Resources, Conservation & Recycling 205 (2024) 107567

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Spatio-temporal metabolic rifts in urban construction material circularity

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ARTICLE INFO

Keywords:
Circular economy
Urban metabolism
Material flow analysis
Life cycle assessment
System dynamics
Socio-ecological systems

ABSTRACT

Global demand for resources currently exceeds Earth's carrying capacity. Representing a majority of global resource use, and associated environmental burdens, cities must address overconsumption by improving material circularity. This work explores the potential for the construction sector to reduce the indirect environmental impacts connected to increasing material circularity in the coming years. An urban metabolism simulation tool based on system dynamics and life cycle thinking is deployed to estimate the effects of circularization on environmental impacts. Illustrating with a case study of Montréal (Canada), impacts are disaggregated to supplier nations, provinces and territories. As material circularity increases over time, impacts decrease in the sub-national and international regions, but increase in the city due to the activities associated with second life valorisation. In supplier regions, especially Brazil, Mexico, and Norway, environmental impacts decrease between 80 and 100 % in all 18 impact categories by 2050. However, these decreases are found to be shared mostly among Canada's more developed trading partners, revealing an environmental justice risk for circular materiality to disproportionally favour the better-off. Five of the 18 categories did not undergo spatial burden-shifting, improving at all spatial levels in the assessment, while 13 showed decreased environmental impacts remotely at the expense of increased impacts within Montréal.

1. Introduction

Demand for building and infrastructure development are growing (Bertino et al., 2021), especially in cities. Urban populations are growing due to rural-urban migration currents, where wealth is concentrated and corresponds with disproportionally high consumption of goods and services (United Nations, 2019). For example, carbon footprints are skewed strongly towards the wealthy, despite the resource efficiency of cities (Sager, 2022). Growth-based economic development with increasing resource demands exacerbate the depletion of natural resources and drive associated environmental damage (Kanters, 2020; Kouchaki-Penchah et al., 2023). Globally, the construction sector is the largest consumer of raw materials and other resources, which predominates in the urban built environment (Rahla et al., 2019). It consumes 3 billion tonnes of raw materials, and around 50 % of steel produced globally (World Economic Forum, 2016). In 2018, the buildings and construction sector represented 36 % of final energy use and 39 % of energy and process-related CO_2 emissions (Global Alliance for Buildings and Construction et al., 2019; Rondinel-Oviedo and Keena, 2022; Smart Prosperity Institute, 2021).

The environmental consequences of construction – resource depletion and generating waste – can be thought of in terms of metabolic rift. Metabolic rift occurs when natural cycles where waste flows are useful and necessary resources to other processes become broken (Moore, 2000). Wastes do not exist in natural cycles, but our civilization, which dwells mostly in cities, uses resources supplied from elsewhere and generates outflows that do not regenerate the depleted sources, instead deposited as wastes (Daly, 2005; Fanning et al., 2022; Xue, 2021).

Circular economy is one approach to resolving this metabolic rift by way of circulating those outflows to inflows rendering the urban metabolism as circular as possible (Cui, 2022; Keena et al., 2022). Circular economy principles are gaining momentum among both academia and industry (Bertino et al., 2021; Kirchherr et al., 2017). On the other hand, ecological economists have promoted degrowth (rather than sustained growth through decoupling) suggesting that growth in demand for resources is inherently unsustainable regardless of how efficiently society uses them (Klitgaard and Krall, 2012; Moser, 2021). These two concepts agree on the problem that is metabolic rift perpetuated by non-circular supply chains, while the latter alone considers this rift a symptom of growth economics (Costanza et al., 2007).

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https://doi.org/10.1016/j.resconrec.2024.107567
Received 14 December 2023; Received in revised form 19 February 2024; Accepted 17 March 2024

While degrowth remains far from mainstream, material circularity is being applied to resolve metabolism rifts in several urban centers. Cities such as Toronto (Beaudoin et al., 2021), Amsterdam (City of Amsterdam, 2020), Paris (Mairie de Paris, 2016) and Brussels (be circular, 2016) have assessed the potential of integrating circular thinking within their urban planning, and often the construction industry emerged as a main sector for developing circular practices (Elliot et al., 2023; Keena et al., 2022b).

Modelling the success of these initiatives is complex (Alberti et al., 2020). Reducing virgin and waste flows can have unintended consequences over time and locations. Some studies have applied systems models, integrating a variety of techniques to unravel the complex flow of materials and/or their impacts (e.g. Goswein et al., 2019). Others have shown the importance of spatial information to disaggregate hotspots of intensity (e.g. Hackenhaar et al., 2022; Lausselet et al., 2020). Designing buildings in a manner aligned with reducing material intensity also englobes other strategies such as: modularity, adaptability, flexibility, and deconstruction or disassembly. These design strategies will enable a higher use-performance while maintaining the value of building materials and components. Circular Buildings have arisen and been put forth as a more holistic approach to circular economy in the built environment. Academia and non-governmental institutions promoted the reliability and efficiency of Circular Buildings to ensure a better transition towards material circularity (Rahla et al., 2019). However, this is hampered by the variety of definitions and interpretations of circular economy, which is especially complex when considering the multiple scales and levels affected by the built environment (e.g. micro, meso, macro) and the subsequent risk of environmental trade-offs (such as burden-shifting) between optimising circularity pitted against strong sustainability (Rahla et al., 2019). Addressing similar points, Leising et al. (2018) argued that material circularity in the building sector should be approached as a “systemic view on the whole life cycle of buildings and by using new technologies and design approaches” in order to generate financial, social and environmental benefits.

A generic dynamic material flow analysis model was developed by Bergsdal et al. (2007) and applied for the diffusion of concrete in the Dutch dwelling stock for the period of 1900–2100. Parameter estimation for the determination of long-term future flows is very difficult, as it is exclusively based on extrapolating the determinants to the future, leading to high uncertainties if these determinants do not follow characteristic long-term patterns (Levasseur et al., 2010; Martínez-Fernández et al., 2021).

A bottom-up building stock model was developed by Heeren and Hellweg (2018) using geo-referenced building data to determine volumetric information of material stocks in Swiss residential buildings. This allows for the development of tailored resource planning strategies. However, the spatialization of upstream impacts was not included, which are known to contribute large portions of the urban metabolism’s environmental burdens (Elliot et al., 2022).

A dynamic systems perspective was taken by Goswein et al. (2019) to assess the flow of materials in the construction sector. They developed a framework to help decide which method to use for construction material assessments. One finding advocates for future work to include spatial heterogeneity of impacts based on disaggregated life cycle assessment (LCA) of flows (Goswein et al., 2019), which can be achieved through hybrid LCA methods as demonstrated by Merciai and Schmidt (2018) with Global Multi-Regional Hybrid Supply and Use Tables.

