way can work synergistically to abate emissions from the construction sector and help Montreal achieve its decarbonization goals.

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 2050 and the carbon emitted from producing and transporting those materials. Below we detail our case city, Montreal, our data sources, and modeling framework.

2.1 Case City: Montreal

Montreal is the second largest city in Canada with 3.7 million people living in the metropolitan area [31]. Our analysis focuses on the Montreal Agglomeration (**Figure 6**) which has 2.0 million inhabitants on the 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* (municipalities/neighborhoods), along with 14 independent municipalities spread across the rest of the Agglomeration [32, 33].

The Montreal Agglomeration contains a diverse range of development patterns with a distinct urban core and the 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 (VM), Westmount (WM), and Côte-des-Neiges-Notre-Dame-de-Grâce (CN). 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 population in post-1960 housing ranges from 100% in suburban Kirkland to 16% in Montreal-Ouest. **Figure 6** shows the existing breakdown of housing types in post-1960 housing in across the Agglomeration's municipalities and arrondissements, their geographical distribution across the Agglomeration, as well as high-density areas (>5,000 people per square kilometer). There is a clear tendency towards single family homes and larger floor area per capita outside the urban core with exception of wealthy enclaves (e.g., Westmount).

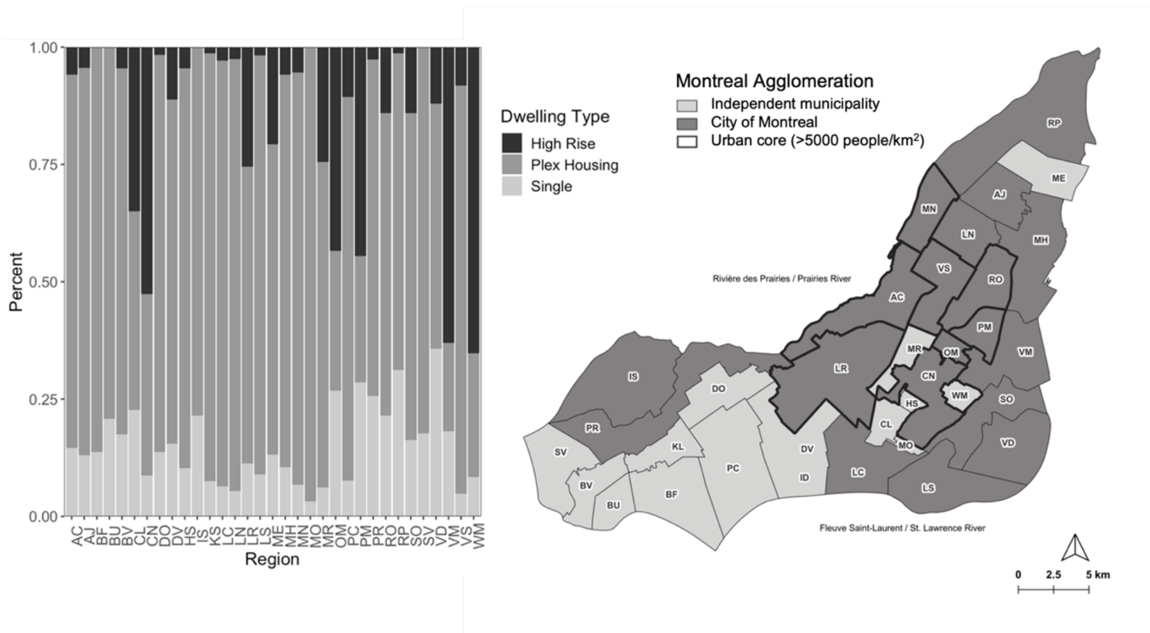

Figure 6 Administrative limits across the Montreal Agglomeration floor area distribution of housing typologies (Left) and floor area per capita (FAC) of post-1960 dwellings (Right)

2.2 Montreal Building Data

Our model analyzes each individual residential building constructed after 1960 on the Montreal Agglomeration to estimate the concrete, steel, and wood stocks in these buildings. We use tax assessor data pulled from the Montreal Property Assessment Database [34] 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 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 database entries have extremely large floor-areas (>5000 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 1500 m^2 per unit or below 10 m^2 per unit. 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 [35]. While some of these entries are likely correct, visual inspection using Google Streetview (www.google.com/maps/) confirms most as erroneous. After removing outliers, our final dataset contains 148,640 residential units across the Agglomeration (see Supplementary Information for the distribution across the agglomeration).

2.3 Estimating Concrete, Steel, and Wood

To estimate tons 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 meter for different housing typologies [9]. Each entry was classified as one of three typologies: single detached, semi-detached housing (single through quadplex), and high-rise apartments five storeys 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 while historic construction differs between the two cities (Montreal's iconic duplex style housing prevalent in neighborhoods such as Le Plateau, for example), but post-1960 construction in both cities is more uniform in form and materials.

Guven et al. scored data quality from 1-5. 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 per square meter 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 storeys 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.

The number of people living in post-1960 construction in each neighborhood is estimated as the product of the average number of inhabitants per dwelling times the number of post-1960 dwellings. The floor area per capita (FAC) is taken as the total square meters 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. Adjusted population is used in all relevant per capita calculations below (e.g., tons of CO_2eq./capita).

2.4 Embodied carbon and land transformation

Carbon intensity and land transformation values for concrete, steel, and wood are taken from the ecoinvent 3.8 database (www.econivent.com) in OpenLCA (www.openlca.org) using the cut-off modeling framework [36, 37] 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_2 equivalents (CO_2e). We also run a scenario using IPCC 100a method with carbon uptake to assess the implications of biogenic carbon on the carbon calculus (see Discussion). **Table S1** in Supplementary Information details the different processes used in ecoinvent 3.8 and their carbon and land intensity factors. We assume materials are produced in Quebec. 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 [38]. Land transformation is determined from the sum of all land transformation flows and converted to impact on a per ton of material basis.

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 kilometers (km) from Montreal; likewise, end stage EW producer

Nordic Structures is 500 km away. Distances are taken ‘as the crow flies’ and without road network analysis. As nearly all processes are Quebec specific, no further transport is added for raw material extraction, product processing, and transportation stages of the life cycle. Where the amounts of a material produced at different sites are known (e.g., tons of steel per producer), weighted average distances are used, otherwise, we use unweighted averages. For concrete and steel, we identify where quarries are located through a Canadian government Principal Mineral Areas, Producing Mines, and Oil and Gas Fields dataset [38]. Production quantities are obtained through industry reports [39, 40], press releases [41-44], and global steel tracking databases [45, 46]. Forestry activity was reported in Canadian governmental reports [47, 48]. EW producers and project data is collected using the Canadian State of Mass Timber map and report [49, 50].

