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Accounting for Greenhouse Gas Emissions of Materials at the Urban Scale-Relating Existing Process Life Cycle Assessment Studies to Urban Material and Waste Composition

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ABSTRACT

Although many cities are engaged in efforts to calculate and reduce their greenhouse gas (GHG) emissions, most are accounting for "scope one" emissions *i.e.*, GHGs produced within urban boundaries (for example, following the protocol of the International Council for Local Environmental Initiatives). Cities should also account for the emissions associated with goods, services and materials consumed within their boundaries, "scope three" emissions. The emissions related to urban consumption patterns and choices greatly influence overall emissions that can be associated with an urban area. However, data constraints and GHG accounting complexity present challenges. In this paper we propose one approach that cities can take to measure the GHG emissions of their material consumption: the solid waste life cycle assessment (LCA) based approach. We used this approach to identify a set of materials commonly consumed within cities, and reviewed published life cycle assessment data to determine the GHG emissions associated with production of each. Our review reveals that among fourteen commonly consumed materials, textiles and aluminum are associated with the highest GHG emissions per tonne of production. Paper and plastics have relatively lower production emissions, but a potentially higher impact on overall emissions owing to their large proportions, by weight, in the consumption stream.

Keywords: Greenhouse Gas Emissions; Scope 3 Emissions; Life Cycle Assessment; Urban Sustainability

1. Introduction

It has been estimated that about 78% of global carbon emissions can be directly and indirectly related tocities [1,2]. To avoid the most catastrophic consequences of global climate change, greenhouse gas (GHG) emissions associated with urban centres must be dramatically reduced [3-5]. Toward this goal, many cities are engaged in efforts to calculate and reduce their greenhouse gas emissions. Most are accounting for GHGs produced within urban boundaries, often referred to as "scope one" emissions. A growing awareness among researchers suggests that in order to achieve globally relevant reductions in atmospheric carbon levels, municipal governments and urban residents should also take responsibility for urban "lifestyle" or consumption emissions: emissions mostly related to the GHGs embodied in the life cycle of material goods (as well as food) consumed in the city (scope 3 emissions) [6-10]. Information about the GHG emissions associated with the manufacturing of specific materials can be used to generate public awareness about implications of material consumption choices and habits. It can also be used to develop municipal policies and programs targeting high-emissions materials for reduction. However, data constraints and GHG accounting complexity present challenges. We suggest that cities can use the solid waste life cycle assessment (LCA) based approach to account for their material consumption. We used the approach to identify a set of materials commonly consumed in cities, and then reviewed published LCA data to develop a range of GHG emissions values for each material. Our review of the studies and our dataset of emissions values are presented.

Cities that measure their GHG emissions follow international protocols such as the International Local Government GHG Emissions Analysis Protocol [11]. These protocols account for emissions perceived to be directly within the control of the local government. "Scope one" includes emissions from facilities that are owned by the local government or emissions produced by citizens' activities within city limits, for example, from motor vehicle transportation. Emissions associated with electrical energy used to operate buildings and emissions from solid waste management are also counted, even though these emissions are sometimes generated outside the city, e.g. at a remote power station.

Several studies have followed similar principals in generating GHG emissions inventories for urban settlements [12-15]. Bi *et al.* [14] produced a bottom up GHG emissions inventory for Nanjing, China. They included emissions from industrial, transport, commercial and household energy consumption; emissions from industrial processes located within the city, and emissions from waste treatment. Kennedy *et al.* [13] generated GHG emissions inventories for ten cities on four continents. Their method includes seven components: electricity, heating and industrial fuels, industrial processes, ground transportation, aviation transportation, marine transportation, and waste.

Few researchers have conducted studies that include urban consumption related or, scope 3, emissions. One challenge has been data limitations [15]. Hillman and Ramaswami [16] calculated GHG emissions for eight US cities including embodied emissions in food, transport fuels, shelter and cross-border freight demands. Yang and Suh [17] accounted for the GHG emissions related to products consumed by Chinese urban and rural households; and Druckman and Jackson [18] calculated the GHG emissions required to satisfy average UK household demand for goods and services between 1990 and 2004. To date, no standard method for assessing GHG emissions from urban material consumption has been determined.