Another approach for estimating construction use of material has been done using LCA and dynamic LCA (Lausselet et al., 2020). In order to get insights on construction material pattern of consumption, Mollaei et al. (2021) modelled two Canadian cities’ (Waterloo and Kitchener) stocks of material by estimating material intensities of residential and non-residential buildings. Although this archetype method allows an estimation of material flows and stocks, it assumes a relative homogeneity in building material intensities and does not account for different aesthetic or economic lifetimes (Stephan and Athanassiadis, 2017; Verberne, 2016). The latter study proposed a bottom-up modelling approach to quantify and spatialize embodied requirements of building stocks, including material use, energy use, greenhouse gas emissions and water use. The model envisioned aiding city councils to quantify and evaluate material and environmental flows and better manage their cities in terms of waste and urban mining. As with Goswein et al. (2019), Stephan and Athanassiadis (2017) noted the importance of future work extending the mapping of spatially disaggregated environmental impacts to the entire life cycle of stocks and flows, to ensure improvements to one environmental indicator do not simply shift to other life cycle stages or other types of impact. This finding also makes implicit the risk of these burdens shifting between regions, due to the unique locations in which different life cycle stages may occur.

Advances have been made to evaluate levels of material circularity of the built environment (Arora et al., 2019). They presented a method to quantify building material stocks and flows, campaigned for improved component-level circularity in construction, to advise policy-making and urban planning in reducing resource consumption (Moser et al., 2019). It is known, however, that reducing stocks does not necessarily lead to more sustainable outcomes if only a limited range of life cycle stages and impact types are quantified (Goldstein et al., 2013; Stephan and Athanassiadis, 2017).

This study aimed to model and assess synergies and trade-offs – both spatial and in between indicators – consequent to optimising the circular metabolism of construction materials. It follows suggestions in the state-of-the-art that suggest circularity of construction materials should be explored through integrated systems modelling, as this has not yet been achieved, and is necessary due to the vast portion of global pollution generated through urban supply chains, particularly in the construction sector. Spatio-temporal dynamics should be considered, such as linking environmental impacts to their geographic locations over time for a range of categories that could potentially compete with circularity indices. As such, a novel method to model an urban metabolism with dynamic flow of construction materials is developed, subject to varying the degree of material circularity, which illustrates the spatio-temporal metabolic rifts and their environmental impacts.

This framework helps answer the research question: if the Material Circularity Indicator (MCI) is sufficiently high for a city, what are the consequences for life cycle impact categories? Material circularity is compared and contrasted with a suite of life cycle impact categories, which are themselves mapped to the location of their impact at multiple geographic levels: nations, regions, and city. The results of a case study are illustrated and discussed, highlighting how this methodological approach provides insight to the epistemology of circular economy, and go on to argue the pro-growth narratives are paradoxical for meeting sustainability goals, carving deeper the metabolic rift that it intends to unite.

Montréal, Canada’s second largest city, is chosen as a case study. This is a suitable case city for a number of reasons. By joining the initiative Circular Cities & Regions Initiative (Circular Cities and Regions Initiative; Federation of Canadian Municipalities) and developing its roadmap for a circular economy (Ville de Montréal, 2023), Montréal has demonstrated its own ambition to increase material circularity (Jordi Pascual, 2022). The number of residential dwellings constructed in Montréal increased more than twofold between 2015 and 2021 (Ville de Montréal, n.d.). Additionally, the construction sector accounts for almost 20 % of the city’s waste (Ville de Montréal, 2020), indicating an impending challenge with impacts associated with material production and waste management as the city grows. The locations of environmental impacts of these flows are included in the system boundary but count only those arising from resources meeting their end use in the city. Material flows and associated impacts are simulated from 2017 to 2050 according to two scenarios: business as usual (BAU) and Optimized Material Circularity (OMC) based on the MCI. The relative potential benefits of the OMC scenario are then mapped over time. The locations of these benefits are then compared to the development level of those locations to understand how well-distributed the gains are for those communities who need them most.

2. Methods

2.1. Scope and system boundary

The scope of this study is a city (Montréal, Canada), whose resource requirements are met from a range of peri-urban (Rest of Québec), national (Rest of Canada), and international supply chains (Rest of World). The scope is limited to construction materials – one of the most environmentally intensive sectors and an important one in urban development – as a first step to illustrate how such a model can be deployed. To simplify the analysis, it is assumed that all upstream impacts from a given material occur where the material is coming from. For instance, for steel imported from the USA, impacts from the entire steel production chain will be shown in the USA even if the iron mine is somewhere else. This modelling framework is shown in Fig. 1.

2.2. Dynamic material flows modelling framework

The model presented in this study uses a system dynamics rationale to trace the stock and flow of urban materials over time. This framework, which is referred to as a dynamic urban metabolism (Elliot and Levasseur, 2022), has been developed over a number of previous socio-ecological system works (e.g., Boumans et al., 2002; Oliveira et al., 2022) and is based on the ESTIMUM method for socio-ecological system modelling (Elliot et al., 2022; Elliot, 2022).

Lacking local physical data for Montréal, the historical material matrix of the city has been developed in three steps. First, the Province of Québec's supply and use table for the year 2017 (Statistics Canada, 2020) is downscaled from the provincial level to estimate Montréal monetary flows using the city's proportion of Québec's economic activity in the construction domain (Institut de la statistique du Québec, 2022). This table consists of a matrix of material categories and the sectors that supply and use them. However, we are only interested in materials used in the construction industry. Nine material categories are considered, which are used by four subsectors of Montréal's construction industry. The residential sector refers to the construction of houses, flats and all residential buildings; the non-residential refers to institutional, commercial and industrial buildings; the infrastructure sector refers to transport engineering construction (e.g., roads, bridges) and the repair construction includes maintenance and repair expenditures related to any type of buildings.

Second, these monetary flows were converted to physical flows using basic price data for 2021 (source: RSMEANS, www.rsmeansonline.com/). Basic prices were inflation-adjusted using the historical conversion index to get 2017 prices per tonne. This enabled us to convert all monetary import flows into physical ones.

Third, those flows were disaggregated by their origin. Materials of Canadian origin were already provided per province (Statistics Canada, 2020). It is assumed all materials are imported to Montréal, i.e. no urban production of construction materials. This is a limitation since a small quantity of materials such as asphalt might have been produced within the city's boundaries. Materials sources from within Canada were thus allocated to each of the 13 provinces and territories. Interprovincial shares of origins for each material import are shown in Table 1. No