Specific End-of-life scenarios are not included in the model due to the inherently long lifespan of buildings. While there is increasing interest in the circular construction economy both by academics [51-53] and practitioners [54], 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 considered in the discussion.

2.5 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 4 details each scenario. Business as usual (BAU) models current building material profiles for dwellings typologies and settlement patterns (i.e., distribution of housing types and floor area per capita) for each arrondissement or independent municipality. For EW material scenarios, bills of materials (BOM) per square meter (gross floor area) are developed based on literature which tracked cross-laminated timber (CLT) and glue-laminated timber (Glulam/GLT) EW based apartment/high-rise style buildings [10, 12-15]. Changes in material use are reported for the entire building and did not clarify specific modifications. This allows us to estimate changes on a square meter 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 tons material was also reported. All quantities are converted from m^3 to total tons. The average tons/m^2 of EW quantities are applied to apartments five storeys 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 utilizes very little steel. EW low-rise and single family construction exists but is uncommon and not considered here.

For urban densification 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 5000 person/km^2, which corresponds to thresholds for supporting transit-oriented development, walkability, and other urban synergies. For existing high-density neighborhoods, 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 Supplementary Information for details on material intensities for the engineered-wood scenarios and the morphological characteristics for the urban densification scenarios across the Agglomeration.

Additional floor area needs by housing type are determined using population projections published by the Government of Quebec [32] 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 Montreal will lose population between 2021 and 2040 (i.e., Baie-D'Urfé, Dollard-Des Ormeaux, Dorval, L'Île-Bizard-Sainte-Geneviève, and Westmount); in these cases, additional floor area requirements are assumed zero.

Table 4 Material and settlement patterns for four Montreal development scenarios through 2040

Scenario	Material Profile	Settlement Pattern	ecoinvent Processes

<table>
<tr><td>BAU-BAU</td><td rowspan="2">BAU
“Business as usual”)</td><td>BAU for each municipality/arrondissement</td><td rowspan="2">• Concrete, average all densities, CA-QC
• Steel, CA-QC
• Softwood beam, average of kiln and air dried, CA-QC
• Freight lorry, EURO6</td></tr>
<tr><td>BAU-UD</td><td>Urban densification, UD</td></tr>
<tr><td>EW-BAU</td><td rowspan="2">EW
(“EW”)</td><td>BAU for each municipality/arrondissement</td><td rowspan="2">• 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</td></tr>
<tr><td>EW-UD</td><td>Urban densification, UD</td></tr>
</table>

3. Results

The material impacts of developing Montreal are significant and substantial. For BAU, the material footprint of Montreal inhabitants is 3.1 tons CO2eq./capita. For BAU-US this decreases to 2.7 tons CO2eq./capita but increases to 7.0 and 4.9 tons CO2eq./capita when considering EW-BAU and EW-UD scenarios. Our model of material stock embodied carbon in Montreal’s residential building stocks shows that carbon 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 impact using our standard IPCC GWP 100a life cycle assessment methodologies. Development scenarios which prioritized densification resulted in lower intensity per capita across many of the Agglomerations neighbourhoods and municipalities. Changes to baseline impacts are lowest in neighbourhoods that already fit ideal material and/or density scenarios. 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.

3.1 Impact Across Building Types

Figure 7 shows the tons of different materials and tons of CO_2eq. per m^2 of each dwelling type (excluding biogenic uptake). High-rise apartments (i.e., ^{3}5 storeys) are the most material and carbon intensive of the building typologies. They require 0.96 tons/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 tons/m^2) and single family (0.39 tons/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 tons/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 carbon intensity of concrete translates directly into high carbon footprints for high-rises. This housing type has 0.121 tons CO_2eq./m^2, twice as carbon intensive of semi-detached (0.06 tons CO_2eq./m^2) and single family dwellings (0.05 tons CO_2eq./m^2). Interestingly, while current high-rise apartments require more concrete and steel per unit area compared to EW construction, their carbon intensity is only marginally higher than EW alternatives due to the high embodied carbon of EW products (0.115 tons CO_2eq./m^2). Strikingly, while the material mass is greatly reduced with EW, this does not translate into significant carbon savings when biogenic emissions are not considered. EW construction only offsets approximately a quarter of a building's mass of concrete and steel per m^2 compared to the traditional structures made of concrete, steel, and wood, of which the CO_2eq./m^2 impact is made up for by the EW material, as shown in **Figure 7**.

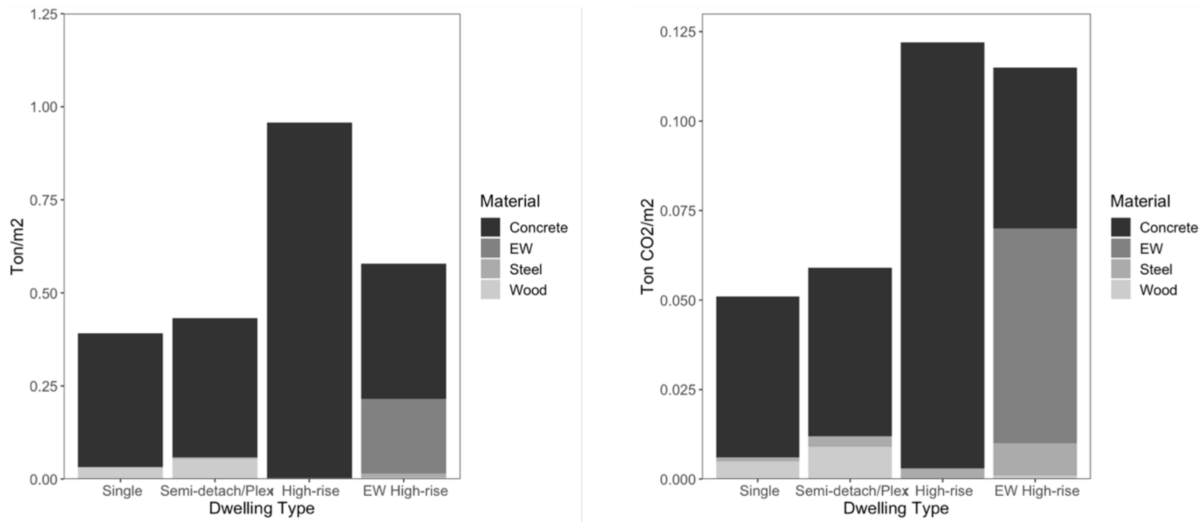

Figure 7 Total material quantity in tons per m² across housing typologies (Left). Carbon intensity in tons per m² across housing typologies (Right).