One GHG accounting approach increasingly being used at the sub-national/urban scale is "environmental input-output analysis" (EIOA) [19-21]. It uses local expenditure data ($) for some consumption items like food and materials, and relates them to carbon emissions in an extension of conventional monetary input-output analysis. However, that approach usually does not provide data at the scale of specific material types such as newsprint and cardboard, or even at the scale of product groups like paper or plastic. Rather, EIOA operates at the industry scale (e.g., emissions per $ value of the national paper or plastic industry). Further, the approach requires cities to have detailed residents' expenditure data to generate input-output tables, a requirement that many cities cannot easily meet.

It follows that if cities are to take on measurement, monitoring and development of policies to reduce material consumption-related GHG emissions, they require local data and a method that is not too onerous [22]. The "solid waste LCA based approach" [23-26] we suggest here overcomes data limitations by using data many cities already collect, solid waste volume and composition data, to identify patterns of material consumption. It then uses data from a wide range of life cycle assessment studies to determine the GHG emissions associated with production of a material or product. For this paper, we used the approach to identify fourteen materials commonly consumed in cities in high income countries, and conducted a thorough review of published, process life cycle studies to determine GHG emissions values for each material. The range of GHG emissions values we present for each material reflects the variability of life cycle characteristics associated with production method and location.

2. Methods

While cities do not commonly monitor or document their residents' material consumption, they do manage and monitor solid waste. The "component solid waste LCA based approach" uses urban waste stream data to identify the major types of materials consumed in urban areas. This approach to estimating urban material consumption was developed by Simmons *et al.* [24]; Chambers *et al.* [26], and Barrett *et al.* [23] as part of their studies on urban sustainability using ecological footprint analysis. It has been used since by some footprint studies at the urban scale [21,22]. The logic behind the approach is that most materials consumed end up in the waste stream, some in a matter of minutes after consumption, others after years. Although waste stream data will not represent the exact quantities of all materials consumed in a city over a given period of time, it is reasonable to assume that the proportions of materials (by weight) found in the waste stream reflect the proportions consumed. In this way, a set of regularly consumed materials can be identified by type and weight. In absence of other urban material consumption data, the waste stream serves as a useful proxy.

We reviewed waste stream documentation and reporting protocols for ten cities in relatively high income countries: Canada, United Kingdom, the United States, Australia and Israel. The purpose of the review was to identify a general trend in the way solid waste is documented, and to generate a list of commonly reported waste items. Cities that monitor and document comercial and household waste composition collect data on the following major categories: metal; glass; plastics; paper; organics; textiles; rubber; and hazardous wastes. Many use more detailed categories. For example, paper is broken down into paper, newsprint, and cardboard. Plastics are identified by type (polyethylene terephthalate [PET]; high density polyethylene [HDPE]; low density polyethylene [LDPE] and polyvinyl chloride [PVC]) and by use such as plastic (film) bags and plastic bottles (e.g., Sydney, AU, 2009; Vancouver, CA, 2010; Seattle, USA, 2010; Edinburgh UK, 2010). One consumer item that appears in the solid waste stream at high volume and is commonly reported as a separate item is diapers (nappies). In both Sydney, Australia and various cities in Israel [27,28], diapers made up approximately 5%, by weight, of the residential waste stream.

For our materials dataset, we selected the fourteen materials most commonly reported in the urban waste stream data we reviewed: paper 1) newsprint, 2) print paper, 3) cardboard, plastics, 4) PET, 5) HDPE, 6) LDPE, 7) PS, 8) PVC, 9) steel, 10) aluminum, 11) glass, textiles, 12) cotton fabric, 13) polyester fabric, and 14) diapers.

The component solid waste LCA based approach draws GHG emissions data from process life cycle assessments. We conducted an extensive review of LCA studies and reports for each of the fourteen materials. The review generated a total of 120 values from 69 sources. For the complete list of studies and their emissions data see Appendix I. From each study, for each material, we extracted the GHG emissions (CO_2e) data.