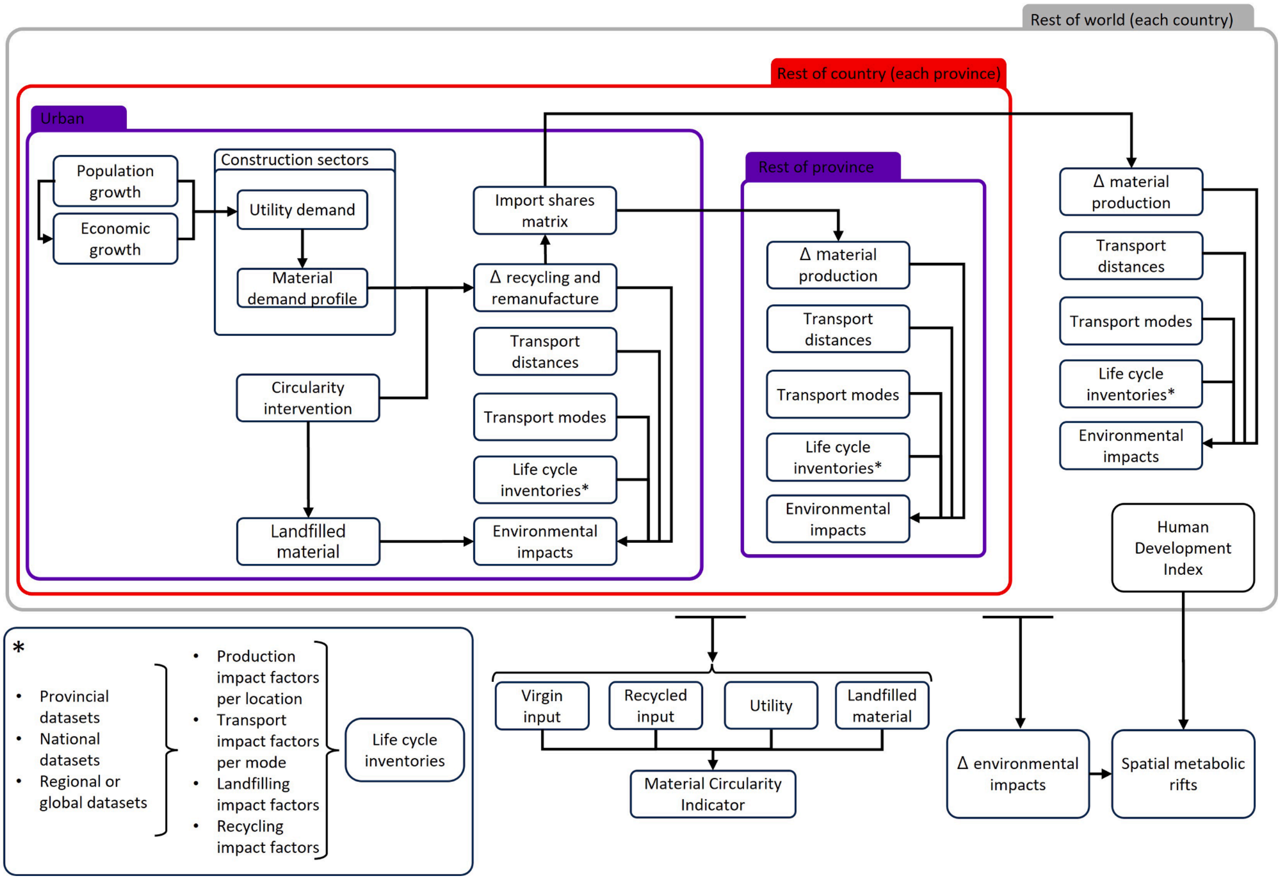

Fig. 1. Simplified system dynamics modelling framework. Square modules represent separate models that feed into the construction demand functions (see Elliot and Levasseur, 2022). Symbols indicate # four types of construction, † nine materials categories, § 160 countries and 13 Canadian provinces and territories, ¶ three modes (ship, train, lorry).

Table 1
Shares of interprovincial imports to Montréal for each material.

Origin in Canada	Asphalt	Cement	Concrete products	Glass	Lime and gypsum	Plastic	Sand	Steel and alloys	Wood
Alberta	4.23 %			6.38 %	9.86 %	1.20 %		6.74 %	1.44 %
British Columbia	0.92 %		0.03 %	3.70 %	5.24 %	0.33 %		0.55 %	0.23 %
Manitoba	0.00 %		0.02 %	0.41 %	2.83 %	0.01 %		0.24 %	0.01 %
New Brunswick	0.76 %			0.61 %	5.16 %	1.80 %		0.26 %	11.74 %
Newfoundland and Labrador									0.08 %
Nova Scotia				0.01 %	0.03 %	0.03 %			1.10 %
Ontario	26.64 %	10.59 %	23.60 %	43.23 %	29.60 %	21.42 %	41.59 %	24.82 %	9.51 %
Prince Edward Island								0.01 %	0.01 %
Quebec	67.45 %	89.41 %	76.35 %	44.20 %	47.29 %	75.16 %	58.41 %	64.55 %	75.87 %
Saskatchewan				1.46 %		0.04 %	0.00 %	2.83 %	0.00 %

imports are recorded from Yukon, Northwest Territories, or Nunavut. Apportioning international imports into separate nation origins was done by multiplying the total international imports by the weighted import matrix. This was made from shares of imports from each country to Canada (source: www.trademap.org/Index.aspx).

Output (end of life) flows are destined for recycling and landfill. Recycling rates are estimated from Recyc-Québec (2018) at the Québec Province level and assumed to reflect the percentages of Montréal (Recyc-Québec, 2021). Circularity is measured using MCI developed by the Ellen MacArthur Foundation (Ellen MacArthur Foundation and ANSYS Granta, 2019). This approach allows us to maximise the MCI for each material flow, and thus characterising an optimal circular urban metabolism profile. The following calculations are used to measure the MCI (Eq. 1) and OMC (Eq. 2) using the virgin (V), waste (W), mass (M), and the utility (X) throughout the life cycle stages for each material at each time step in the system dynamics model. Utility is defined as the product of a lifetime variable which accounts for increases in the service life relative to industry standard, and a functionality variable which accounts for changes in the number of functional units supplied by the product. In this case, we do not consider changes in the lifetime of number of functional units, resulting in the utility value X being set to 1. This, however, is scaled to 90 %, by convention, which sets the minimum MCI value for a fully linear product to 0.1, while a theoretical maximum MCI has a value of 1, when V and W are zero. A full derivation of the MCI is given in the Ellen MacArthur Foundation's technical guide "Circularity Indicators – An approach to Measuring Circularity" (Ellen MacArthur Foundation and ANSYS Granta, 2019).

$$\mathrm{MCI} = 1 - \left(\frac{V+W}{2M}\right)\cdot\frac{0.9}{X} \quad (1)$$

$$\mathrm{OMC} = 1 - \left(\frac{V_{min}+W_{min}}{2M}\right)\cdot\frac{0.9}{X_{max}} \quad (2)$$

The model was run with this optimal circularity to calculate the associated profile of environmental impacts. These results can then be compared with business as usual impacts, with the goal of identifying any potential compromises that could arise with this type of circular strategy. The recycled content used in the BAU scenario, along with the recycling rate and MCI used in the OMC, are shown in Table 2.

Table 2
End of life assumptions for each material category used to determine the material circularity optimisation.