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

3.2 Material Intensity Across the Agglomeration

Figure 8 shows the tons of concrete (A), steel (B), and wood (C) per capita across the Agglomeration. In terms of combined material intensity, the top three areas of the Agglomeration are Senneville (49.2 tons/capita), Hampstead (38.9 tons/capita), and Westmount (32.5 tons/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 tons per capita, but this ranges from 12.5 tons/capita in Montreal-Est to 42.7 tons/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 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 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 tons/capita or less. Again, Senneville, with its large suburban homes, has the highest per capita steel use (0.4 tons/capita).

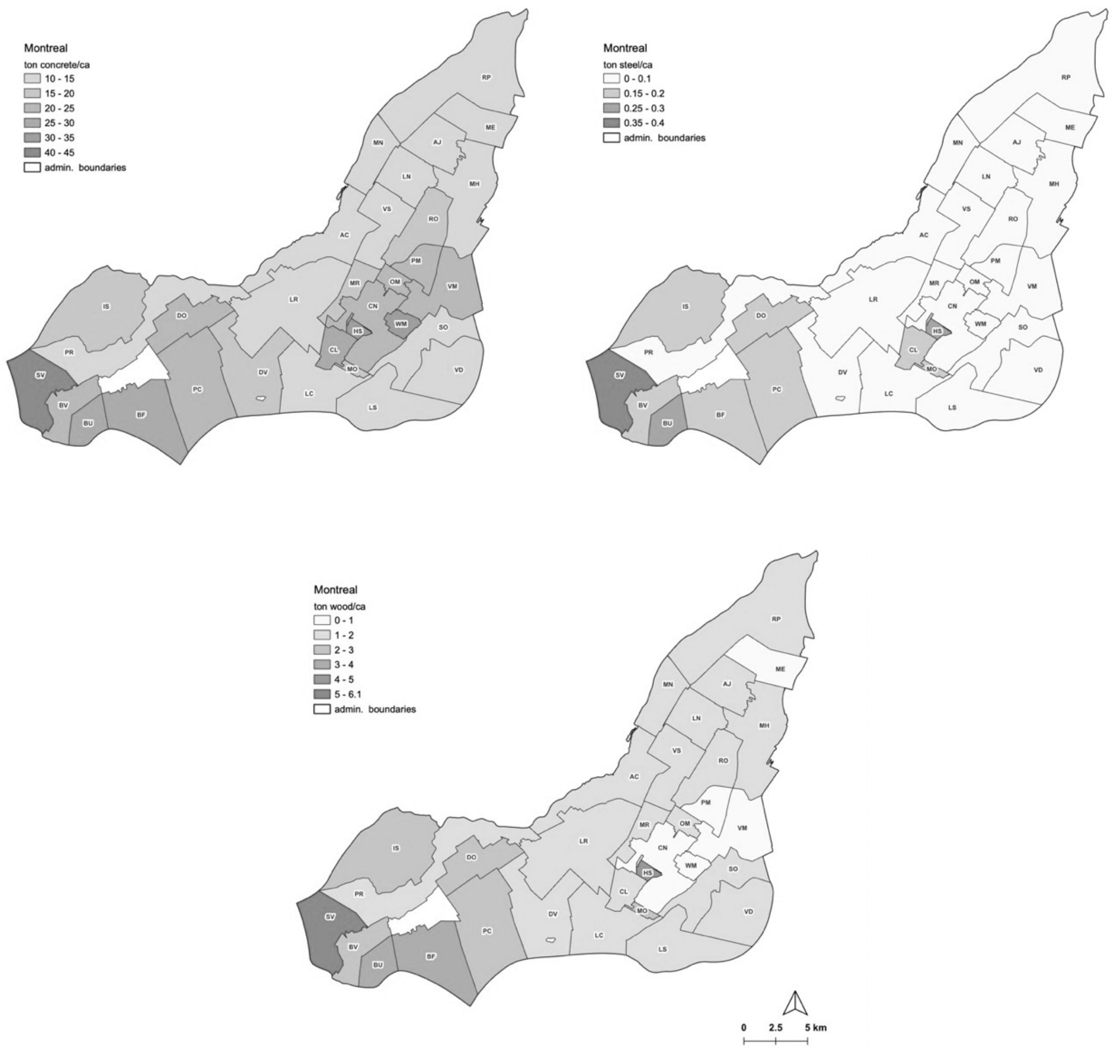

Figure 8 Current material density in tons per capita across the Agglomeration of Montreal's neighborhoods and municipalities for concrete (Left), steel (Middle), and wood (Right).

3.3 Embodied Carbon in Recent Construction

Average carbon emissions across the Agglomeration were estimated to be 2.7 ± 1.3 tons CO_2eq./capita ranging from 1.9 tons CO_2eq./capita Montreal-Est up to 7.7 tons CO_2eq./capita Senneville. 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/capita) and land area per capita. Unsurprisingly, low-density suburban regions beyond the urban core exhibit the highest per capita impacts, namely Senneville (7.7 tons CO_2eq./capita), Hampstead (HS, 6.1 tons CO_2eq./capita), and Baie-D'Urfé (4.9 tons CO_2eq./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 carbon 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 generally lower FAC, also had elevated impact, primarily due to an increased need for concrete and steel in construction. Interestingly, there was little correlation between pre-tax income, housing types across neighbourhoods, or percent of new construction with BAU-BAU embodied carbon impact per capita. Likewise, while there was some correlation between high FAC and low population density, they are not interlinked.

Areas with the lowest impact were found to be those with high rates of new construction and a mix of housing types. Montreal-Est (1.9 tons CO_2eq./capita), Le Sud-Ouest (2.0 tons CO_2eq./capita), and Verdun (2.0 tons CO_2eq./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 materially Usage. 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-Marie, 3.9 tons CO_2eq./capita) and low rates of post-1960 construction (e.g., Outremont, 3.9 tons CO_2eq./capita).

3.3 Embodied Carbon in Future Scenarios

For potential development scenarios, densification reduced carbon 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 carbon 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 271% and 195% increase in embodied carbon was observed in EW-BAU and EW-UD, respectively.

Figure 9 shows per capita embodied emissions across the entire Agglomeration for the four scenarios. Montreal can reduce embodied carbon in future construction by only 1.9% relative to baseline using current materials and denser settlement patterns. Interestingly, both EW scenarios resulted in increased carbon impact of approximately 2.3 and 1.6 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 carbon 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 per 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 explored here. Additional impacts drivers come from underground parking in the high-rise buildings for both standard and EW buildings, where concrete was used.

