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The material footprints of cities and importance of resource use indicators for urban circular economy policies: A comparison of urban metabolisms of Nantes-Saint-Nazaire and Gothenburg

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ABSTRACT

Material consumption has been increasing steadily since the beginning of the 20th century. The urban metabolism field of research is one of the fields that focuses on understanding and measuring this increase at the city level. Many studies have been carried out to calculate the material consumption at the domestic scale. But it is also important to include the non-domestic scale to account for the amount of materials extracted outside the city that were needed along the supply chains to produce the final products consumed in the city. This is referred as the material footprint, which provides a consumption-based indicator of resource use. The objective of this study was to develop a method to measure the material footprint of the cities of Nantes-Saint-Nazaire (France) and Gothenburg (Sweden), both port cities and pioneers in the implementation of urban policies targeting a circular economy. The methodology combines urban material flow analysis with multi-regional input-output database to extend the urban metabolism beyond the administrative boundaries of cities. We then calculated the absolute and per capita material footprints of the two cities and its material disaggregation. We compared these results with domestic material consumption. Further analysis of the urban material footprint was performed by spatializing the flows in the global economy to understand the extent of consumption due to cities. The results show that on average the material footprint is 2.4 times larger than the domestic material consumption in Gothenburg and 1.9 times larger in Nantes-Saint-Nazaire. A decoupling between material footprint and domestic material consumption can be observed, as the material footprints grew much faster than the domestic material consumption. Regarding the material disaggregation, the most significant category is non-metallic minerals, which weighs more than 50% on average of the total material footprint balance sheet and also increased the most. In conclusion, future work should thus better integrate material footprint, as there is a need to better understand the externalization of urban metabolism and to identify what aspects urban circular economy policies should focus on.

1. Introduction

Material consumption has been increasing steadily since the beginning of the 20th century, with two major periods of acceleration (between 1945 and 1970, and from 2002 on), but which are not homogeneous in space (Görg et al., 2020). The two phases of accelerated resource use occurred in different regions of the world. In this article we focus on the second phase, notably on the issues of interdependence between countries, especially the “global appropriation of resources by the high-income countries” (Schaffartzik et al., 2014b, 2019). Socio-metabolic research on the Anthropocene (Haberl et al., 2019) has made it possible to identify these socio-ecological transformations that have political and social implications, and are embedded in economic history (Magalhães et al., 2019; Moore, 2016).

Resource consumption can be measured at the domestic scale (within countries) by tracking the amount of materials used. This is the Domestic Material Consumption (DMC) indicator which corresponds to what is extracted and imported into the territory, minus what is exported. But it is also important to include the non-domestic scale to account for the amount of materials extracted outside the country that were needed along the supply chains to produce the final products consumed in the country. This is referred as the material footprint indicator (MF), and

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"provides a consumption perspective of resource use" (Wiedmann et al., 2015). Indeed, this consumption-based approach integrates the allocation of all the environmental responsibility to the final consumer.

The material footprint has been widely discussed at country level (Eisenmenger et al., 2016; Kovanda and Weinzettel, 2013, 2013, 2013; Munoz et al., 2009; Plank et al., 2018; Schoer et al., 2012) including in publications by the UNEP and the International Resource Panel (Fischer-Kowalski et al., 2011; Swilling et al., 2018), but not at the city level. Yet, as the UNEP shows, the weight of cities is largely responsible for the increase in material and energy consumption, particularly as a result of the urbanisation of the world (Swilling et al., 2018). This is even more relevant since, based on interviews with stakeholders and analysis of local policies (Bahers, 2022), we identified a few barriers that stakeholders face when integrating material footprint issues. These obstacles are of two kinds: the difficulty of correctly measuring the material footprint and its characteristics, and the lack of knowledge of the issues at stake (notably the questions of outsourcing of resources).

This focuses on the analysis of the material consumption at urban level from the perspective of resource use. To be able to do this, we investigate the material footprints of cities and how they can be measured. We also want to understand the differences between DMC and MF, and how this can support the development of more effective urban circular economy policies.

In this sense, the aim of this article is to investigate the contribution of the urban metabolism field of research to accounting for the material footprints of cities. The urban metabolism concept focuses on the transformation of materials and energy by cities, corroborated by socio-technical and socio-ecological processes (Bahers et al., 2019; Barles, 2009; Pincetl et al., 2012; Rosado et al., 2016). Several studies have been made to calculate DMC but it has been done mostly at the scale of megacities (Kennedy et al., 2015; Pincetl, 2012; Zhang et al., 2017) and less on other types of cities, and very rarely with MF indicators. For this study, we chose the specific case of port cities, as we have previously shown that they form nodes in the metabolic relations with their hinterlands (Bahers et al., 2020), hinterlands being spaces from which resources (mineral, organic, energy) are extracted to be ultimately consumed in the city (Billen et al., 2012; Krausmann, 2013). To be able to quantify the DMC and MF for the cities, we developed a methodology that consisted in combining an urban material flow analysis with a multi-regional input-output database to extend the quantification beyond the administrative boundaries of cities, which has never been done on the urban scale.

By understanding the relationship between the material flows of cities and the material footprints connected to them, we question the externalization and the outsourcing of the metabolism of cities. We also question the political dimension of material footprints, through urban policies that aim to reduce them. Indeed, for several years, cities have been developing circular economy policies that aim to limit the consumption of resources and the production of waste (Ghisellini et al., 2016; Gravagnuolo et al., 2019). This leads us to question the impact of cities and what the role of material footprint in circular economy policies can be.

The article is organized as follows: in section 2, we describe our methodology, followed by a description of the metabolism of the case study cities in section 3. We give the results of the material footprint study and of our analysis of policy barriers in section 4, and finally discuss the spatialization of the material footprints in section 5.

2. Method: from urban material flows analysis to material footprints

We chose to combine two methodological approaches for measuring the material footprint of cities. Our aim was to combine the data obtained through an urban material flows analysis with the data contained in a multi-region input-output database, in order to extend the urban metabolism beyond the administrative boundaries of cities. When accounting for materials, we therefore want to explicitly include indirect flows linked to the materials and energy (from extraction, distribution, manufacturing) necessary for import and export (Athanassiadis et al., 2016; Eisenmenger et al., 2016; Lutter et al., 2016; Schaffartzik et al., 2014a). Integrating material footprint data leads us to produce critical indicators that go further than methodological cityism (Wachsmuth, 2012).

2.1. *Accounting for domestic material consumption*

Several methods are available to account for urban metabolism (Rosado et al., 2014; Zhang, 2013). We chose economy-wide material flow analysis (EW-MFA) (Eurostat, 2018), as it is robust and also produces comparable indicators. The data collected corresponds to extraction, imports and exports, as well as emissions to the environment. The domestic material consumption (DMC) indicator derived from this method is the most widely used not only in the literature, but also by national policies to assess their sustainability trajectories. DMC is what is extracted (domestic extraction, DE) from the land plus what is imported, minus the exports. Contrary to what national policies may believe, this indicator does not make it possible to measure the ecological performance of a city, region or state. It is mainly useful to assess the metabolic profile, i.e. whether it is an extractive, parasitic or autonomous economy (Magalhães et al., 2019, Krausmann, 2013).

$$\mathrm{PTB} = \mathrm{Imports} - \mathrm{Exports}$$

$$\mathrm{DMC} = \mathrm{DE} + \mathrm{PTB}$$

To avoid the pitfall of the "black box" lens of urban metabolism, our approach not only analyzes the impacts of what is extracted and consumed in cities, but also what is imported and exported from other regions.

We started by conducting an urban EW-MFA of the cities of Nantes-Saint-Nazaire and Gothenburg. We could have chosen the NUTS 2 scale of Europe, as a lot of statistical data is available on these regions. However, the NUTS 2 scale is too big and does not correspond to the metropolitan area of Nantes-Saint-Nazaire and Gothenburg. We therefore chose to work at a finer and smaller scale, based on the municipalities that belong to the metropolitan areas (See supplementary information: Main Data inputs and Sources Collected for Gothenburg Metropolitan area for an example of the data used and the spatial scales for each source). Gothenburg includes 13 municipalities, with a total population of 0.95 million; Nantes-Saint-Nazaire is composed of 61 municipalities (grouped in 5 inter-municipalities) with almost 0.9 million inhabitants.