Material	Recycled content of imports	Recycling rate of outputs (BAU)	Recycling rate of outputs (OMC)	Optimum MCI
Asphalt	0.3	0.49	0.49	0.37
Cement	0.05	0.0	0.75	0.44
Concrete	0.05	0.0	0.75	0.46
Glass	0.52	0.78	0.78	0.68
Gypsum	0.05	0.081	0.75	0.46
Plastic	0.3	0.0	0.3	0.37
Sand	0.5	0.65	0.75	0.65
Steel	0.4	0.53	0.83	0.65
Wood	0.5	0.57	0.73	0.88

Growth in workforce population and economic activity drives residential, non-residential, and repair construction. Infrastructure demand is flat, assuming steady material demand year-on-year. Material flows are linked to environmental impact factors, estimated using life cycle inventory data. This life cycle thinking approach facilitates the multi-regional impact assessment by distinguishing between impacts during resource extraction, manufacturing, and transportation to the city, and construction and use of materials in the urban setting.

Material flows and stocks fluctuate as driven by population and economic trends, and policy interventions (Elliot et al., 2020). Additional scenarios are built to reflect possible interventions to facilitate circular material flows, and these are assessed across a set of environmental impact categories. As such the trade-offs between impact categories was analysed to determine if circularities can in fact produce unintended burden-shifting to worsten the environmental footprint of the complex urban ecological system (Grimm et al., 2008, 2000). Coupled with the multi-regional spatial disaggregation of impacts, the model simulates both the future trade-offs between impact categories, and maps these differences to geographic areas.

2.3. Environmental impacts of material flows

Environmental impacts are estimated for the 18 midpoint environmental impact categories characterised in the ReCiPe impact assessment method (Huijbregts et al., 2016). The full list of impact categories and their units is shown in **Supplementary Material 1**. All 18 impact categories are reported in the results section, and the impact categories showing the most important synergies and trade-offs are highlighted: terrestrial acidification potential (TAP), metal depletion potential (MDP), global warming potential (GWP, i.e., climate change), and water depletion potential (WDP). Environmental impacts of urban metabolism flows are estimated using impact factors taken from *ecoinvent v3.4* (Wernet et al., 2016) with *ReCiPe* characterisation factors (Huijbregts et al., 2016). System processes were used for cradle-to-gate impact factors to capture the environmental burden generated along the supply chain until they are deployed to the city's construction sector. International- disaggregation of material flow origins (defined above) is used to allocate the pre-urban impacts between provinces and nations, thus revealing not only the magnitude of impact but the region in which it occurs. Transportation impacts are estimated by multiplying shipping and lorry distances from supplier locations by *ecoinvent* tonne-kilometre impact factors. Distances were estimated using main port terminal distances from Sea-Distances.org website, which are disclosed in **Supplementary Material 2**. At the end-of-life, materials are recovered and enter one of two alternative waste streams: landfill or recycling facility. These destinations operate according to different processes and have different environmental profiles. As such, waste management impact factors are defined separately for landfill and recycling **(Supplementary Material** 1).

2.4. Scenario development

The business as usual (BAU) scenario simulates material flows in Montréal from 2017 to 2050 based on defined drivers (population, workforce, and economic activity), and subsequently estimates the associated environmental impacts at different spatial scales. The exploratory scenario uses an OMC for each of the material flows as estimated using MCI (Ellen MacArthur Foundation, 2017). In the OMC scenario, recycling rates are applied to each material's end of life implemented in the system dynamics model from the year 2030 onwards. That is the year when Montréal aims to divert at least 85 % of waste away from landfills (Curtis, 2019). These altered recycling rates are shown in Table 2, leading to increased MCI and thus additional repurposed feedstock to substitute virgin material demands. The OMC is inspired by anticipated changes to Montréal's waste management system. These changes include a new waste collection and sorting facility. Increased economic costs and benefits associated with this implementation are not taken into account in this study, and it is likely that increased costs are outweighed by the benefits in the long-term (Babí Almenar et al., 2023).

We compare the environmental impacts of the BAU and OMC scenarios across space and time. We go on to link the spatial locations to their Human Development Index (HDI; UNDP, 2024), and thereby explore a potential link between distribution of environmental improvements of the two scenarios and development level. HDI ranges from 0 to 1, and are grouped into low (<0.55), medium, (0.55–0.69), high (0.7–0.79), and very high (>0.8).

3. Results

3.1. Material flows

In 2017, Montréal's demand for construction materials totaled 1542 kilotonnes. Sand accounted for 53 % of the total, and concrete products accounted for 22 %. Materials were sourced predominantly from within the Province of Québec ranging from 47 % of lime and gypsum products