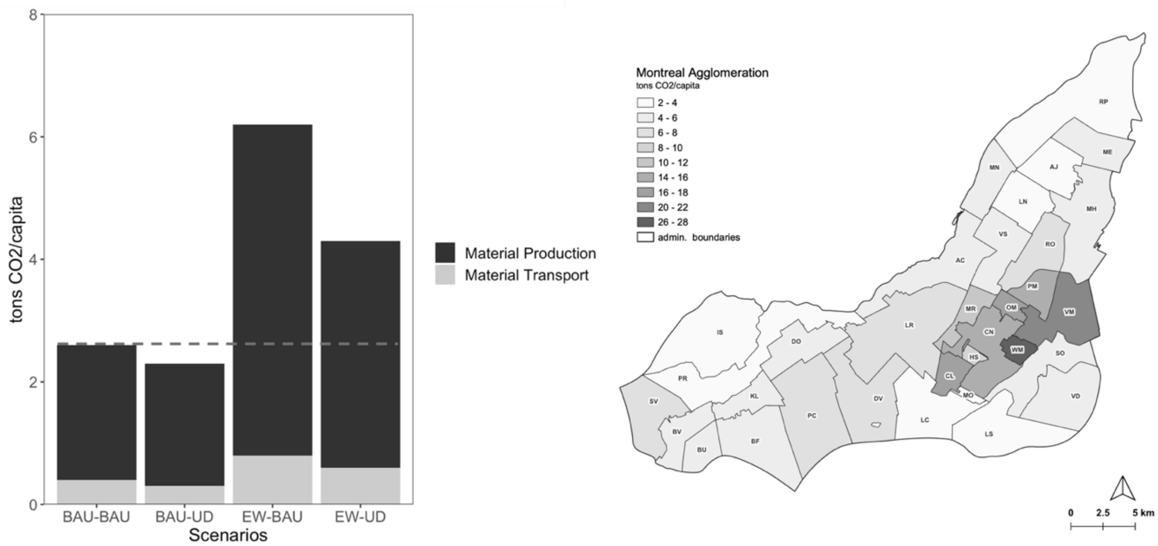

Figure 9 Weighted average carbon impact across building scenarios (Left). Tons CO_2 per capita on the Agglomeration of Montreal for EW-BAU development (Right).

City-wide metrics mask how different areas of the Agglomeration perform under our scenarios. **Figure 9** 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 Supplementary Information 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 tons/capita. Notably, Côte-Saint-Luc (CL), Westmount (WM), Outremont (OM), Ville-Marie (VM), Le Plateau-Mont-Royal (PM), and Côte-des-Neiges-Notre-Dame-de-Grâce (CN), saw the highest impact increase (3-5 times increase) with material profile shifts, despite optimizing for housing typology (i.e. moving toward 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 carbon accounting, our findings underscore that if popular assumptions that timber is carbon negative or neutral are wrong, then wholesale transitions to wood may exacerbate carbon emission of construction and work counter to urban decarbonization goals.

4. Discussion

Our baseline model does not consider carbon sequestration and therefore does not fully capture the potential of wood to sequester and store carbon. We developed a heat map of material and carbon impact across Montreal. Shifting to EW without biogenic considerations does not necessarily improve the carbon impact of Montreal. Our results show that considering biogenic carbon and CO_2 uptake via sustainable forest management could result in a 30-fold decrease in carbon impact for EW scenarios compared to BAU. This means that while the initial embodied carbon cost of EW construction is higher than concrete and steel construction, long-term benefits of wood-based buildings could contribute to vastly decarbonizing Montreal's built environment. Further, locking up carbon in wood provides an additional advantage in the long term (i.e., through 2040) over producing construction materials such as concrete or steel. While these benefits are highly variable and questioned, we believe they could highlight best case scenarios for future development. These topics are discussed below.

4.1 Impacts of Biogenic Carbon on Carbon Footprint

Although our results showed that shifting to EW can increase carbon emissions from construction, we excluded biogenic carbon sequestered during tree growth. This is a conservative assumption that reflects current uncertainties in forest carbon dynamics and is representative when unsustainable forest management practices are used. For instance, clear cutting forests for timber fundamentally shifts ecosystems regimes and leads to significant losses of organic carbon from soil [55]. However, sustainable, alternative forest management practices are able to improve forest carbon storage to ensure sustainable harvest dynamics [56].

Including carbon uptake during sequestration using the IPCC GWP 100a carbon 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 10** shows the tons of carbon per square meter 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 tons CO_2/m^2 of footprint, significantly improving the environmental burden of high-rise construction for Montreal's development (a 30-fold decrease).

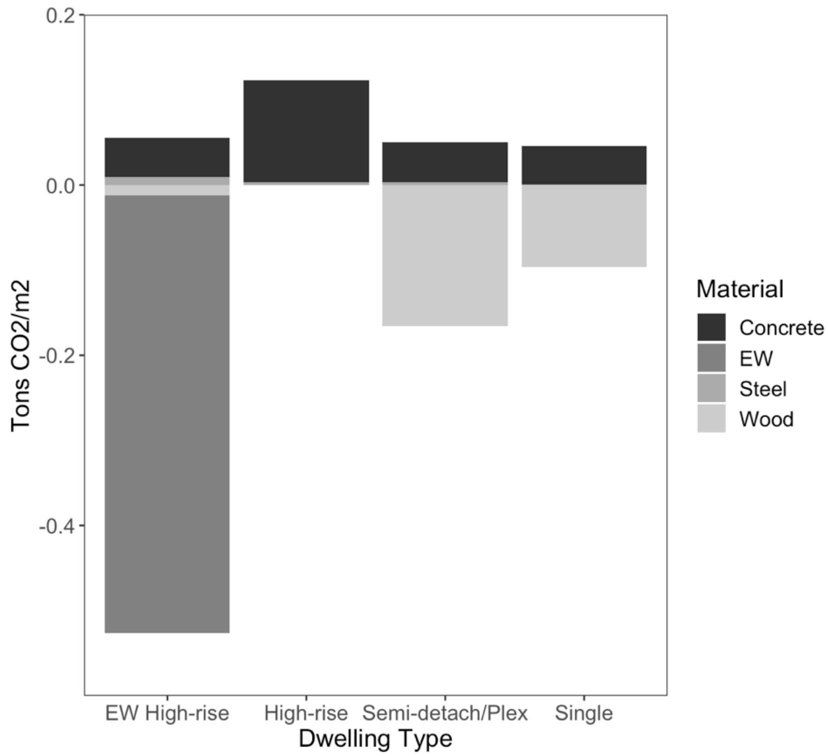

Figure 10 Biogenic carbon impact per square meter of building area

All development and material scenarios are carbon negative when biogenic carbon uptake is considered. These changes are most pronounced in the EW-BAU scenario, where significant amounts of carbon would be stored in EW throughout neighbourhoods with significant high-rise construction. Neighbourhoods characterized 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 carbon impact, though shifts towards less dense housing need to be examined further.