Our literature review included LCA studies in academic literature, and in commercial and industrial publiccations. The studies include data from European, North American, Asian, and Australian sources among others to reflect world-wide production systems and conditions. Each LCA study sets its own boundaries and scale. In order to present comparable emissions values we made an effort to include studies that used similar parameters, assumptions, and scales. Overall we made an effort to cover cradle to gate data. This means data associated with the manufacturing process from materials extraction to finished product that leaves the factory gate. This approach avoids double-counting the energy and materials associated with the end of life cycle in which products are managed as wastes and for which local governments also maintain records through their regular waste management functions. In the case of plastics most of our values are for plastic polymers owing to lack of available LCA data on finished products. Our review of studies published in Chinese yielded few results. For most products we have only one data source from China.

Because the component solid waste LCA based approach relies on emissions data from LCA studies, it is limited by the availability and accuracy of those studies. LCA is well established in academic and private Industrial realms, but comparability and credibility of LCA studies requires improvement [29]. Several bodies are working to improve standardization; for example, the European Commission project, European Platform on Life-cycle Assessment, resulted in a handbook of recommendations for life cycle impact assessment in Europe [30]. Continued standardization of LCA protocols will benefit cities that choose to account for consumption related emissions using LCA based approaches.

3. Results

Tables 1 and **2** summarize our GHG emissions review. **Table 1** shows the minimum, maximum, mean and the standard deviation of emissions for materials in ascending order by type: glass; paper products; plastics; steel; diapers; aluminum; textiles. N represents the number of studies from which data was collected for each material. The table displays the relative GHG emissions among materials by unit of material (per tonne).

However, it is the total amount consumed that determines the actual impact of a material on the urban GHG emissions. Textiles and aluminum generate the highest GHG emissions per unit of material, but they represent a relatively smaller part of the overall weight of the urban waste stream (or consumption) in cities we reviewed.

Paper products have relatively lower GHG emissions per tonne, but comprise a significant proportion of many urban commercial and residential waste streams. For urban planners and policy makers, both the GHG emissions associated with a material's per unit production, and the total, on-going quantities consumed are necessary data.

Table 1. Range of life cycle GHG emissions associated with materials, "cradle to gate".

	N	Min	Max	Mean	Standard Deviation
Sub Category		Kg CO_2e/t	Kg CO_2e/t	Kg CO_2e/t	Kg CO_2e/t
Glass	8	600	1800	990	370
Cardboard	9	560	1620	890	330
Newsprint	8	780	1670	1120	350
Printing Paper	15	420	3110	1290	770
HDPE	6	580	1950	1015	670
PVC	6	1400	2510	1920	370
PET	8	1070	2890	2240	600
LDPE	6	1870	2760	2360	380
PS	8	1180	4660	2970	1120
Steel	20	1600	4020	2530	730
Diapers	3	2600	4390	3580	900
Aluminum	9	7900	18,180	10,840	3170
Cotton Fabric	9	12,760	30,000	21,500	6770
Polyester Fabric	5	15,120	32,500	26,200	9600

Table 2. CO_2e and CO_2 emissions of materials by production location.

	Europe		America		Asia		Australia	
	Kg CO_2e/t	Kg CO_2/t	Kg CO_2e/t	Kg CO_2/t	Kg CO_2e/t	Kg CO_2/t	Kg CO_2e/t	Kg CO_2/t
Glass	600 - 1047	550 - 940	n/a	585 - 1250	n/a	1820	n/a	765
Printing Paper	830 - 1560	420 - 1460	520 - 1600	1410	n/a	2480	2200 - 3000	n/a
Newsprint	720 - 1230	784 - 1230	n/a	n/a	n/a	n/a	n/a	n/a
Cardboard	557 - 1080	615 - 990	580 - 3140	n/a	330 - 1600	n/a	1600	n/a
PET	2780 - 3480	1890 - 3700	1810 - 2660	1070 - 2330	n/a	1340	n/a	n/a
PVC	2280 - 3860	2150 - 3600	2740 - 3480	2390 - 3060	1770	1410	n/a	n/a
Polystyrene	4080 - 4860	3250 - 3990	n/a	n/a	n/a	3390	n/a	n/a
HDPE	2315 - 3430	510 - 2980	1080 - 3270	1010 - 2770	n/a	2030	1970	n/a
LDPE	2700 - 3590	2250 - 3100	3330	2820	n/a	1860	2760	n/a
Aluminum	8670 - 15,400	680 - 12,400	7100 - 10,700	7940 - 12,000	21,500 - 22,500	18,180	16,300 - 22,400	n/a
Steel	1800 - 2430	1700 - 3570	n/a	1560 - 2670	n/a	1720 - 3750	2300 - 6800	n/a
Cotton Textile	n/a	6500	n/a	7700 - 16,000	n/a	12,700-16,240	25,000	15,700
Polyester	n/a	5000	n/a	n/a	n/a	15,120	31,000	20,000 - 32,500