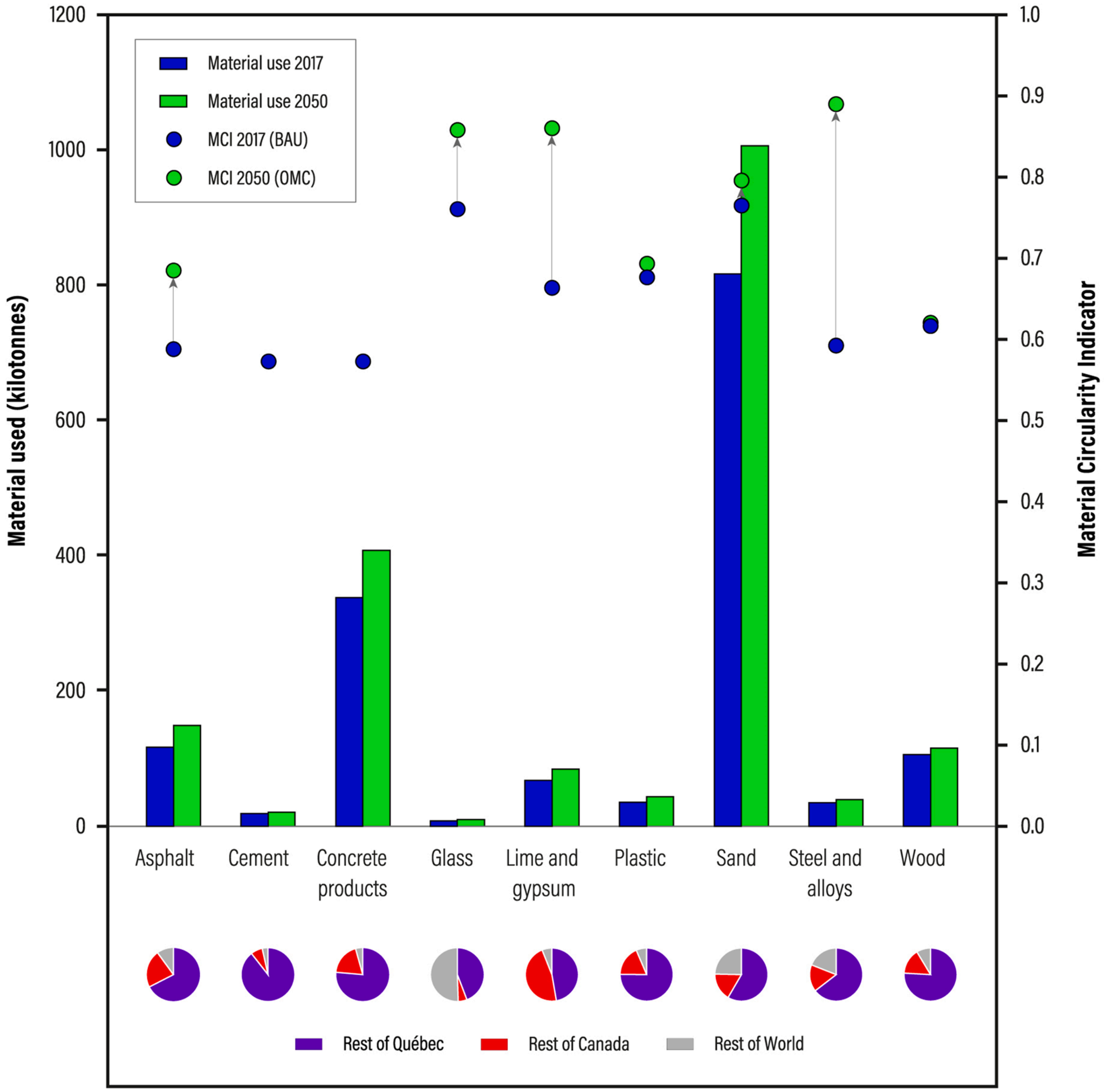

Fig. 2. Tonnage of materials used in 2017 and 2050 with material circularity indicator (MCI) measured at 2017 and at 2050 under the optimal scenario showing maximum potential improvement in circularity. Below bar chart, proportion of each construction material originating from Rest of Québec (ROQ), Rest of Canada (ROC), and Rest of the World (ROW).

up to 89 % in the case of cement. Overall, 65 % of Montréal's 1542 kt material demand was sourced from Québec; 19 % was sourced from elsewhere in Canada; and the remaining 17 % was from international sources. The variation in tonnage flows between materials between 2017 and 2050, together with the proportions of those materials' origins are shown in Fig. 2. MCI is overlaid to show the initial indices in 2017 compared to the potential increases per material in 2050 under the OMC scenario.

Overall, 66 % of the 1542 kt supplied to Montréal's construction sector in 2017 came from virgin materials. Materials flow out in different rates compared to inflows. In 2017, 109 kt of materials were recovered from Montréal's construction sector, half of which was landfilled. At the end of their service life, outflows are not necessarily recovered as the same material they once were. Under the BAU scenario, these recovered materials are exported to enter and substitute input flows in successive product systems elsewhere. In 2017, 61 % of the exported recovered material belonged to the aggregate category (cement, concrete products, sand), 20 % to the steel and alloy category, and 13 % was asphalt. These portions remain steady between 2017 and 2050 (**Supplementary Material 3**).

Under the OMC scenario, the recovered materials re-enter the urban metabolism subject to the city's demand for those materials. By 2024, an estimated 60 kt of recycled material could supplement the city's material demand, offsetting 4 % of total imports. Recycling rates vary greatly, so while sand and cementitious aggregates represent 62 % of material recovered, the circular flow only substitutes 4 % of the construction sector's demand for that category. Better gains are made in material categories that have high recycling rates. For example, steel and alloy circular flows substitute 32 % of its demand, and glass 19 %. These portions improve again in 2030, when recycling rates improve. Ville de Montréal plans to divert 85 % of material from landfills by 2030 (Ville de Montréal, 2019). In total, 130 kt of materials could be recovered in 2030, substituting 8 % of the demand in the following year. This 2 % increase is attributed to increased recovery and recycling of steel and alloy, for which 60 % of its demand could be substituted by circular flows. However, other materials are limited in their recovery and recyclability. For example, under the OMC scenario, only 2 % of plastic demand is substituted by reuse of recovered plastics, and the sand and aggregates category (which has significantly higher demand than other materials), reaches only 7 % circularity. This leaves majority portions of each material demand to be met by non-local sources even under the highest recovery and reuse rates.

3.2. *Environmental impacts*

Prior to the simulated increases in MCI, environmental impacts are closely aligned with the total tonnage of material supplies. The majority of environmental impacts occurred in the Production stage processes, with relatively small contributions from Transportation and End-of-Life. Over the duration of the simulation up to 2050, the environmental impacts increase steadily with BAU conditions. When OMC conditions were introduced, demand for imports dropped, pulling down Production impacts for most categories, and having ripple effects on Transportation and End-of-Life impacts to boot. Terrestrial acidification potential (TAP) and metal depletion potential (MDP) experience the largest relative improvements. These results are shown in Fig. 3, ordered from top left to bottom right by total relative change between scenarios.