The urban core of the Montreal Agglomeration would benefit most from a switch to EW construction, as it has little light-frame construction to offset other material impacts unlike much of the rest of the Agglomeration. Specifically, inner neighbourhoods such as Westmount, Ville-Marie, Outremont would benefit from the transition, whereas more suburban areas would see increased benefit on the continued use of light frame timber. Interestingly, for biogenic scenarios larger wood buildings have a higher capacity to lock up more carbon per capita; nonetheless, increased operational energy of large floor area dwellings (i.e., from increased demand for heating, lighting, etc.), as well as optimal waste management for wood from the built environment must both be determined.

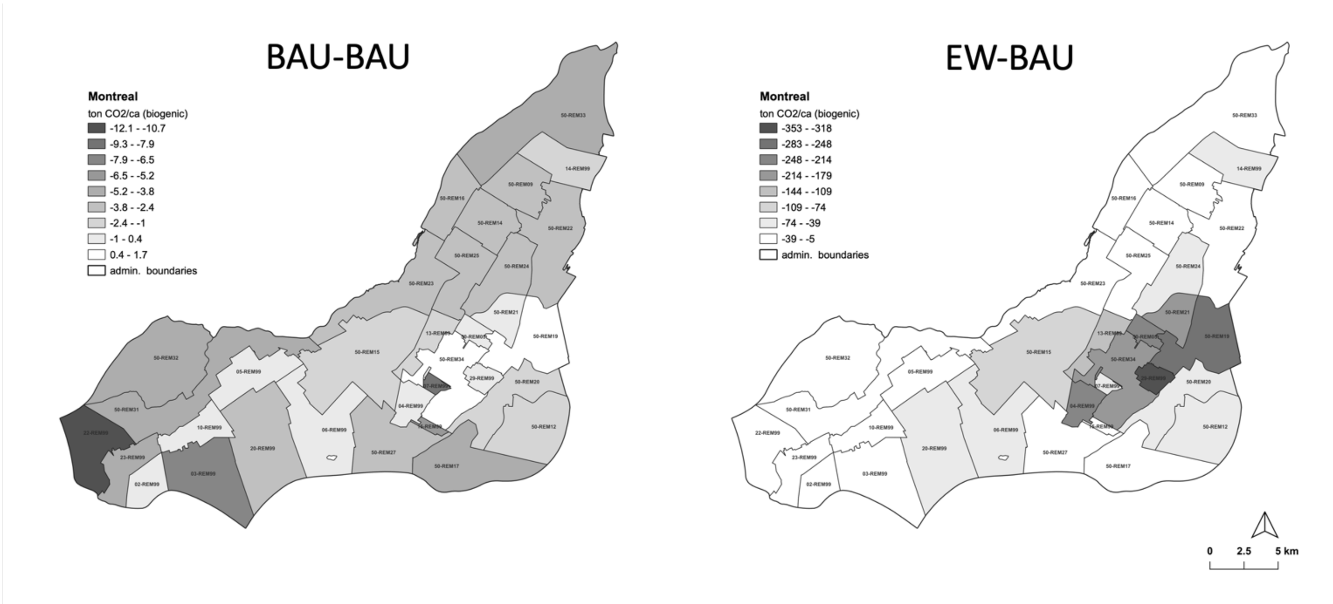

Figure 11 Biogenic carbon impact with material shift for BAU (Left) and EW material shift-BAU development (Right).

4.2 Land Use

Even if EW at scale can reduce carbon emissions, there is a concern that an increase demand for wood products could result in a shift away from sustainable forest management [57], 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 tons stored in non-Boreal forests, and another 10,453 million tons in the Boreal [58]. As of 2021, Quebec forestry contributed 22% of Canadian national wood supply across approximately 318,600 km^2 of publicly available (i.e. provincial and federal) land. 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.

Consequently, 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 shown in **Figure 12**, 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 330 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. Fortunately, all scenarios comprised an insignificant percentage of QC's land mass (i.e., less than 0.2% by forested area across all scenarios) and a small percentage of the 43,000 km^2 of third-party certified forests in the province. Land use numbers were considerably higher than transformation impacts. BAU scenarios required 3200 and 3370 km^2 of total land occupation for BAU-BAU and BAU-UD, respectively. For EW material profiles, land occupation needs jump to 2.38×10^4 and 1.36×10^4 km^2 of land for EW-BAU and EW-UD, respectively, highlighting the vast quantity of land needed to support EW supply as opposed to traditional building methods.

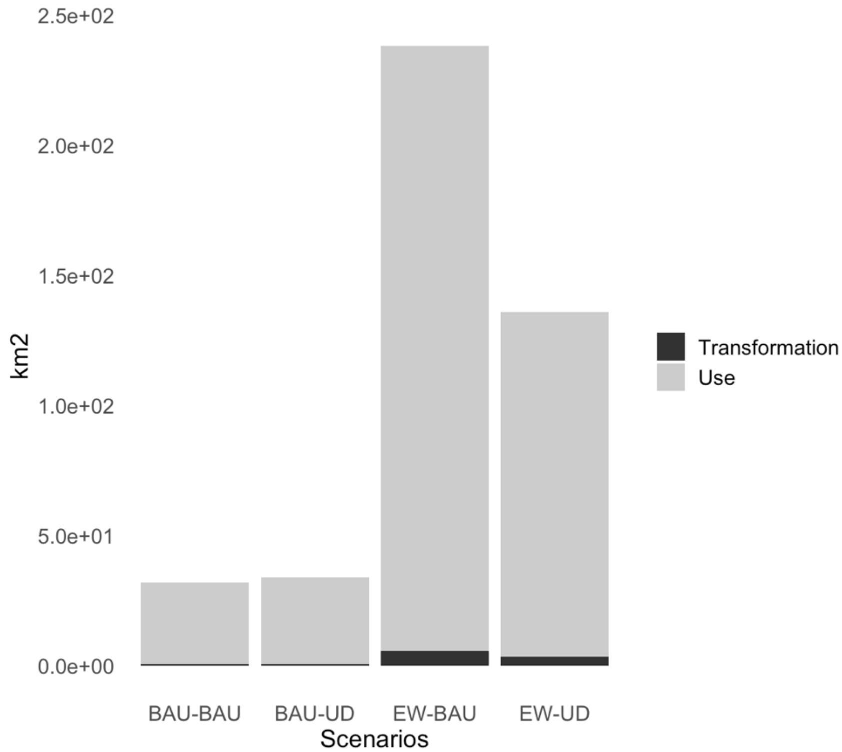

Figure 12 Inventory of land occupation and transformation across future scenarios

Transboundary impacts of material production should of course 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 technically within the capacity of QC forestry sector, a nuanced evaluation of the indirect land impacts much be considered. These externalities have not necessarily been quantified here, though carbon imbalances with indirect land use change for palm oil [59], corn ethanol, as well as many other biofuel feedstocks [55, 60, 61] are just some examples of significant land use changes resulting from sustainability-motivated initiatives.