The study period for Gothenburg we used was from 1998 to 2011, as extensive research was conducted during this period. The present study used the results of research conducted by (Kalmykova et al., 2015; Rosado et al., 2016). For Nantes Nantes-Saint-Nazaire, the period chosen, from 2000 to 2018, is more recent mainly due to the availability of freight transport data from 2000. Both studies used data at the municipal or metropolitan level. The statistics concern urban extraction, including minerals, food and agricultural biomass, and imports and exports of all types of goods (manufactured products, petroleum products, agricultural and food products, wood, metals, construction minerals, chemical products). These freight flows originate from national and international sources, and are transported by truck, train or plane. An uncertainty analysis was conducted for Gothenburg, in which it is shown that the DMC values have a range of uncertainty for the period in analysis of 11.2%–22.6% (Patrício et al., 2015).

2.2. *Transforming domestic material consumption into a material footprint*

To be able to capture indirect flows, we need to incorporate in the DMC of cities all the resources used to enable them. We therefore also calculated the raw material consumption (RMC) that corresponds to the material footprint of consumption (Eisenmenger et al., 2016; Fischer--Kowalski et al., 2011; Schaffartzik et al., 2014a). This indicator takes indirect flows of imports and exports into account, making it "a consumption-based indicator of resource use" (Wiedmann et al., 2015). It highlights the material effort beyond the city limits. This indicator reveals the materiality of goods to be allocated to the consumer.

We chose the EORA database, a multi-region input-output database containing data from 1970 with indicators that evolve over time (Schandl et al., 2018). We preferred this database to the Input-Output tables from Eurostat (Zhang et al., 2014), since the Eurostat dataset only starts in 2008, and to the Wuppertal Institute Coefficient approach (Bahers et al., 2019) since the Wuppertal dataset is static (Lutter et al., 2016). The EORA database has been used many times in very robust studies for different purposes (Giljum et al., 2019; Schandl et al., 2018; Wiedmann et al., 2015, 2020) and has also been used by the International Resource Panel (IRP, 2019). The EORA database is calculated at the level of nations. We therefore calculated coefficients calculated using the raw trade balance (RTB), which corresponds to imports in raw material equivalent minus the exports in raw material equivalent (Eurostat, 2018), already used in other studies (Cahen-Fourot and Magalhães, 2020; Magalhães et al., 2019). These coefficients are measured for the four main categories of material flows (Biomass, Fossil fuels, Metal ores, Non-metallic minerals), from 1990 to 2018. These four broad categories are the most frequently used in urban metabolism quantification studies (Bahers et al., 2019; Barles, 2009; Rosado et al., 2014; Voskamp et al., 2017), and are the most methodologically robust (Eurostat, 2018).

$$RTB = IMP_{RME} - EXP_{RME}$$

$$MF = DE + RTB$$

Some assumptions had to be made to combine the EW-MFA with EORA categories. In particular, we considered that fertilizers belong to the category of minerals and that metallic manufactured products belong to the category "metals", such as in the Eurostat guide (2018). Similarly, although we differentiate between domestic and international imports (and exports), we used the same coefficients of raw material equivalent because there is no better assumption for the subnational level.

2.3. Spatial analysis of the material footprints

We performed a further analysis of the flows of materials related to material footprints by spatializing world flows. This made it possible to understand the extent of outsourcing of consumption due to cities. For this analysis, we used the category non-metallic minerals. The import data used came from Eurostat and concerned imports via the two ports in 2017 (Eurostat, 2019). We linked these data with the Comtrade trade database ("UN Comtrade: International Trade Statistics," 2022) between countries. In addition, we chose two materials within the category of non-metallic minerals: cement and sand. These two materials are among the most important by weight and enable a more detailed analysis. We consequently identified not only the main import flows of cement and sand, but also indirect flows of sand that feed the countries that export cement (because sand is one of the main components of cement).

3. Case study: The metabolisms of Nantes-Saint-Nazaire and Gothenburg

The metropolitan areas of Nantes-Saint-Nazaire and Gothenburg share two aspects that are important for our study: they are both ports and have implemented pioneer urban policies in circular economy (CE).

Nantes-Saint-Nazaire is the 4th largest port in France (30 million tons per year)[1] and consists of a complex network of highly energy-intensive industrial sites operating in the steel, petrochemical and agri-food industries. In particular, the port is home to the 2nd largest crude oil refinery in France. Gothenburg is the largest port in Sweden (39 million tons per year).[2] Industry in the port of Gothenburg is more oriented towards manufactured products, including Volvo cars, but is also an entry port for fossil fuels, hosts a large chemical industry cluster, as well as receiving waste that feeds an incinerator connected to a large urban heating network.

Concerning the local policies of the CE, Nantes-Saint-Nazaire has developed several strategies.

- An industrial symbiosis approach[3] that started in 2014 aimed at increasing the competitiveness of companies, optimizing the industrial port space and reducing its environmental footprint.
- A roadmap for the CE was adopted in October2, 018.[4] It is organized around three axes: "an organic loop for bio-waste; a technical loop for the re-use and repair of small-scale electrical equipment, and a technical loop for a sustainable and circular BTP that consists in reinforcing the recycling of construction waste.

In Gothenburg, a "CE" strategy has been implemented since 2016. The objectives of the project entitled "Circular Gothenburg"[5] are to "lead, coordinate, support and co-create the transition to a circular economy" in the City of Gothenburg's areas of competence. This includes municipal processes and activities that help citizens to live more circularly. The focus of the strategy is to reduce waste (what started in 2000 (Corvellec et al., 2013; Zapata Campos and Zapata, 2017)), reduce the impact on the climate and increase resource efficiency. Actions have been undertaken to this end including.

- The establishment of "Fixoteks" i.e., repair workshops in the city. They are staffed, located close to where people live, open to all, and their aims are to meet, learn, repair and redesign objects, borrow tools, exchange toys, clothes and books.
- A new framework agreement (public procurement) for the reuse and redesign of furniture in the city.
- Public procurement for circular flows within the construction and demolition process: A state-funded project started in 2019 and makes recommendations or suggestions on how public procurement requirements can be formulated to support circular construction and demolition.

We conducted 40 interviews in Nantes-Saint-Nazaire and in Gothenburg between 2018 and 2022, to understand the implementation of circular economy policies (Bahers, 2022). The questions addressed the role of the interviewee in the urban metabolism, the main obstacles and the levers used in the circular economy policies, and the territorial and social approach to the circular economy. The results of this investigation show that Circular Economy policies do not include reducing

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[1] Available on the official website of the port: < https://www.nantes.port.fr/fr/nantes-saint-nazaire-port>.

[2] Available on the official website of the port: <https://www.portofgothenburg.com/about-the-port/the-port-of-gothenburg/>

[3] Available on the official website of the port: <https://www.nantes.port.fr/fr/nos-engagements/agir-en-faveur-de-lenvironnement/durabilite-des-activites-portuaires>.

[4] Available on the official website of the city: <https://metropole.nantes.fr/territoire-institutions/projet/ambitions-territoire/33-engagements-pour-la-transitio>.

[5] Available on the official website of the city: <https://goteborg.se/cirkularagoteborg >

externalized impact of supplies and waste, as the stakeholders are just discovering the issues of hidden flows. Second, the metabolic relationship between city and hinterland remains a blind spot and the circular initiatives are urban-oriented. However, it should be noted that many actors emphasized their desire to work on proximity and on urban energy and material autonomy. These obstacles and levers lead to a deeper understanding of these issues and are an additional motivation from the actors.

4. Understanding the differences between DMC and MF

In this section, we present - in parallel - results for the DMC and MF indicators for the two metropolitan areas. The first series covers the period 1998 to 2011 for Gothenburg and the second the period from 2000 to 2018 for Nantes-Saint-Nazaire, enabling a direct comparison between 2000 and 2011. The results are first shown for each city in absolute terms (Fig. 1) and then in relative terms per capita (Fig. 2). The last section shows differences according to the main categories (Fig. 3).

4.1. *Comparison of absolute values*

Fig. 1 summarizes the results, expressed in kilotons, of the EW-MFA and the material footprints of the two cities: the curves representing Nantes-Saint-Nazaire are in gray and curves representing Gothenburg are in orange. We also believe it is important to show the trajectories of these curves, which is why the dotted lines show the simple linear regression.