Another way to understand these results is to think of the life cycle

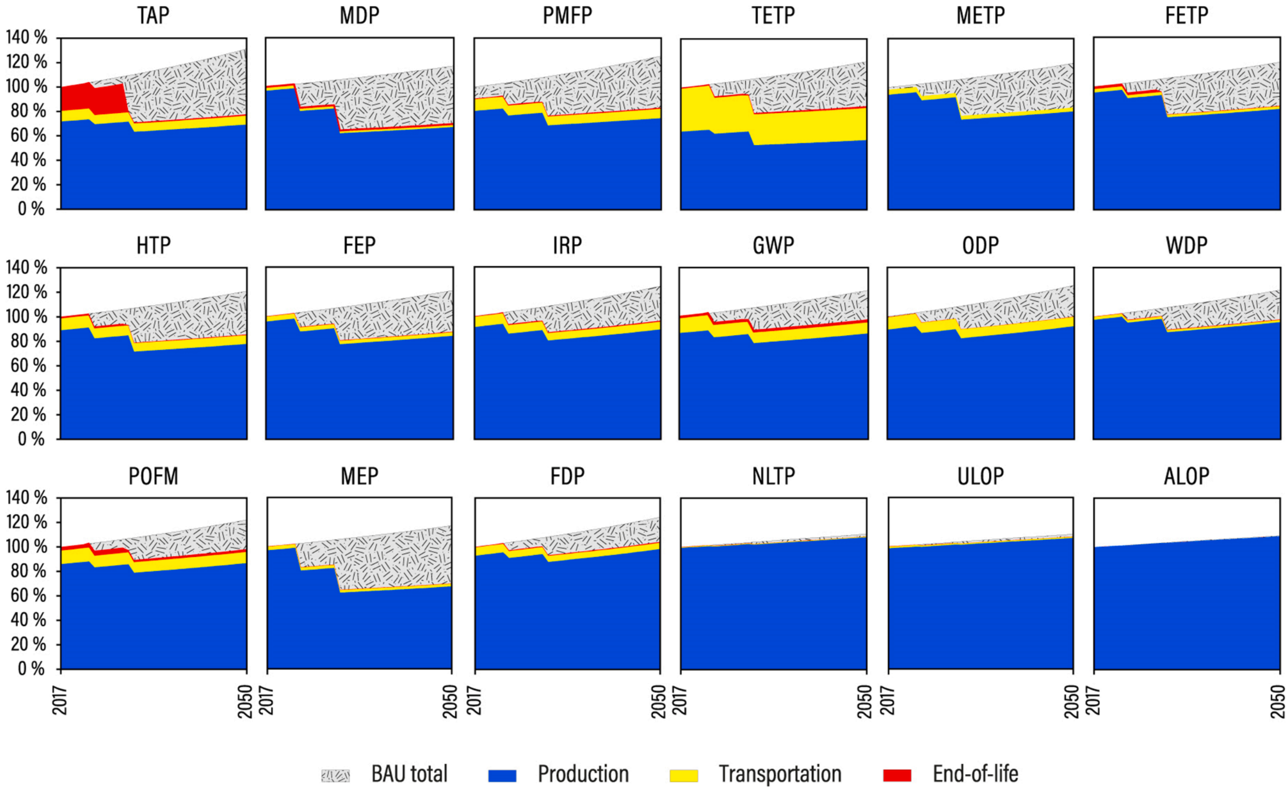

Fig. 3. Change to impacts of material flows between 2017 and 2050. Background shading shows business as usual trajectory while foreground shows impact changes in production (blue), transportation (yellow) and end-of-life (red) stages in OMC scenario. Abbreviations are: Terrestrial acidification potential (TAP), Metal depletion potential (MDP), Particulate matter formation potential (PMFP),Terrestrial ecotoxicity potential (TETP), Marine ecotoxicity potential (METP), Freshwater ecotoxicity potential (FETP), Human toxicity potential (HTP), Freshwater eutrophication potential (FEP), Ionizing radiation potential (IRP), Global warming potential (GWP), Ozone depletion potential (ODP), Water depletion potential (WDP), Photochemical oxidant formation potential (POFP), Marine eutrophication potential (MEP), Fossil depletion potential (FDP), Natural land transformation potential (NLTP), Urban land occupation potential (ULOP), Agricultural land occupation potential (ALOP).

stage impacts in terms of the location in which they occurred. The geolocation of impacts resembles the source of supplies. Montréal's globally distributed supply chains means environmental impacts were also distributed across nine of the 13 Canadian provinces and territories as well as the 160 international trading locations. The 83 % of total materials sourced from Canada accounted for 78 % of global warming potential (GWP) and water depletion potential (WDP) alike, the majority of which occurred in Québec, where only 65 % of materials were sourced. While no materials were sourced from Montréal in the BAU scenario, the city was subject to small portions of most environmental impacts (typically less than 1 % for all categories).

Focusing now on only four especially relevant impact categories, results can be shown to undergo trade-offs. TAP, MDP, along with the globally relevant GWP and WDP are chosen for this deeper analysis of trade-offs. Between 2017 and 2050, environmental impacts at international supply locations decrease under the OMC scenario, while Montréal's impacts increase. These urban impacts arise due to the substitution of distal extraction and manufacturing activities by Montréal's material recovery and recycling activities.

Comparing BAU and OMC in 2050, TAP is simulated to decrease by around 55 % overall, followed by MDP with a decrease of 47 %. However, in Montréal, TAP is anticipated to increase over ten-fold, while MDP could increase over 140 %. GWP and WDP experience the same directional trade-off: GWP decreases 20 % overall but increases 230 % in the city, and WDP decreases 24 % overall but increases by almost 500 % at the urban level. Other impact categories follow similar trends of shifting impacts away from supplier regions into Montréal where end-of-life activities are accounted. For example, PMFP decreases 40 % overall, but increases by sixteen times in Montréal – the largest relative increase at the city level.

4. Discussion

4.1. Circular urban metabolism trade-offs

The environmental performance of Montréal's construction sector improves under the OMC scenario compared to BAU. Subject to increased material recovery rates at the time of demolition, and use of