Remarkably, 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. Comparatively limited deforestation is attributed to forestry due to sustainable practices as opposed to 'mining, oil, and gas' operations which contribute more significantly [47]. Nonetheless, deforestation rates should be closely monitored to ensure a stable and healthy forest supply.

4.3 FAC and Built Form

It is clear from our findings that Montreal's carbon impact is not due solely materials used in construction, but also about the types of dwellings we build. Naturally, 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 dramatically towards smaller floor footprints, these buildings are almost exclusively high-rise, which require increased quantities of concrete, which in turn negate the embodied carbon savings. Materials cannot be replaced without considering the effects of high-FAC housing, as optimization of both material usage with housing typology is required to effectively decarbonize.

The City of Montreal has already begun to consider how sustainability can be meshed into the city's built form [62, 63]. Special consideration of roadblocks (i.e., monetary, operational, administrative) faced by developers who could choose to build elsewhere, as well as Montreal's citizens who require both societal infrastructure and reasonably affordable housing. Programs such as Partenariat Climate MTL (The Climate Montreal Partnership) [64] aim to educate and support all stakeholders on what it will take to reach decarbonization 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 optimize 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.

4.4 Future work

This study is a first attempt to account for the material and 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, aluminum, 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 [65, 66]. 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. Additionally, assessment of 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 carbon savings. Furthermore, though the scope of this study was bound by the geographical limits of the Agglomeration of Montreal, which ignored large swathes of suburban development off the island. A broader investigation into increased urbanization 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.

Next, inclusion of various End-of-life scenarios would further elucidate the true carbon footprint of Montreal's built environment. 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 [67]. While emerging technologies and interest in repurposing construction materials are increasing [51, 52, 68, 69] 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 carbon impact [70]. Research has shown that there are benefits to EW building [71-73] 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 necessary first step in assessing the carbon and land use impact of construction across the Agglomeration of Montreal. When it comes to construction, Montreal benefits heavily form Quebec's industrious and diverse supply chain across all materials. While the carbon impact of Montreal's neighbourhoods varies greatly amongst themselves, the carbon impact of the average Montrealer has much room for improvement if the city is to be a global leader low/carbon urbanism.

As developers consider the benefits and costs of switching the EW construction, it will be vital to consider housing typology to minimize 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.

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Connecting Text to Chapter 4

In **Chapter 3** we provide manuscript for peer review. The paper comprises of an abbreviated literature review of relevant and recent studies, outline our research objectives, and present findings on how the carbon footprint and land use inventory of various future development scenarios on the Montreal Agglomeration. **Chapter 4** provides a more in-depth discussion on our findings, key considerations, and potential future work based off our results.

Chapter 4. Discussion

Processes representative of those used throughout Montreal were identified. Their impacts were quantified using the 100-year International Panel on Climate Change Global Warming Potential (IPCC GWP 100a) method which links emissions to products. The primary focus of this work in on embodied carbon, which provides a conservative "worst case scenario" accounting framework and was deemed most appropriate given uncertainties in future waste management scenarios. Biogenic scenarios which include carbon uptake – an important factor, particularly when studying wood products – was also assessed.

The following discussion aims to contextualize our findings, as well as challenges and gaps in our study. Our original hypotheses for this work were that switching from historically used materials like concrete and steel to EW in conjunction with increased settlement density would improve both the carbon impact and land use inventory of new residential construction in Montreal. Our results were not as optimistic.

4.1 Answering our Research Questions

Through this work we were able to prove, to some extent our original hypotheses, though some results were unexpected, particularly for embodied carbon scenarios.

Question 1: What is the embodied carbon in recent residential construction in the Montreal Agglomeration?

We found the average embodied carbon footprint of the Montreal Agglomeration to be 2.7 ± 1.3 tons CO_2eq./capita. There was a wide range of footprint across the municipalities/*arrondissements* with a low in Montreal-Est at 1.9 tons CO_2eq./capita up to 7.7 tons CO_2eq./capita Senneville. FAC was a significant driver of carbon footprint and was generally associated with wealthier, more spread-out neighborhoods. Both unadjusted and post-1960 adjusted FAC were found to be strong drivers of per capita impact, indicating that large houses were a hot spots of carbon intensity across the island. While we believed that increasing density through housing typology could have a beneficial effect on the embodied carbon footprint, the high carbon density of high-rises with structurally necessary, and materially intense, foundations and parking, drove up per capita impacts.

Using our baseline calculations on modern residential construction, we then looked to answer our next question:

Question 2: How does shifting from historically used materials and urban densification influence embodied carbon in future residential construction through 2040?

On a high level, switching to EW did not lower the embodied carbon footprint per capita in the Montreal Agglomeration, though switching to engineered wood was favorable for biogenic scenarios. Recently published work by Peng et al. on wood harvests and emissions echo our findings that while using wood appears to be a low-carbon solution for buildings, the reality is more complicated [102].

We found that a shift from traditional building methods used in cities, like steel and concrete, to a mix of engineered wood and light frame timber did not necessarily improve the embodied carbon footprint of Montreal's built environment on a per capita basis. For our scenarios, switching to engineered wood and increasing density could increase the carbon impact of a neighborhood by 158%, while failing to also increase density resulted in a 431% increase. Increasing density was beneficial in BAU material usage and engineered wood scenarios in neighborhoods that had low FAC, indicating a potential area that carbon impact could be reduced. When comparing scenarios, increasing density, and continuing to build with standard materials had the most beneficial impacts, with some neighborhoods experiencing up to a 66% reduction in T CO_2eq./ca.

Accounting for biogenic carbon results in the lowest impact for GHGs, a finding echoed in reviews [76] and other primary resources (see **Table 2**). For biogenic scenarios, BAU-UD, EW-BAU, and EW-UD scenarios all resulted in a negative carbon impact per capita in every neighborhood, indicating that both material shifts and strategic density increases have the potential to reduce the average Montrealer's carbon footprint, so long as carbon is both sequester during forest growth and stored in wood products. These results also show minimal potential to store carbon in both light frame timber, and up to an order of magnitude of carbon reduction in engineered wood scenarios. EW-BAU outperformed EW-UD, due to the continued need for carbon intensive materials like concrete and steel in the structure of engineered wood high-rises, demonstrating that medium density could be a better solution to balance housing needs and carbon impact of the Montreal Agglomeration.