Fig. 1 shows that large changes in MF over time are occurring. The differences are mainly due to the RTB, as DE evolves but only slightly with regard to the changes in RTB. These changes depend on the categories of materials (Section 4.3 shows in more detail the evolution of material footprints by category in more detail). For example, the MF in Gothenburg decreases between 2004 and 2005 because the RTB of non-metallic minerals in Gothenburg decreased by half. Between 2010 and 2011, we observe an increase in growth since the RTB for metals increased significantly in Gothenburg. In Nantes-Saint-Nazaire, the RTB of metallic minerals decreases significantly in Nantes-Saint-Nazaire between 2006 and 2013, which implies a decrease in the MF. Yet the RTB of non-metallic minerals increased by almost double between 2008 and 2009, hence the strong increase of the MF. The hypotheses for these variations may be linked to major development projects in the metropolis that require a large volume of materials, or changes in economic structures in the territories concerning manufacturing or port logistics. Indeed, in the early 2000s, it was also the beginning of the urban renovation of the industrial wasteland of the Ile de Nantes into a new urban project of housing, shops and offices. Thus, the construction industry in Nantes-Saint-Nazaire experienced a sharp increase in 2006 and 2007, but followed by a sharp decline from 2009 to 2014. The effects of the 2008 crisis were postponed until 2009, but have been major since then (−9.8% on average annually between 2009 and 2014 according to INSEE). Similarly for jobs, the evolution is very strong until 2008 (+5.4% each year since 2004), then a fall in jobs follows between 2008 and 2014. The 2008 crisis can also be seen in the evolution of MF in Gothenburg.

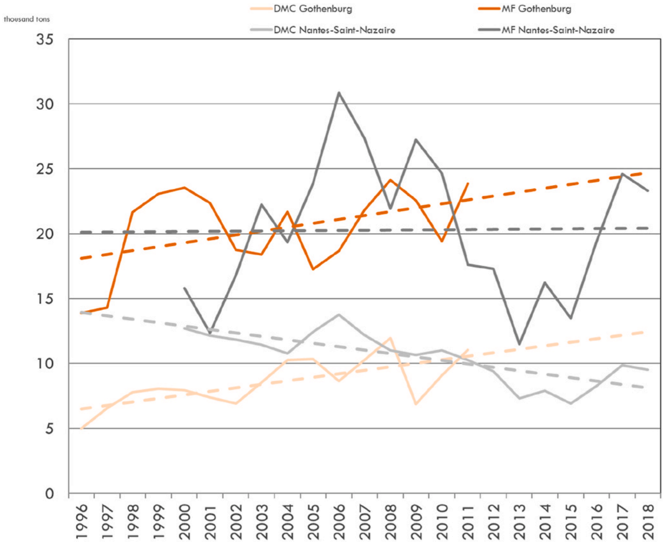

Fig. 1. DMC and MF for Gothenburg and Nantes-Saint-Nazaire from 1998 to 2018 (Source: Rosado et al., 2016; and authors' computations).

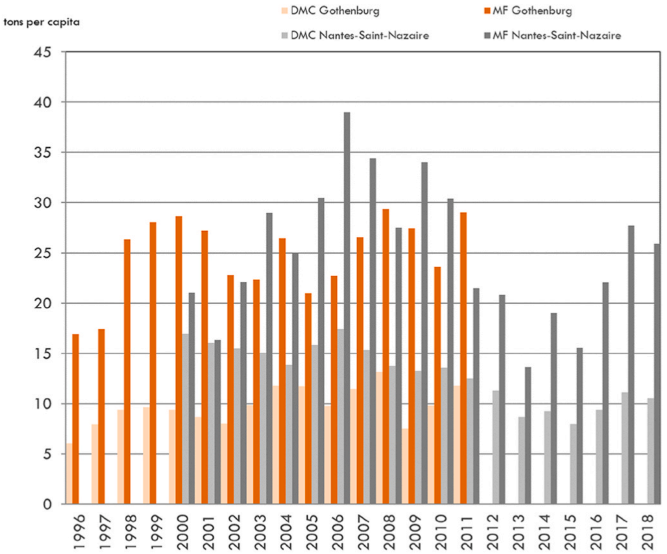

Fig. 2. DMC and MF per capita per city (Source: Rosado et al., 2016; and authors' computations).

Fig. 1 reveals a highly significant difference between the indicators: on average, the MF is 2.4 times larger than the DMC in Gothenburg and also 1.9 times larger in Nantes-Saint-Nazaire. The material footprint is therefore much larger than direct material consumption. The gap is not constant over time but oscillates between 2.1 and 3.2 in Gothenburg, and between 1.2 and 2.5 in Nantes-Saint-Nazaire. This is explained by the important role of imports/exports in both cities (compared to domestic extraction) (cf. Table 1). Therefore, cities in general are highly dependent on hinterlands. However, both the DMC and MF curves of the two cities are similar, even if there are marked differences in some years (2001, 2006, 2009), but in 2011, both indicators were almost identical in the two cities.

The evolution of the curves reveals the decoupling between MF and DMC in Nantes-Saint-Nazaire: due to a substantial reduction in the DMC over the period, versus a slight reduction in the MF. At its highest peak in 2006, the DMC was 13.7 million tons, while it was lowest in 2015 at 6.9 million tons. Conversely, the MF was low in 2000 (15.7 million tons), and high in 2018 (23.3 million tons). This result is also in agreement with the national case study by Magalhães and colleagues (Magalhães et al., 2019), where DMC decreased while RTB (raw trade balance) increased, which is also known as a post-industrial consolidation regime. In the port city of Nantes-Saint-Nazaire, the RTB is above 12.9 million tons until 2000, but higher in 2018 (19.3 million). The strong decreases from 2013 to 2015 are linked to a reduction in port activity, and therefore a strong decrease in RTB (50% decrease between 2012 and 2013). The city has a globalized metabolic profile on the input side and a regional one on the output side: imports are mostly international (72% in Table 1) and more important than exports which are regional and intranational (64% in Table 1).

In Gothenburg, the increase in DMC was slight, whereas the increase

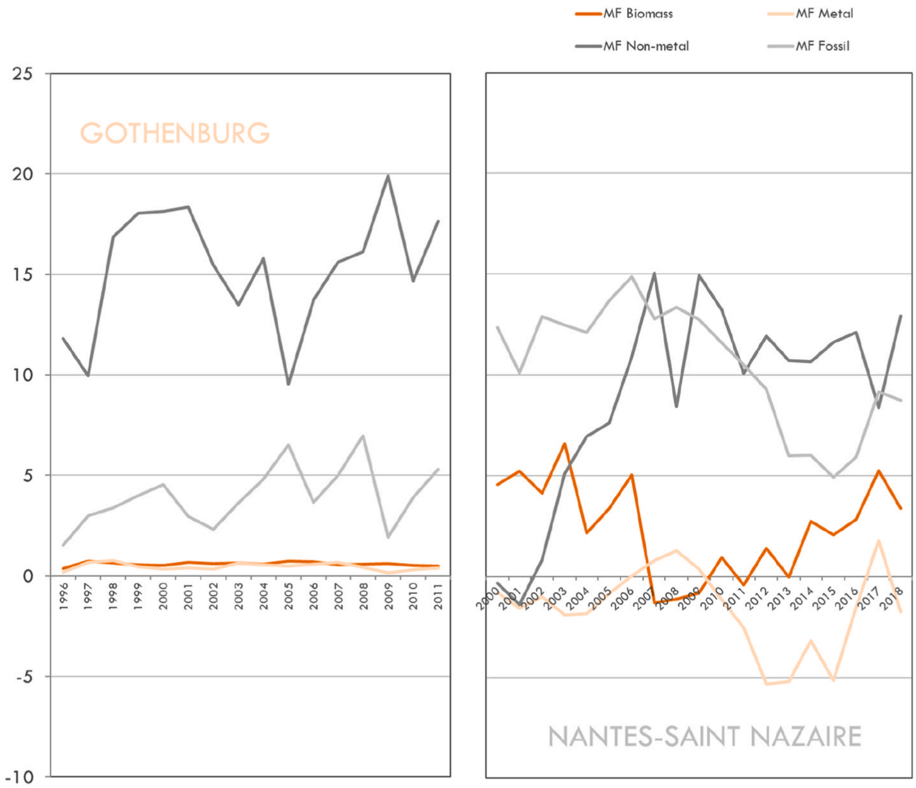

Fig. 3. MF per category (Gothenburg upper graph, Nantes-Saint-Nazaire lower graph) (Source: Rosado et al., 2016; and authors' computations).