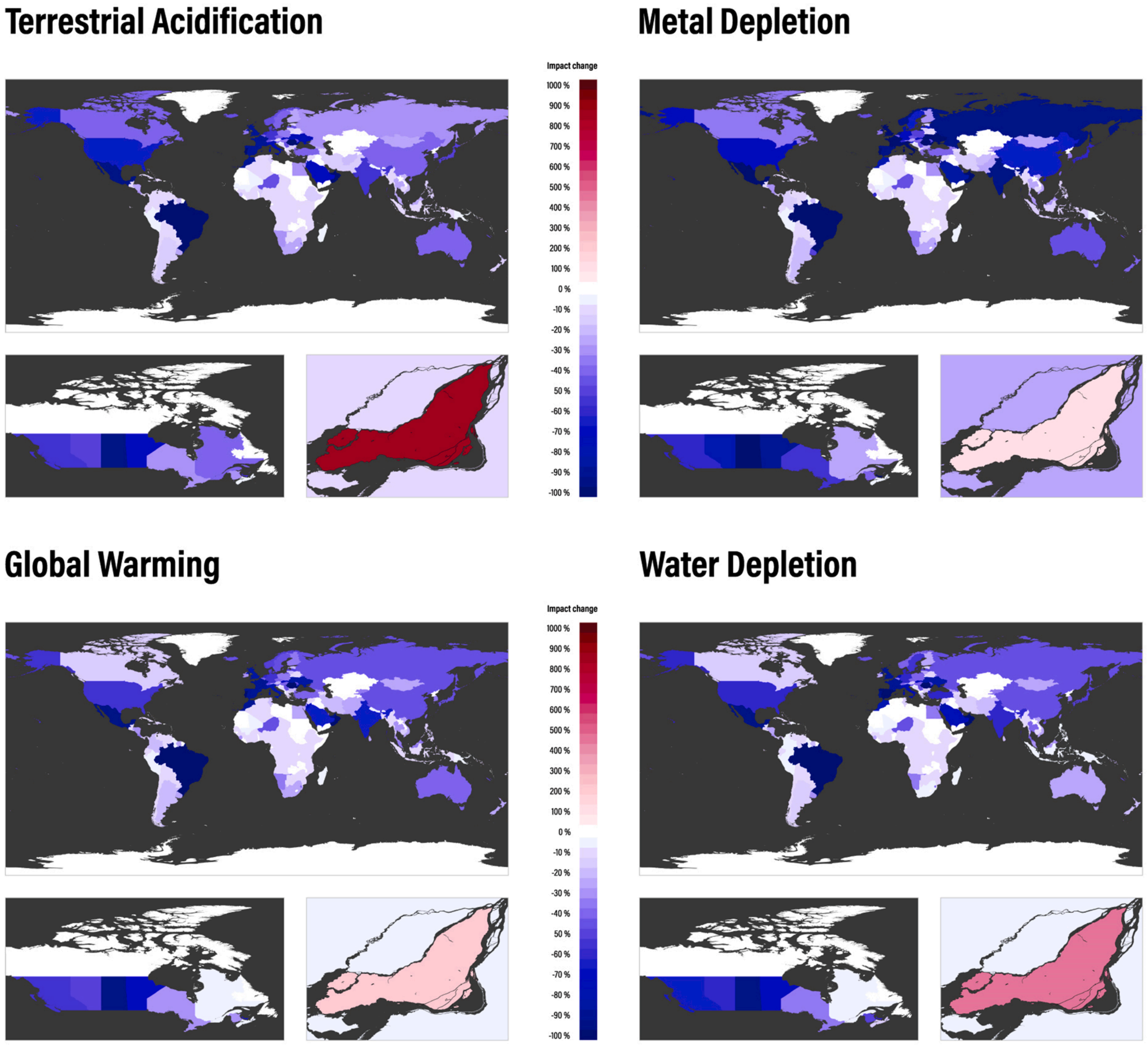

Fig. 4. OMC impact change in 2050 compared to BAU across spatial levels (global, national, urban) showing relative trade-offs for Terrestrial Acidification Potential, Metal Depletion Potential, Global Warming Potential, and Water Depletion Potential. For the animated version of this figure see Supplementary Material 4 (http://doi.org/10.5281/zenodo.10843099).

those recovered products, the urban metabolism becomes more circular. While this can reduce demand for virgin materials and their associated environmental impacts, these are replaced by activities in the urban environment that pose risks of trade-offs, both between impact categories (burden-shifting) and re-location of impacts ("spatial burden-shifting"). For example, expansion of mass timber construction in Montréal may reduce climate change impacts associated with concrete and steel production in distal locations but may increase other impacts related to waste management locally (Meyer et al., 2024). From a global perspective, the OMC provides benefits and incurs no negative trade-offs in all of the 18 impact categories. However, when considering the heterogeneity of impacts at different spatial levels, these overall improvements are achieved with the consequence of spatial burden-shifting. In other words, some locations will experience increased environmental impacts. Moreover, these shifts change the type of environmental impacts generated, and this too can affect locations whose specific challenges may be worsened. These far-away impacts are shown for Canada in Fig. 4 (play the animated video version of Fig. 4 in **Supplementary Material 4; http://doi.org/10.5281/zenodo.10843099**), with the inset showing Montréal on the backdrop of the Rest of Québec, and for international (rest of world). Shading reflects the relative difference between 2050 impacts under the OMC scenario compared to 2050 impacts under the BAU scenario.

One of the important tradeoffs to consider is the exchange of landfilling for recycling. Under the BAU scenario, fixed recycling rates are used and the remainder is landfilled locally. Urban waste management impacts are generated and allocated to Montréal. Meanwhile, the portion that is recycled also generates impacts in Montréal's local environment, but without a local demand for those materials the model assumes they are exported for use in other non-local product systems. As such, the recycling activities are counted as part of subsequent life cycles, and their environmental impacts are not allocated to Montréal. This trend is likely to be generalizable to cities that have large quantities of material flows and impacts linked beyond their urban limits. However, the specific spatial distribution of impacts and therefore the distal benefits associated with increasing material circularity are unique.

Under the OMC scenario, recycling rates are increased for most recovered materials. A portion is still landfilled, albeit less and thus generating less environmental impact. However, the higher recycling rates create a trade-off situation whereby more recycling-related impacts are generated in Montréal. Moreover, as those recycled materials are used to supply subsequent material demand, the recycling-related impacts become part of the city's impact allocation. That is because, unlike when those recycled materials are exported to non-local supply chains, they are now supplying local chains. The result is that Montréal's impacts increase when materials are circulated, but these circular flows replace supply chains from non-local sources, thus decreasing remote impacts, and also decreasing net impacts in general.

It is necessary to balance those benefits by understanding the spatial trade-offs (Seto et al., 2012). What this tells us it that the OMC scenario delivers many benefits at the global level, and could be harnessed by many municipalities to bring down overall environmental impacts in the global construction sector. To that end, circular economy advocates must understand the potential spatial burden-shifting arising from circular urban metabolism. These findings are sensitive to the uncertainty associated with the assumptions and simplifications used to model construction materials flows and locations that are presented in the Methods section. However, despite uncertainties, these results show that the model developed can help decision makers identifying potential spatial burden-shifting when implementing material circularity strategies in the construction sector.

Most urban environmental policies are based on territorial inventories and reduction targets. For example, governments need to adopt a consumption-based GHG inventory in addition to their territorial inventory to avoid shifting GHG emissions elsewhere (Peters, 2008; Wiedmann et al., 2020). Our paper confirms exactly that. Governments could develop consumption-based inventories, implement reduction targets which will then favour the establishment of policies for the deployment of the circular economy as these policies would help reaching these targets.

4.2. Risks of environmental injustice

Spatial burden-shifting may become a focus of environmental justice in the future (Shi et al., 2016; Zhang and Seto, 2011). Some environmental indicators only make sense at a global level (e.g. climate change), while their related impacts can be locally very different, as shown in these results and others (Vanham et al., 2019). It implies that when talking about environmental impacts reduction, two aspects must be considered: the global amount of reduction reached and the local variation of these impacts (Liu et al., 2015; Seto and Shepherd, 2009).

Mapping spatially-heterogenous impacts helps facilitate the discussion of spatial burden-shifting within the circular economy realm, and how environmentally just these shifts may really be. For instance, focusing on WDP, the OMC scenario shows a decrease of 94 % for Mexico and of almost 100 % for Brazil, and an increase five-fold in Montréal compared to the BAU scenario. While Brazil and Canada are among the countries with the largest resources of renewable freshwater worldwide (Statista, 2022), Mexico is an arid country, often facing water scarcity events (Arreguin-Cortes et al., 2020). Hence, the implication of "borrowing" water from other countries for local purposes cannot be solely measured in terms of volume (Li et al., 2020).

Having the broadest picture of a city's environmental footprint – as LCA-extended urban metabolism coupled with worldwide impact mapping allows – is necessary for understanding fully environmental degradation dynamics. The spatial consideration of these impacts shall get a more prominent place since most industrial activities have been displaced to Global South countries (Fuhr, 2021), leading to a significant spatial burden-shifting from Global North countries to developing ones. This consequence of neocapitalism through international trade has been the fastest growing driver for global CO_2 emissions (Fuhr, 2021) partly due to the fact that production shifted to economies with a least efficient energy use and with a higher carbon content. Hence, shifting consumption habits to more locally based products and reducing the overall use of virgin materials – as promised by circular strategies – would allow to reduce overall environmental impacts while also hindering the current "environmental colonialism" perpetuated against the most vulnerable countries (Fuhr, 2021).

Fig. 5 helps illustrate that point. The benefits gained by the supplier nations through the optimal material circularity scenario are grouped by those nations' HDI. This shows that the trickle-down effect of reduced environmental burdens most strongly benefits those countries with higher development levels. In this case, the less developed trading partners reap smaller benefits from a potential increase in Montreal's construction material circularity.