Question 3: How much land is required to scale up EW construction in future Montreal?

Our land inventory impacts were generally favorable towards developing the city with wood-based construction. For increasing density was only beneficial to land use metrics when EW was used to build with EW-UD requiring 57% less land transformation and use than EW-BAU. Increasing density without material shifts had the opposite effect with our BAU-UD requiring about 5% higher land transformation and 6% high land use.

For all scenarios, we found there was sufficient sustainably managed forest area to support development in the Montreal Agglomeration. Still, vigilance in properly protecting QC's forested land cannot be understated. Growth beyond the population growth estimates use here, an uptick in new construction beyond what is necessary, or export of wood products from QC could all vastly change the forest, and therefore, carbon sequestration dynamics. A report by the World Resources Institute finds that growing demand and competition for wood and/or forested land has potential to burden forests through 2050 [103].

Further, the Montreal Agglomeration is predicted to grow at a relatively small rate through 2040, at an average of 2.35%, with some independent municipalities actually predicted to decline in population [104]. Canada is an increasingly urban country. With populations increases estimated to reach above 17% between 2021 to 2068, increased demand for urban housing should be expected [105]. Faster growing cities and municipalities such as throughout Canada, such as East Gwillimbury of Toronto (+44% from 2016-2021), have the potential to overburden forest production if caution is not taken [106].

4.1.1 Impacts Beyond Carbon and Land Inventory

Carbon footprint and land inventory are both extremely important and useful in communicating high level environmental impacts, especially to those working outside of Industrial Ecology and environmental studies. However, other impacts should not be overlooked. Increased industrial activities in forests could lead to biodiversity loss, eutrophication, acidification, photooxidant formation [107]. Berch et al. outlined that increased rates of wood product harvest led to significant biodiversity loss with increased forest biomass harvest [108]. This finding is echoed by others across, along with loss of soil nutrient density [109]. For example, physical disturbances by logging activities were found to significantly reduce forest productivity, and soil quality over both short- and mid-term time horizons [110].

Given the potential for such environmental degradation, the sustainability metrics beyond carbon and land of industrial scale logging cannot be overlooked. Further, our study only considers upscaling EW within Montreal, which is growing relatively slowly. Increased global demand for both QC, Canadian, or globally sourced EWP could have implications beyond our estimates.

4.1.2 Waste Management Assumptions

While assumptions of how construction material waste is managed were excluded from this work, the implications of various end-of-life scenarios cannot go entirely unexplored. Permanent versus long term storage scenarios has potential to greatly change the carbon footprint and overall impact of using wood to replace other materials. Landfilling wood, for example, not only releases previously captured carbon back into the atmosphere during decomposition, it does so as both CH_4 and CO_2 – further, very few studies have assessed the decomposition dynamics EW compared to untreated wood [111]. Regardless, while CH_4 has a significantly shorter lifespan that CO_2, it comes at a price as the GWP is between 25-28 times higher over a 100 year timescale [112]. One potential approach to achieve permanent or long term storage is burying timber [113].

A more optimistic scenario could include efficient use of EW and other wood waste, for example as biomass conversion to energy via methods like pyrolysis [114-116]. Additionally, CO_2 from waste biomass can be converted to methane (sometimes known as renewable natural gas) by a process called power-to-gas. This can be injected into the gas grid substituting fossil natural gas. This is a particularly interesting option in regions with low carbon electricity, such as QC, due to the high electricity demands of power-to-gas processes. Similarly, waste biomass has the potential to be an energy source for green hydrogen production [117].

While this work primarily addresses conservative, worst case, end-of-life scenarios (i.e., landfill), these may not necessarily be the future for construction materials. Today, 60% of construction materials end up in landfill, globally [118]. In QC, those numbers are closer to 50%, respectively, mostly aggregates such as concrete that are substitutable by EW [119]. New policies and technologies to repurpose and recycle concrete, steel, and wood could have significant beneficial implications to Montreal’s carbon footprint. A push towards a circular approach, for example, could help reduce impacts, but requires an adequate understanding and participation by stakeholders [120].

Creative use of material byproducts could further reduce the upfront embodied footprint of concrete, steel, and wood. Fly ash and steel slag can be used in enhanced rock weathering, both of which not only significantly reduces waste output [121], but has demonstrated some potential to reduce need for cementous material [122, 123]. Pyrolysis has been explored as end-of-life strategy for energy generation [114, 115], however, wood panels formed with adhesives have been shown to produce NOx emissions, making many EW products poor candidates for this process [116].

According to the EPD sustainable building standard EN 15804, LCAs of buildings should not account for biogenic carbon either as a credit for storage (e.g., in EW) or as a pulse (e.g., from landfill decay) [124]. This assumes that what goes in must come out, and no net carbon is removed permanently. However, if additional GWP should arise, for example in the case of landfilled timber decaying and releasing methane to the atmosphere, then that should be accounted for. Some regions do not landfill timber construction materials (QC, for example). However, if the scope of this research is to be broadened to other regions where landfilling of timber is commonplace (e.g., New Zealand), then end-of-life modelling needs to be considered [125].

This would involve several factors such as the way in which the landfill is managed (e.g., methane capture and/or flaring) or unmanaged (such as clean filling). Moreover, exposure of the landfill to weather, especially humidity, and the species of trees being landfilled, which affects important parameters such as the degradable organic carbon fraction [126]. In a worst-case scenario, timber construction waste could generate a large and rapid emission of methane at the end-of-life. Under ideal conditions, however, biogenic carbon stored in construction waste can be used to generate methane, which can be captured through landfill pipe systems, and burned to generate electricity, substituting fossil fuels in the grid mix.

Our choice to focus primarily on embodied carbon over biogenic carbon accounting methods is echoed by others such as Andersen et al., as biogenic carbon can misleadingly skew towards better, and likely improbable outcomes [76]. How biogenic carbon should be accounted for is still contested amongst LCA researchers, but can provide a useful perspective to best case scenario dynamics of storing carbon within the built environment [127].

Here we revisit our research questions and ground our findings to both the greater body of literature, as well as potential for future studies.

4.2 Comparison to Literature Values

Here we find that the carbon footprint of Montreal is significant, but not abnormal. Recent literature echoes the findings here regarding adverse carbon footprint results when switching to EW. To ground our results in the existing literature we compare our findings to similar studies across the world. Lotteau et al. performed an extensive literature review of LCA studies on the built environment [128]; relevant studies (i.e. 100 years or not specified, that report per capita carbon footprint) are summarized in Table 4, along with our own findings.