Table 1
Absolute values of import and export (on average over the period of the case studies) by national or international scales.

	Average (in ktons)	Share of imports/exports
Gothenburg National Imports	10 932	35%
Gothenburg International Imports	20 440	65%
Gothenburg National Exports	12 854	44%
Gothenburg International Exports	16 501	56%
NSN National Imports	8623	28%
NSN International Imports	22 366	72%
NSN National Exports	13 726	64%
NSN International Exports	7671	36%

in the MF was very large. The DMC started at 4.9 million tons in 1996 and ended at 11 million tons in 2011. At its lowest point in 1996, the MF was 13.8 million tons, while at its last and highest point in 2011, it was 23.8 million tons. The question then is, what happened after 2011? According to national indicators (from the EORA database), the DMC in Sweden remained stable while the MF continued to increase strongly. This therefore points to a case of a very high externalization of the metabolism explained by the increasing supply from outside the Gothenburg borders. Thus, the supply from international sources represents twice the supply from national sources (the rest of Sweden) (averaged over the period) (cf. Table 1). Thus, RTB has increased significantly between 1996 and 2018 (1.8 times).

To conclude this section, it is worth mentioning the second great acceleration hypothesis. According to our results, this increase in material consumption is not directly visible in domestic consumption, but more so in the material footprint. This is consistent with the fact that this great acceleration is more likely to materialize in emerging economies (the BRICS (Brazil, Russia, India, China and South Africa, but especially China) (Görg et al., 2019). However, there are clear links between these hinterlands and European cities. Indeed, the consumer durables purchased in Nantes-Sant-Nazaire and Gothenburg represent consumption elsewhere in the emerging economies, but also in the rest of the world, and contribute directly to this second great acceleration. This planetary urbanization (Arboleda, 2016; Brenner, 2014) is evidenced by the fact that urban metabolism extends well beyond urban boundaries. To sum up, the MF indicator makes it possible to account for the metabolic weight of the link between the city and the global hinterlands.

4.2. *Comparison of material footprint per capita*

We consider that the absolute values of the DMC and MF are more important (and worrying) than the relative values, because it is the total volumes of flows that threaten the equilibrium of the ecosystems and not the performance per individual. However, these per capita metabolic ratios provide obvious and appropriate points of comparison. Fig. 2 summarizes the values presented above according to the number of inhabitants.

In Nantes-Saint-Nazaire, the DMC per capita dropped from 16.9 t/cap in 2002 to 10.6 t/cap in 2015. However, MF per capita increases from 21.1 t/cap in 2000 to 25.9 t/cap in 2018. In Gothenburg, the DMC per capita remained almost stable after 1998, whereas the MF per capita increased strongly (from 16.9 t/cap in 1996 to 29 t/cap in 2011).

Comparing the two cities shows that the DMC per capita is higher in Nantes-Saint-Nazaire than in Gothenburg. This difference has tended to diminish since 2011 (11.8 t/cap and 12.5 t/cap), which is also suggested by the trends. Similarly, the MF per capita is a bit higher in Nantes-Saint-Nazaire than in Gothenburg, although in some years (2000, 2001, 2002, 2008, 2011) it is the opposite.

In conclusion, while a decrease in consumption implies a reduction in material intensity, an increase in MF has a completely different narrative. Indeed, the material intensity that takes into account the hidden flows (that corresponds to MF) is in fact increasing and is much higher (between 1.9 and 2.6 times higher) than the material intensity of direct consumption. This situation is partly explained by the importance of imports and exports to cities, as metropolitan areas are far from being autonomous in terms of extraction (of materials or biomass). This is logical but underlines the importance of understanding the role of the hinterland in urban metabolism.

These differences raise questions about the situation in the two countries. According to the EORA database, the DMC per capita in Sweden increased from 11.8 t/cap in 1996 to 17.2 t/cap in 2011 (cf. Table 2). The ratio (DMC in Gothenburg/DMC in Sweden) is therefore a factor of 0.6. In France, the DMC per capita was 14.6 t/cap in 2000 and 12.6 t/cap in 2011. There is therefore an average factor of 1.1 for the DMC per capita (even if it decreased significantly after 2011). These values remain the same order of magnitude, like the results of other studies (Bahers et al., 2019; Liu et al., 2021; Niza et al., 2009; Rosado et al., 2016; Sastre et al., 2015), which confirms the consistency of our study of EW-MFA. The gap can mainly be explained by the higher share of DE in the country than in the city. Similarly, the differences are not so substantial for the MF: in Sweden the MF per capita increased from 20.5 t/cap (in 1996) to 31.7 t/cap (in 2011); in France, the MF per capita was 20 t/cap in 2000 and 21.2 t/cap in 2015, which is a bit lower than the MF in Nantes-Saint-Nazaire. The MF of cities is therefore quite representative of the MF of France and Sweden as a whole, but also of other countries (Fischer-Kowalski et al., 2011; Wiedmann et al., 2015), although there are years with higher values (e.g. 2000, 2007, 2011 in Gothenburg; 2003; 2005, 2006, 2009 in Nantes-Saint-Nazaire). As already mentioned, extraction is low in cities, so the MF is unbalanced by the high weight of imports and exports in raw material equivalents.

Table 2 aims to compare the obtained results in MF and DMC with other cities present in the literature. Although the methodology applied in this study was never done and the comparison with other studies might be limited, it seems that MF results from other cities are in the same order of magnitude as Brussels, but are smaller than Beijing and Shangai values. The work of Jin et al. (2021) shows that the material footprints of Beijing and Shanghai are dominated by non-metallic minerals, as in our case study cities (see following section). The cities of Beijing and Shanghai are undergoing continuous morphological change and urbanization, which requires a very large material flow. Athanassiadis et al. (2016) explains for MF of Brussels that cities are often consumption centres with low production capacities, which rely heavily on their hinterland to meet their needs. Thus the impact on the hinterland is much greater for cities than for countries.This interpretation is also quite appropriate for our case study.

In the following section, we show the results of these MF for the main categories of flows.

4.3. Comparison of material disaggregation

The Fig. 3 below present the results in terms of broad material categories, which the International Resource panel calls “National 4 category material flows”, for the MF of each city. Thus, for both periods, the material footprints are given for biomass, metal ore, non-metallic mineral and fossil fuel categories. It is important to analyze the material disaggregation according to these four broad categories to better understand this MF and its constitutive characteristics. Indeed, the MF of cities is made up of the MF of these four major flows. However, these major flows do not have the same origins, volumes, or environmental contributions and do not meet the same needs of cities. It is consequently necessary to measure these material footprints separately to analyze their techno-economic role.

Table 2
Comparison of estimates of DMC and MF in other territories (tons/capita).

Territory (year)	DMC (tons/capita)	MF (tons/capita)
Gothenburg (2011)	11.8	29.0
Nantes-Saint-Nazaire (2018)	10.6	25.9
Sweden (2011)	17.2	31.7
France (2018)	11.4	21.2
Brussels region (2007)[a]	22	28
Beijing (2015)[a]	–	*35*
Shanghai (2015)[a]	–	*38*
Rennes (2012)[b]	11.2	*37.7*

[a] using IO approach (Athanassiadis et al., 2016; Jin et al., 2021).
[b] using Wuppertal Institute Coefficient (Bahers et al., 2019).

The MF of biomass appears to be quite low for both cities: on average 2 million tons per year for Nantes-Saint-Nazaire and 0.6 million tons per year for Gothenburg. However, this masks a surprising phenomenon: in some years, the MF of biomass is even negative in Nantes-Saint-Nazaire when raw material equivalent of exports largely exceeds imports in raw material equivalent (i.e. the RTB of biomass is negative). This indicator reveals the very powerful role of external supply, materialized by the material footprint of biomass imports. This dimension of bioeconomy outsourcing is in line with the concerns of the increasing of “land footprint” in Europe (O’Brien et al., 2015), which is the foreign land used to produce imported agricultural goods. It is clear that if an urban strategy is to strengthen the local bioeconomy (Buck and While, 2021), it cannot simultaneously consolidate an increase in the footprint of biomass supplies. The MF of biomass helps understand this controversy.