4.3. Urban metabolic rifts

Environmentally and spatially-extended dynamic urban metabolism provides an advanced framework for assessing the future benefits and trade-offs of material circularity. This model shows how the economic growth, urban population, and their demand for materials together have global environmental consequences across all impact categories. The circular economy concept deployed in this model is of material circularity, using waste streams to substitute and potentially offset new demand. However, the model revealed that the annual waste streams are meagre compared to demands, so even if all outputs could be reused the tonnage simply does not replace the need for imported virgin materials (and it is not even close). While these results are promising for impact reduction, these reductions are not at the magnitude to be a solution for a city's socio-ecological rift.

Extending the service life of buildings and infrastructure for which

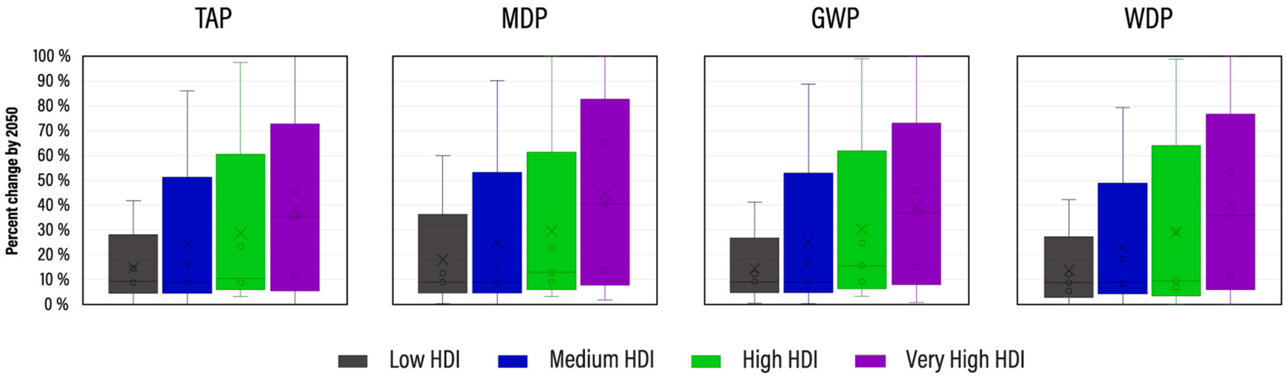

Fig. 5. Disparate share of environmental benefits across development levels. Improvement to environmental conditions under the OMC scenario compared to BAU in 2050 is skewed to countries with higher development.

the metabolic flows are used would be a more effective circular strategy to reduce the demolition rate, also reducing the useful tonnage recovered, and the tonnage of material demand. More research is needed in this area, focusing on extending the service life of buildings, and behavioural changes, which would require improvements to data quality.

This work shows that in spite of the widespread environmental benefits of increasing material circularity, the benefits do not go far enough within the time-frame considered, meaning other actions are needed. Construction waste streams do not amount to anywhere near the tonnage needed to meet demand. The increasing demand perpetuates this metabolic rift over time. Potential partial solutions such as increasing service life of buildings, which was not modelled in this work, demonstrate that less growth is necessary, even when material circularity is high. In other words, resolving the metabolic rift requires returning waste streams to a place they can be used as input resources, *and* requiring less of those resource inputs. Without a reduction in demand, either through extending the service life of buildings and infrastructure, or by reducing the absolute service of those stocks, material circularity alone is insufficient in the short-term. Extending service life in the construction sector over the long-term and shifting the materiality argumentation towards degrowth-compatible narratives in which reduced inflows may be demanded is likely to provide benefits for the environmental performance of the construction sector.

4.4. Limitations and future research opportunities

This work showcases a novel system dynamics method for illustrating spatial burden-shifting to better understand the unintended consequences of using only material circularity as a strategic goal. Notwithstanding, material circularity is only one of the many ways a system can be circularized. This simplification does not invalidate the main purpose – that is to show how different locations fare over time as supply chains attenuate, but more work is needed to understand the magnitude of a wholly circular system. Furthermore, the lack of complete data, typical in life cycle thinking and urban metabolism research, required the downscaling of provincial input data as proxy for the city of Montreal. This follows standard practice, but ideally urban-level models would be supported by robust and high spatial and temporal datasets. The model could also be improved by disaggregating the materials' production value chains in order to determine the exact location of each activity. For instance, impacts associated with the steel production chain have been entirely allocated to the regions where steel is coming from, even if some activities such as mining could have occurred elsewhere. Lastly, the use of static impact factors possibly places these environmental impact results on the pessimistic side. If producer states improve production practices in the next decades, as is anticipated, the environmental footprint of cities like Montréal would decrease. In spite of these limitations, which should be addressed in future research works, this study shows the importance of developing such urban metabolism models based on system dynamics to better understand and plan the deployment of circular economy strategies in the future.

5. Conclusions

This study aimed to model and assess synergies and trade-offs consequent to optimising the circular metabolism of construction materials. This dynamic urban metabolism method integrated life cycle inventory data, spatially-heterogenious supply chains, and socio-economic dynamics to simulate future multi-level environmental impacts linked to the construction sector of Montréal, Canada between 2017 and 2050. This integrated spatio-temporally dynamic approach advances the state-of-the-art circular economy models that tend to focus on linear or static frameworks.

It was found that recycling and reuse of construction materials reduces all 18 environmental impact categories that were measured. However, the model revealed spatial burden-shifting: the phenomenon of reducing an environmental burden in one location while increasing it somewhere else. Notwithstanding, these shifted burdens turned out to be overall improvements, although raising the problem of environmnetal justice for people living in the affected regions. The winners of Montréal's material circularization are not the residents of Montréal, but those located in the supplier regions, especially Brazil, Mexico, and Norway – for whom environmental impacts decrease between 80 and 100 % in all 18 impact categories by 2050. Five of the 18 categories did not undergo spatial burden-shifting, improving at all spatial levels in the assessment, while 13 showed decreased environmental impacts remotely at the expense of increased impacts within Montréal. This illustrates the importance of systems-thinking in complex non-linear settings such as the interface of global supply chains and their urban consumers if society is to properly understand and solve the environmental crises of our time. The authors propose further research on the extension of service life in the construction sector, and suggest that the circular economy champions shift away from pro-growth narratives and emphasize the need to also consume less, and more towards a mediated approach in which the effects of the least developed supplier regions are not the last to benefit.

CRediT authorship contribution statement

Thomas Elliot: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Marie Vigier:** Writing – review & editing, Writing – original draft, Project administration, Funding acquisition, Data curation, Conceptualization. **Annie Levasseur:** Writing – review & editing,

Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This research was funded by the Centre for Intersectional Studies and Research on the Circular Economy (CERIEC) and the Canada Research Chair on Measuring the Impact of Human Activities on Climate Change.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107567. Supplementary Materials 1-3 are also stored at http://doi.org/10.5281/zenodo.10842548, and Supplementary Material 4 is stored at http://doi.org/10.5281/zenodo.10843099.

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