Table 5 Carbon footprint of global residential construction; table adapted from review by Lotteau et al.

Location	Notes	GWP (tons CO_2eq./capita)	Ref
Melbourne, Australia	Residential housing today	7.8	[30]
Toronto, Canada	Residential housing today	3.3	[79]
Hammarby Sjostad, Sweden	Residential housing today, apartments only	2.8	[80]
La Rochelle, France	Residential housing today	0.6	[81]
Montreal, Canada	BAU-BAU	3.1	--
	BAU-UD	2.7	
	EW-BAU	7.0	
	EW-UD	4.9	

BAU material scenarios performed similarly to studies from Toronto and Sweden, whereas BAU-BAU and BAU-UD scenarios were about 5 times and 4.5 times higher, respectively than a similar study in La Rochelle, a much smaller city on the Atlantic Coast of France. While EW-BAU and EW-UD scenarios had a higher carbon footprint than most comparable studies, they still both outperformed the per capita carbon footprint of Melbourne.

4.3 Future Work and Next Steps

While this work is a first step in estimating the carbon footprint of Montreal's built environment, there is much work to be done. Here we looked specifically to readily available, high-quality data, focused on strictly residential buildings. Future studies should aim to refine building typologies specific to Montreal and may provide more precise material diet and environmental impact metrics. Addition of other building materials, such as brick, glass, aluminum, or more refined estimations of the broad categories studied here (i.e., wooden doors versus wooden window frames) could provide further insight. 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 for the city and island.

For this study, we assumed that concrete, steel, wood, would account for most of the material and carbon impact in Montreal's built environment. However, it cannot go without note that clay brick is widely used across the Montreal Agglomeration, particularly in low storey dwellings. Brick dry density can range from 2250-2800 kg/m^3 [129], slightly higher than concrete which has a tighter density range of roughly 2300-2430 kg/m^3 (see Supplementary Information). However, conformation of bricks can vary depending on use case (i.e. engineering/structural versus façade) and therefore can be more challenging to accurately assess. Further, details on brick use are not always readily available, an issue noted by Guven et al. in their assessment, which leaned on assumptions and guidance from external experts rather than explicit BOMs. Future work could aim to better model brick use across the Montreal Agglomeration, and provide more granular material and impact assessment.

Next, inclusion of various end-of-life scenarios would further elucidate the true carbon footprint of Montreal's built environment. The author acknowledges 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 researchers may look deeper into emerging technologies for concrete, steel, light frame timber, and engineered wood, as well as further accessing policy shifts both throughout QC and Canada.

Many have shown the importance of refurbishment of the built environment [130]. Further investigation into the turnover rate of Montreal's current built form and those more suitable to refurbishment than replacing may yield variations in the results shown here. Additionally, while the scope of this study was bound by the geographical limits of the Island of Montreal, urbanization is not. A broader investigation into increased urbanization off the island is vital to measure the impact of urban sprawl in the greater-Montreal, and subsequently throughout QC and the broader Greater Lakes Megalopolis.

It is my hope that future work may further elucidate the connections between Montreal and its hinterlands, which ultimately allow the city, and others across Canada, to continue to grow. A broader understanding beyond land transformation will allow future planners to better consider the urban impact on rural regions throughout QC regarding economic development, conservation of biodiversity, maintenance of vital forested land as a carbon sink, as well as countless other services that QC's landscape provides. Canada is a land of both abundant natural resources and a thriving urban population. To understand and protect such a diverse and beautiful place is of the utmost urgency.

Connecting text to Chapter 5

In **Chapter 4** we discuss the overarching themes of our findings and provide more context for to how this work relates broadly to development in Montreal and to the field of Industrial Ecology, as a whole. We then provide more insight into areas where this research could be expanded upon in the future. In **Chapter 5** we summarize the outcomes of this research and our contributions to the knowledge base in our field.

Chapter 5. Summary of Work

Our findings provide a first look into the potential to develop the Montreal Agglomeration in a sustainable manner through material and settlement pattern shifts. Decarbonizing the city will not be an easy task, but we show that there is a path to reducing the carbon footprint while responsibly managing the local land stock within QC to reach this goal. We connect Montreal to its hinterlands and begin to elucidate the urban rural linkages that exist within QC which have potential to improve the city's future environmental footprint.

5.1 Conclusions

We find that switching the EW from BAU material stocks may increase the residential carbon footprint across the Montreal Agglomeration. This means that our initial hypothesis that switching to what we considered a low-carbon material diet was not entirely correct, as only several neighborhoods across the Agglomeration saw a decrease in carbon footprint with material shifts.

Our second hypothesis that increased urban density would improve the carbon footprint was true to an extent. We found that density could be optimized and that overcorrecting towards high-rise construction did not improve carbon scenarios. However, many neighborhoods with low rates of high-rise construction still met our >5000 people/km^2 threshold; and mimicking these types of dense development improved outcomes.

Our third hypothesis that increased urban density improved land use change was false between BAU-BAU and BAU-UD scenarios but was true between our EW-BAU and EW-UD scenarios. It is important to note that EW scenarios between seven and thirteen 13 times higher when switching to engineered wood. However, we found that the available third-party certified sustainable forests in QC were plentiful enough to support EW construction. It should be noted that this assessment was complete strictly on an available land basis and that other impacts of forest product production could have adverse effects on the local environment.

On a high level, we found that biogenic scenarios were far more favorable than embodied carbon accounting. In general, we were surprised to find that the embodied carbon impacts of material and density shifts did not have a greater positive impact across the Montreal Agglomeration. Results were neighborhood/municipality specific, which makes a case for a hyper-local approach to decarbonizing the Montreal's future building stock.

5.2 Contributions to Knowledge

This research uses a bottom-up building stock model of nearly 150,000 individual buildings to determine the embodied carbon and land use impacts of modern residential construction across the Agglomeration of Montreal, QC, Canada. We then explore urban growth scenarios to 2040 to estimate the impact of both changing the urban form and using EW as a substitute for concrete and steel across both the city and the island which make up the Montreal Agglomeration.

This work makes three important contributions to the literature: first, we determine that shifting towards high-density settlement patterns and smaller homes reduces the carbon footprint, but substantial high-rise construction can actually increase carbon footprints because of the upfront carbon cost of producing engineered wood products, as well as necessary other materials for tall wood buildings. Second, we find that when considering embodied carbon, a full transition to engineered wood does not necessarily decrease carbon impacts for all areas of Montreal. Third, we show that while scaling up engineered wood construction increases land use impacts compared to current materials, there are abundant third-party certified forests in QC to support engineered wood development at scale in Montreal.

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