For metallic materials, the same process occurs as with biomass, reinforced by the fact that the market is much more global. The MF of metals (which includes metallic manufactured products) is not necessarily very high, and is even negative in some years in Nantes-Saint-Nazaire. However, the DMC is very low because exports of metallic manufactured products in both cities are important. Thus, the MF of metals is stable but low in both cities.

The case of fossil fuels is different. Firstly, the level of MFs was very high compared to the two previous categories: between 12.3 million tons in 2000 and 8.7 million tons in 2018 for Nantes-Saint-Nazaire, and between 3.9 million tons in 2000 and 5.3 million tons in 2011 for Gothenburg. However, the DMC of fossil fuels in Gothenburg was stable and decreased slightly in Nantes. This is evidence of a dangerous paradox in the fossil fuel sector: while consumption is decreasing in our cities, the footprint is increasing. In addition, the DMC is on average 2.9 million tons per year in Gothenburg and 4.6 million tons per year in Nantes-Saint-Nazaire. This means that the MF of fossil fuels is 1.4 times higher (on average) than the DMC of fossil fuels in Gothenburg, and 2.3 times higher than the DMC of fossil fuels in Nantes-Saint-Nazaire. More importantly, this ratio gradually increases in both cities from 0.7 to 1.8 (in Gothenburg), and from 1.8 to 2.6 (in Nantes-Saint-Nazaire). The decoupling of economic growth from environmental impacts has often been discussed (Conrad and Cassar, 2014; Fischer-Kowalski et al., 2011; Kalmykova et al., 2015). In this case, we see an inverse decoupling of consumption and the material footprint: even if consumption falls, the material footprint continues to increase. Thus, the externalization of fossil fuel consumption and energy cannot absolve developed countries of responsibility for their impacts (Krausmann, 2013; Tanguy et al., 2020). This is why it is important to calculate the actual carbon footprint of cities (Chen and Zhu, 2019; Porse et al., 2016; Wiedmann et al., 2016), and not only the local energy consumption of the cities.

The most significant category is non-metallic minerals. It is the category that weighs most heavily on the total MF balance sheet. On average, the MF of non-metallic minerals in Gothenburg is 15.3 million tons and 10.6 million tons in Nantes-Saint-Nazaire (since 2002). This illustrates the technomass accumulation and the role of local-global interaction in extended urbanization (Inostroza, 2014; Inostroza and Zepp, 2021). The weight of direct imported minerals accumulates in urban housing and infrastructure. However, it also accumulates elsewhere, in particular through extraction waste that remains in the extraction areas and hence does not pass through the cities. The MF curve of non-metallic minerals in Gothenburg increased significantly over the period 1996 to 2011, like in Nantes-Saint-Nazaire from 2000 to 2018.

The role of the material footprint of this category is therefore predominant. For this reason, in the following section we examine the link between this category and the hinterlands in more depth.

5. The impact of the urban material footprint in the hinterlands

We extended our analysis of the material footprint of cities by studying the flows from a spatial perspective. This enabled a better understanding of the extent of outsourcing of consumption due to cities. Where does the extraction and production of the material originate? Which supply chains are responsible for material trade exchange? We use the category of non-metallic minerals to provide information for our discussion. As we saw in the previous section, non-metallic minerals represent the most important flow in the urban material footprint. This flow also reveals a sector that is among the most impactful for climate change (Stephan and Athanassiadis, 2018; UNEP, 2019), the main cement and sand import flows.

The Figs. 4 and 5 represent the raw material requirements of non-metallic minerals along the supply chains of goods and services that satisfy the final demand of Gothenburg and Nantes-Saint-Nazaire, and the foreign hot spots of the resource. We can see that these hot spots are located all over the world. No continent escapes the circulation of these materials, not even Oceania, which seems very far for the transport of heavy and cheap materials.

In Gothenburg, trade is very dense around the Baltic Sea. The material footprint of mineral consumption is therefore significant in Norway, Finland, Poland, Lithuania, Denmark and Germany. But much of the sand also comes from much farther afield, from India, China or South Africa. In 2017, the majority of cement came from the USA, Canada, Spain, Italy and China. It highlights the complex circulations of flows, and hot spots that go beyond the last seller of goods. Obviously, these flows are even more complicated to trace.

In Nantes-Saint-Nazaire, some flows have similar origins to flows to Gothenburg, including sand from Belgium or Germany, and cement from Spain. Global hotspots are also involved, such as sand from the USA, China or Australia, and cement from Vietnam, Malaysia, or Columbia. It is important to note that these flows are governed by the global commodity market and that origins change over time. Checking previous years showed that some flows are stable but that countries are sometimes replaced (e.g. Slovakia, Portugal or Japan).

This spatialization of the material footprint is crucial to understand the interdependence of extractive and consumer countries. Sand is now a symbol of the problem of resource governance, as it is a material that tends to be depleted at a very rapid rate. UNEP thus calls for global governance on this issue (UNEP, 2019),[6] which is in line with our cartography: although it is a cheap and heavy commodity, it is transported over thousands of kilometers to meet urban final demands, especially in Europe. It would be interesting to extend this analysis by identifying the environmental conflicts related to the extraction of this material around the world. The EJAtlas database[7] could be used for this purpose (Martinez-Alier, 2021). However, we currently lack the data needed to connect countries of origin with extractive companies. This would make it possible to identify links with the conflicts listed in the EJAtlas but would require a dedicated investigation like the study of the supply chains of corporations (Goldstein and Newell, 2019, 2020) to identify the companies listed in the conflicts as exporting materials to Gothenburg and Nantes-Saint-Nazaire.

6. Conclusion: The importance of resource use indicators for circular economy policies in cities

The objective of this work was to develop a method to measure the material footprint of the cities of Nantes-Saint-Nazaire and Gothenburg. We compared these results with domestic material consumption, which is better known and has already been the subject of consolidated work.

Our results reveal an average difference between the MF and the DMC that is 2.4 times larger in Gothenburg and 1.9 times larger in Nantes-Saint-Nazaire between 1998 and 2018. The material footprint is therefore much larger than the direct material consumption in both cities. Concerning the changes that occurred between 1998 and 2018, in Nantes-Saint-Nazaire, we observed a decoupling of the MF and DMC: with a substantial decrease in the DMC over the period concerned, and a slight increase in the MF. In Gothenburg, the increase in DMC was small, whereas the increase in the MF was very large. These results illustrate the materiality of the second great acceleration. According to our results, this increase in material consumption is not directly apparent in domestic consumption, but is more visible in the MF since 2002. Therefore, the MF makes it possible to account for the metabolic weight of this link between the city and its globalized hinterlands and to illustrate their direct contribution in the global resource use (IRP, 2019).

When we compared the two cities, we saw that both the MF per capita and the DMC were in the same order of magnitude in Nantes-Saint-Nazaire and in Gothenburg. The “real” material intensity (MF) was much higher than the material intensity of direct consumption (between 1.9 and 2.6 times higher). This situation is partly explained by the importance of imports and exports of cities, as metropolitan areas are far from being autonomous in terms of extraction.

Thus to better understand this MF and its constitutive characteristics, it is important to analyze the material disaggregation. The MF of biomass and metals appears to be quite low for both cities. The case of fossil fuels is different. The level of MFs remains high and is continuing to grow compared to the two previous categories. However, the DMC of fossil fuels is stable in Gothenburg and is decreasing slightly in Nantes-Saint-Nazaire. This reveals a dangerous paradox in the fossil fuel sector: while consumption is decreasing in our cities, the footprint is increasing. The most significant category is non-metallic minerals. It is the category that weighs most heavily on the total MF balance sheet and increases. We extended the analysis of the material footprint of minerals by studying the flows from a spatial perspective. This provided a better understanding of the extent of outsourcing of consumption due to cities. These hot spots of extraction are located all over the world. Therefore, there is strong interdependence between extractive and consumer countries that is revealed by the spatialization of the material footprint.

As Ghisellini et al. (2016) writes, these UM indicators can be used in conjunction with GDP to measure the decoupling of economic growth from environmental impacts, which is “the ultimate goal of promoting CE”. Gravagnuolo et al. (2019) also write that “flow analysis, energy assessment, footprints, input-output analysis, network analysis, and life-cycle assessment” are the main methods to evaluate CE. So urban circular economy policies should be at least partly aimed at reducing DMC and MF in cities. However, we have shown that these two indicators do not necessarily follow a parallel evolution. Consistent metrics are needed to understand the footprint of cities on their hinterlands. The role of EC’s urban policies is therefore to understand what their footprint is made of in order to avoid externalizing their impacts and to control the supply and disposal chains. It is not enough to reduce local impacts, as it is also necessary to avoid worsening the impacts in the hinterlands. This corresponds to the call for research that combines multiple scales (Cui, 2018) and that develops “urban-rural balanced collaboration” (Ulgiati and Zucaro, 2019) to support the contribution of urban metabolism to the sustainability of cities. The role of these policies would therefore also be to reflect on the interdependencies with the hinterlands.

These results lead us to suggest future work on the importance of resource use indicators for circular economy policies in cities. The first step is to try to harmonize the measurement of urban MF and to incorporate it in UM policies. As it stands, it is difficult to calculate, and

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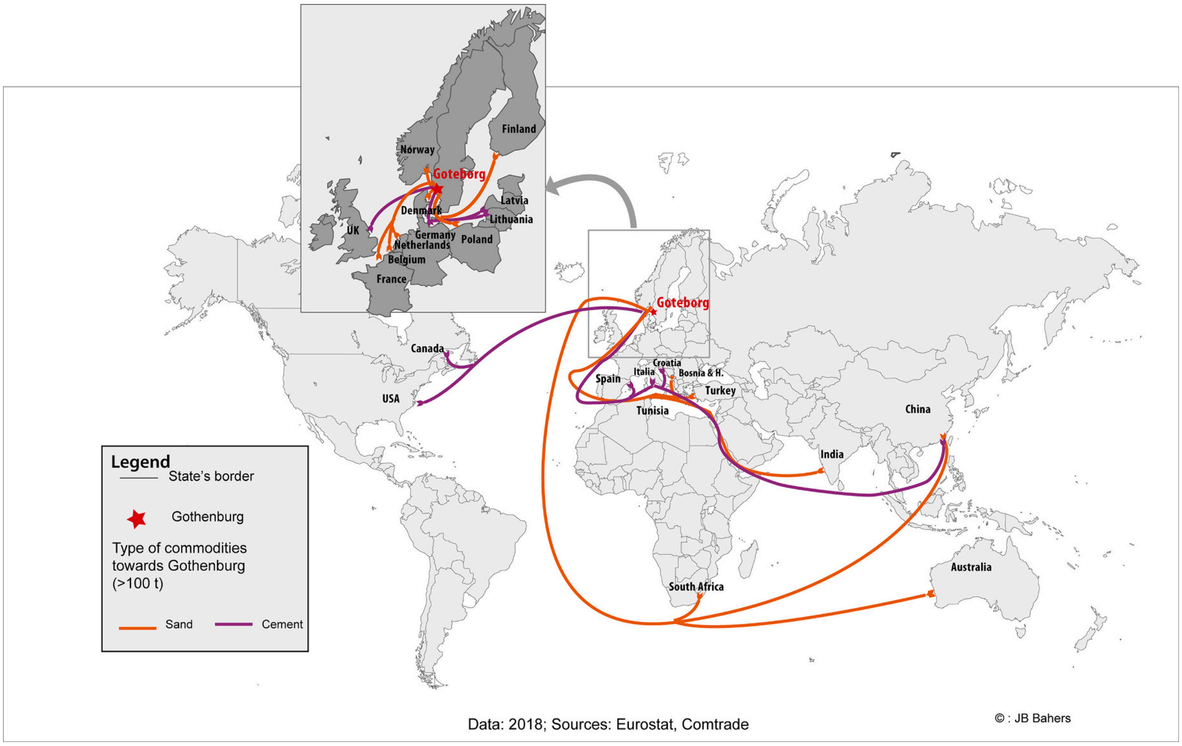
[6] https://www.unep.org/news-and-stories/press-release/rising-demand-sand-calls-resource-governance.

[7] EJAtlas (Global Atlas of Environmental Justice) available on<https://ejatlas.org/>



Data: 2018; Sources: Eurostat, Comtrade

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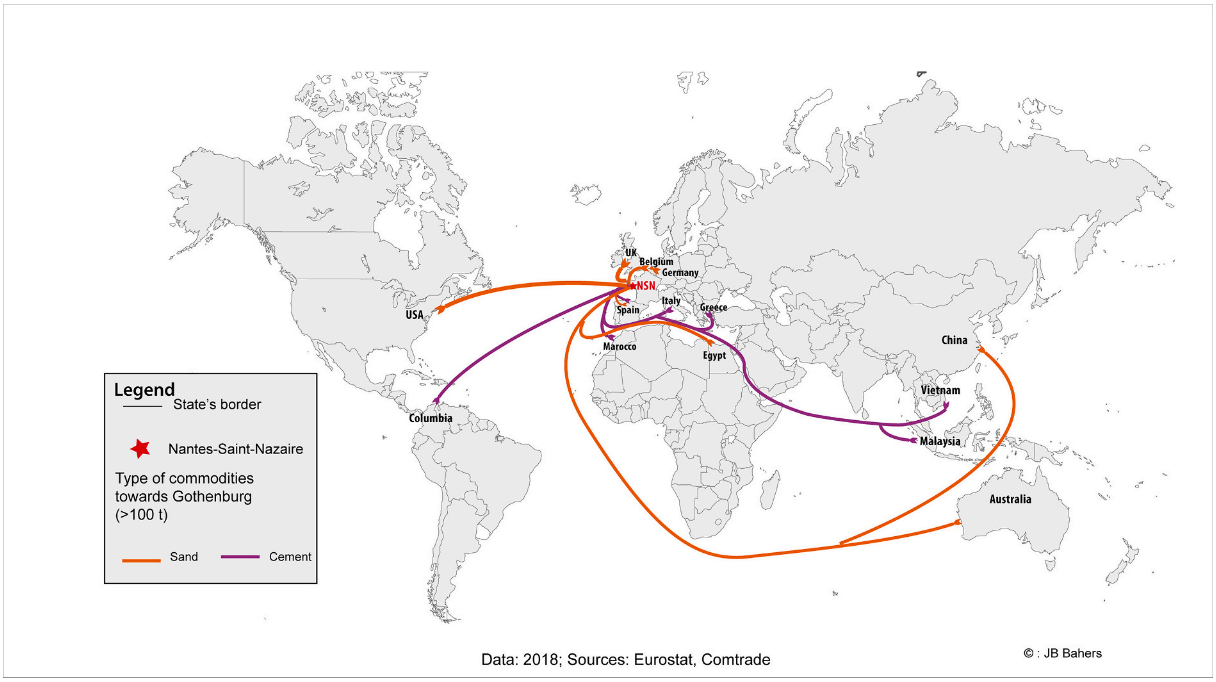
Fig. 4. Hinterlands of the material footprint of non-metallic minerals in Gothenburg (Source: Eurostat, Comtrade and authors' computations, Data from 2018).



Data: 2018; Sources: Eurostat, Comtrade

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Fig. 5. Hinterlands of the material footprint of non-metallic minerals in Nantes-Saint-Nazaire (Source: Eurostat, Comtrade and authors' computations; Data: 2018).

therefore complex to integrate and use by stakeholders. A lot of DMC work is currently underway at the city level,[8] but it is important to integrate MF more effectively, as there is a need to better understand the externalization of urban metabolism. Otherwise, urban circular economy policies may focus on domestic consumption and not prevent the material footprint from increasing.

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.

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[8] To an overview, see the website of the association Metabolism of cities available on<https://metabolismofcities.org/>

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clpl.2023.100029.

References

Arboleda, M., 2016. In the nature of the non-city: expanded infrastructural networks and the political ecology of planetary urbanisation: in the nature of the non-city. Antipode 48, 233–251. https://doi.org/10.1111/anti.12175.

Athanassiadis, A., Christis, M., Bouillard, P., Vercalsteren, A., Crawford, R.H., Khan, A.Z., 2016. Comparing a territorial-based and a consumption-based approach to assess the local and global environmental performance of cities. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2016.10.068.

Bahers, J.-B., Barles, S., Durand, M., 2019. Urban metabolism of intermediate cities: the material flow analysis, hinterlands and the logistics-hub function of Rennes and le mans (France). J. Ind. Ecol. 23, 686–698. https://doi.org/10.1111/jiec.12778.

Bahers, J.-B., Tanguy, A., Pincetl, S., 2020. Metabolic relationships between cities and hinterland: a political-industrial ecology of energy metabolism of Saint-Nazaire metropolitan and port area (France). Ecol. Econ. 167, 106447 https://doi.org/10.1016/j.ecolecon.2019.106447.

Bahers, J.-B., 2022. Urban metabolic infrastructures: apprehensions and futures. In: Metabolism Studies: Materiality and Relationality in the Anthropocene (Lyon, France).

Barles, S., 2009. Urban metabolism of Paris and its region. J. Ind. Ecol. 13, 898–913.

Billen, G., Garnier, J., Barles, S., 2012. History of the urban environmental imprint: introduction to a multidisciplinary approach to the long-term relationships between Western cities and their hinterland. Reg. Environ. Change 12, 249–253. https://doi.org/10.1007/s10113-012-0298-1.

Brenner, N., 2014. Implosions/Explosions: towards a Study of Planetary Urbanization. JOVIS Verlag.

Buck, N.T., While, A., 2021. The urban bioeconomy: extracting value from the ecological and biophysical. J. Environ. Plann. Manag. 64, 182–201. https://doi.org/10.1080/09640568.2020.1763931.

Cahen-Fourot, L., Magalhães, N., 2020. Matter and Regulation: Socio-Metabolic and Accumulation Regimes of French Capitalism since 1948 (Paper).

Chen, S., Zhu, F., 2019. Unveiling key drivers of urban embodied and controlled carbon footprints. Appl. Energy 235, 835–845. https://doi.org/10.1016/j.apenergy.2018.11.018.

Conrad, E., Cassar, L.F., 2014. Decoupling economic growth and environmental degradation: reviewing progress to date in the small island state of Malta. Sustainability 6, 6729–6750. https://doi.org/10.3390/su6106729.

Corvellec, H., Zapata Campos, M.J., Zapata, P., 2013. Infrastructures, lock-in, and sustainable urban development: the case of waste incineration in the Göteborg Metropolitan Area. J. Cleaner Prod. Spl Issue: Adv. Sustain. Urban Transform. 50, 32–39. https://doi.org/10.1016/j.jclepro.2012.12.009.

Cui, X., 2018. How can cities support sustainability: a bibliometric analysis of urban metabolism. Ecol. Indicat. 93, 704–717. https://doi.org/10.1016/j.ecolind.2018.05.056.

Eisenmenger, N., Wiedenhofer, D., Schaffartzik, A., Giljum, S., Bruckner, M., Schandl, H., Wiedmann, T.O., Lenzen, M., Tukker, A., Koning, A., 2016. Consumption-based material flow indicators — comparing six ways of calculating the Austrian raw material consumption providing six results. Ecol. Econ. 128, 177–186. https://doi.org/10.1016/j.ecolecon.2016.03.010.

Eurostat, 2019. Database - Eurostat [WWW Document]. URL. https://ec.europa.eu/eurostat/data/database. accessed 5.27.19.

Eurostat, 2018. Economy-wide Material Flow Accounts Handbook.

Fischer-Kowalski, M., Swilling, M., Von Weizsacker, E.U., Ren, Y., Moriguchi, Y., Crane, W., Krausmann, F.K., Eisenmenger, N., Giljum, S., Hennicke, P., Kemp, R., Romero Lankao, P., Siriban Manalang, A.B., Sewerin, S., 2011. Decoupling : Natural Resource Use and Environmental Impacts from Economic Growth (Technical Report). United Nations Environment Programme.

Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. 114, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007.

Giljum, S., Wieland, H., Lutter, S., Eisenmenger, N., Schandl, H., Owen, A., 2019. The impacts of data deviations between MRIO models on material footprints: a comparison of EXIOBASE, Eora, and ICIO. J. Ind. Ecol. 23, 946–958. https://doi.org/10.1111/jiec.12833.

Goldstein, B., Newell, J.P., 2020. How to track corporations across space and time. Ecol. Econ. 169, 106492 https://doi.org/10.1016/j.ecolecon.2019.106492.

Goldstein, B., Newell, J.P., 2019. Why academics should study the supply chains of individual corporations. J. Ind. Ecol. 23, 1316–1327. https://doi.org/10.1111/jiec.12932.

Görg, C., Plank, C., Wiedenhofer, D., Mayer, A., Pichler, M., Schaffartzik, A., Krausmann, F., 2020. Scrutinizing the Great Acceleration: the Anthropocene and its analytic challenges for social-ecological transformations. Anthropocene Rev. 7, 42–61. https://doi.org/10.1177/2053019619895034.

Görg, C., Plank, C., Wiedenhofer, D., Mayer, A., Pichler, M., Schaffartzik, A., Krausmann, F., 2019. Scrutinizing the great acceleration: the Anthropocene and its analytic challenges for social-ecological transformations: the Anthropocene review. https://doi.org/10.1177/2053019619895034.

Gravagnuolo, A., Angrisano, M., Fusco Girard, L., 2019. Circular economy strategies in eight historic port cities: criteria and indicators towards a circular city assessment framework. Sustainability 11, 3512. https://doi.org/10.3390/su11133512.

Haberl, H., Wiedenhofer, D., Pauliuk, S., Krausmann, F., Müller, D.B., Fischer-Kowalski, M., 2019. Contributions of sociometabolic research to sustainability science. Nat. Sustain. 2, 173. https://doi.org/10.1038/s41893-019-0225-2.

Inostroza, L., 2014. Measuring urban ecosystem functions through 'Technomass'—a novel indicator to assess urban metabolism. Ecological Indicators, Contemporary concepts and novel methods fostering indicator-based approach to urban complexities 42, 10–19. https://doi.org/10.1016/j.ecolind.2014.02.035.

Inostroza, L., Zepp, H., 2021. The metabolic urban network: urbanisation as hierarchically ordered space of flows. Cities 109, 103029. https://doi.org/10.1016/j.cities.2020.103029.

IRP, 2019. Global Resources Outlook 2019: Natural Resources for the Future We Want. United Nations Environment Programme.

Jin, Y., Wang, H., Wang, Y., Fry, J., Lenzen, M., 2021. Material footprints of Chinese megacities. Resour. Conserv. Recycl. 174, 105758 https://doi.org/10.1016/j.resconrec.2021.105758.

Kalmykova, Y., Rosado, L., Patrício, J., 2015. Urban economies resource productivity and decoupling: metabolism trends of 1996–2011 in Sweden, stockholm, and Gothenburg. Environ. Sci. Technol. 49, 8815–8823. https://doi.org/10.1021/acs.est.5b01431.

Kennedy, C.A., Stewart, I., Facchini, A., Cersosimo, I., Mele, R., Chen, B., Uda, M., Kansal, A., Chiu, A., Kim, K., Dubeux, C., Rovere, E.L.L., Cunha, B., Pincetl, S., Keirstead, J., Barles, S., Pusaka, S., Gunawan, J., Adegbile, M., Nazariha, M., Hoque, S., Marcotullio, P.J., Otharán, F.G., Genena, T., Ibrahim, N., Farooqui, R., Cervantes, G., Sahin, A.D., 2015. Energy and material flows of megacities. Proc. Natl. Acad. Sci. USA 112, 5985–5990. https://doi.org/10.1073/pnas.1504315112.

Kovanda, J., Weinzettel, J., 2013. The importance of raw material equivalents in economy-wide material flow accounting and its policy dimension. Environ. Sci. Pol. 29, 71–80. https://doi.org/10.1016/j.envsci.2013.01.005.

Krausmann, F., 2013. A city and its hinterland: vienna's energy metabolism 1800–2006. In: Long Term Socio-Ecological Research, Human-Environment Interactions. Springer, Dordrecht, pp. 247–268. https://doi.org/10.1007/978-94-007-1177-8_11.

Liu, N., Zhang, Y., Fath, B.D., 2021. The material metabolism characteristics and growth patterns of the central cities of China's Beijing-Tianjin-Hebei region. Ecol. Model. 448, 109532 https://doi.org/10.1016/j.ecolmodel.2021.109532.

Lutter, S., Giljum, S., Bruckner, M., 2016. A review and comparative assessment of existing approaches to calculate material footprints. Ecol. Econ. 127, 1–10. https://doi.org/10.1016/j.ecolecon.2016.03.012.

Magalhães, N., Fressoz, J.-B., Jarrige, F., Le Roux, T., Levillain, G., Lyautey, M., Noblet, G., Bonneuil, C., 2019. The physical economy of France (1830–2015). The history of a parasite? Ecol. Econ. 157, 291–300. https://doi.org/10.1016/j.ecolecon.2018.12.001.

Martinez-Alier, J., 2021. Mapping Ecological Distribution Conflicts: the EJAtlas. The Extractive Industries and Society. https://doi.org/10.1016/j.exis.2021.02.003.

Moore, J., 2016. Anthropocene or Capitalocene ? PM Press, Oakland.

Munoz, P., Giljum, S., Roca, J., 2009. The raw material equivalents of international trade: empirical evidence for Latin America. J. Ind. Ecol. 13, 881–897.

Niza, S., Rosado, L., Ferrao, P., 2009. Urban metabolism: methodological advances in urban material flow accounting based on the Lisbon case study. J. Ind. Ecol. 13, 384–405.

O'Brien, M., Schütz, H., Bringezu, S., 2015. The land footprint of the EU bioeconomy: monitoring tools, gaps and needs. Land Use Pol. 47, 235–246. https://doi.org/10.1016/j.landusepol.2015.04.012.

Patrício, J., Kalmykova, Y., Rosado, L., Lisovskaja, V., 2015. Uncertainty in material flow analysis indicators at different spatial levels. J. Ind. Ecol. 19, 837–852. https://doi.org/10.1111/jiec.12336.

Pincetl, S., 2012. Nature, urban development and sustainability – what new elements are needed for a more comprehensive understanding? Cities. Curr. Res. Cities. 29, S32–S37. https://doi.org/10.1016/j.cities.2012.06.009.

Pincetl, S., Bunje, P., Holmes, T., 2012. An expanded urban metabolism method: toward a systems approach for assessing urban energy processes and causes. Landsc. Urban Plann. 107, 193–202. https://doi.org/10.1016/j.landurbplan.2012.06.006.

Plank, B., Eisenmenger, N., Schaffartzik, A., Wiedenhofer, D., 2018. International trade drives global resource use: a structural decomposition analysis of raw material consumption from 1990-2010. Environ. Sci. Technol. 52, 4190–4198. https://doi.org/10.1021/acs.est.7b06133.

Porse, E., Derenski, J., Gustafson, H., Elizabeth, Z., Pincetl, S., 2016. Structural, geographic, and social factors in urban building energy use: analysis of aggregated account-level consumption data in a megacity. Energy Pol. 96, 179–192. https://doi.org/10.1016/j.enpol.2016.06.002.

Rosado, L., Kalmykova, Y., Patrício, J., 2016. Urban metabolism profiles. An empirical analysis of the material flow characteristics of three metropolitan areas in Sweden. J. Clean. Prod. 126, 206–217. https://doi.org/10.1016/j.jclepro.2016.02.139.

Rosado, L., Niza, S., Ferrão, P., 2014. A material flow accounting case study of the lisbon metropolitan area using the urban metabolism analyst model. J. Ind. Ecol. 18, 84–101. https://doi.org/10.1111/jiec.12083.

Sastre, S., Carpintero, Ó., Lomas, P.L., 2015. Regional material flow accounting and environmental pressures: the Spanish case. Environ. Sci. Technol. 49, 2262–2269. https://doi.org/10.1021/es504438p.

Schaffartzik, A., Duro, J.A., Krausmann, F., 2019. Global appropriation of resources causes high international material inequality – growth is not the solution. Ecol. Econ. 163, 9–19. https://doi.org/10.1016/j.ecolecon.2019.05.008.

Schaffartzik, A., Eisenmenger, N., Krausmann, F., Weisz, H., 2014a. Consumption-based material flow accounting. J. Ind. Ecol. 18, 102–112. https://doi.org/10.1111/jiec.12055.

Schaffartzik, A., Mayer, A., Gingrich, S., Eisenmenger, N., Loy, C., Krausmann, F., 2014b. The global metabolic transition: regional patterns and trends of global material flows. Global Environ. Change 26, 87–97. https://doi.org/10.1016/j.gloenvcha.2014.03.013, 1950–2010.

Schandl, H., Fischer-Kowalski, M., West, J., Giljum, S., Dittrich, M., Eisenmenger, N., Geschke, A., Lieber, M., Wieland, H., Schaffartzik, A., Krausmann, F., Gierlinger, S., Hosking, K., Lenzen, M., Tanikawa, H., Miatto, A., Fishman, T., 2018. Global material flows and resource productivity: forty years of evidence. J. Ind. Ecol. 22, 827–838. https://doi.org/10.1111/jiec.12626.

Schoer, K., Weinzettel, J., Kovanda, J., Giegrich, J., Lauwigi, C., 2012. Raw material consumption of the European Union–concept, calculation method, and results. Environ. Sci. Technol. 46, 8903–8909.

Stephan, A., Athanassiadis, A., 2018. Towards a more circular construction sector: estimating and spatialising current and future non-structural material replacement flows to maintain urban building stocks. Resour. Conserv. Recycl. 129, 248–262. https://doi.org/10.1016/j.resconrec.2017.09.022.

Swilling, M., Hajer, M., Baynes, T., Bergesen, J., Labbé, F., Kaviti Musango, J., Ramaswami, A., Robinson, B., Salat, S., Suh, S., 2018. The Weight of Cities–Resource Requirements of Future Urbanisation. UN Environment/International Resource Panel (IRP), Paris.

Tanguy, A., Bahers, J.-B., Athanassiadis, A., 2020. Outsourcing of urban metabolisms and its consequences: a multiscale energy flow analysis of a French port-city. Resour. Conserv. Recycl. 161, 104951 https://doi.org/10.1016/j.resconrec.2020.104951.

Ulgiati, S., Zucaro, A., 2019. Challenges in urban metabolism: sustainability and well-being in cities. Frontier. Sustain. Cities. 1.

UN Comtrade: International Trade Statistics, 2022 [WWW Document]. https://comtrade.un.org/data/. accessed 8.18.22.

UNEP, 2019. Sand and Sustainability: Finding New Solutions for Environmental Governance of Global Sand Resources. UNEP.

Voskamp, I.M., Stremke, S., Spiller, M., Perrotti, D., van der Hoek, J.P., Rijnaarts, H.H.M., 2017. Enhanced performance of the Eurostat method for comprehensive assessment of urban metabolism: a material flow analysis of amsterdam. J. Ind. Ecol. 21, 887–902. https://doi.org/10.1111/jiec.12461.

Wachsmuth, D., 2012. Three ecologies: urban metabolism and the society-nature opposition: three ecologies. Socio. Q. 53, 506–523. https://doi.org/10.1111/j.1533-8525.2012.01247.x.

Wiedmann, T., Lenzen, M., Keyßer, L.T., Steinberger, J.K., 2020. Scientists' warning on affluence. Nat. Commun. 11, 3107. https://doi.org/10.1038/s41467-020-16941-y.

Wiedmann, T.O., Chen, G., Barrett, J., 2016. The concept of city carbon maps: a case study of melbourne, Australia. J. Ind. Ecol. 20, 676–691. https://doi.org/10.1111/jiec.12346.

Wiedmann, T.O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., Kanemoto, K., 2015. The material footprint of nations. Proc. Natl. Acad. Sci. USA 112, 6271–6276. https://doi.org/10.1073/pnas.1220362110.

Zapata Campos, M.J., Zapata, P., 2017. Infiltrating citizen-driven initiatives for sustainability. Environ. Polit. 26, 1055–1078. https://doi.org/10.1080/09644016.2017.1352592.

Zhang, Y., 2013. Urban metabolism: a review of research methodologies. Environ. Pollut. 178, 463–473. https://doi.org/10.1016/j.envpol.2013.03.052.

Zhang, Y., Liu, H., Chen, B., Zheng, H., Li, Y., 2014. Analysis of urban metabolic processes based on input-output method: model development and a case study for Beijing. Front. Earth Sci. 8, 190–201. https://doi.org/10.1007/s11707-014-0407-1.

Zhang, Y., Li, Y., Zheng, H., 2017. Ecological network analysis of energy metabolism in the Beijing-Tianjin-Hebei (Jing-Jin-Ji) urban agglomeration. Ecol. Model. 351, 51–62. https://doi.org/10.1016/j.ecolmodel.2017.02.015.