With these data, policies and programs can be directed toward reducing consumption of materials with high aggregate impact.

In our review of LCA studies we found variations in material emissionsvalues for studies conducted indifferent parts of the world (**Table 2**). While these variations can be explained by variations in LCA methods and data availability, they also likely reflect characteristics of local production methods and energy sources (e.g., coal based electricity vs hydroelectric sources). As more LCA data from countries like China become available, these variations may be more prominently expressed.

A database of GHG emissions for use by city governments around the world could make accounting for urban consumption emissions a feasible endeavor. To account for variability in GHG emissions associated with production location, such a database could provide an average value for each material that reflects the range of countries in which the goods are produced. The average could even reflect each nation's proportion of the global production market for individual materials. The database would also report minimum and maximum emission values. Cities could choose minimum, average or maximum emissions data for on-going monitoring.

4. Conclusions

Among researchers, efforts are being made to overcome data challenges, and account for scope 3 emissions, *i.e.*, those associated with the embodied energy of material goods that are consumed within cities. The use of waste as a proxy for material consumption overcomes a major limitation of data availability for urban planners and policy-makers. Still, it is important to acknowledge that the solid waste LCA based approach probably does not capture the entire volume of materials consumed, and that the approach is highly dependent on the quality and specificity of solid waste data collection and documentation. Further, determination of GHG emissions values for materials depends on the quantity and quality of accessible, published LCA studies.

Our review of process life cycle assessment studies revealed that only a limited number use detailed, primary data. The literature is also lacking in studies related to production in China, a major manufacturer. Despite these gaps we were able to generate a range of GHG emissions values for each of fourteen materials commonly consumed in cities. Among these materials we found that textiles and aluminum are associated with relatively high GHG emissions per tonne of production, compared to other materials such as paper and plastics. However, paper and plastics are consumed (found in the waste stream) in higher quantities, by weight, than aluminum and textiles so they could have equal or greater impact on overall consumption-related emissions. Cities aiming to account for consumption-related emissions and to develop programs to reduce high impact material consumption need material-specific information on both GHG emissions per unit of production, and overall quantities of consumed.

We found an increasing number of material LCAs are being conducted or commissioned by commercial and industrial associations such as the World Aluminum Association, the European Container Glass Federation or the European plastic producers association. Individual companies are also publishing information on the GHG emissions of their products. Perhaps more industry based studies will become available as carbon taxes and cap and trade systems are expanded. Consumer pressure for more ecologically benign products may also encourage more reporting.

We see the material LCA approach as a valuable, accessible approach for cities working to assess, monitor and develop policy to reduce their consumption based contributions to global GHG emissions.

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Appendix 1

Carbon dioxide and GHG emissions values; life cycle assessment data sources.

Material	Kg $CO2_e$/t	Kg CO_2/t	References
Glass	600		Humbert, S., Rossi, V., Margni, M., Jolliet, O. and Loerincik, Y. (2009) Life cycle assessment of two baby food jars vs plastic pots. *International Journal of Life Cycle Assessment*, **14**, 95-106.
		791	FEVE European Container Glass Federation (2012) Life cycle inventory-data availability. http://www.feve.org/ index.php?option=com_content&view=article&id=79&Itemid=18
		843; 823	Hischier, R. (2007) Life cycle inventories of packaging and graphical papers. Ecoinvent-Report No. 11, Swiss Centre for Life Cycle Inventories, Dubendorf.
		900	Hekkert, M., Joosten, L., Worrell, E. and Turkenburg, C. (2000) Reduction of CO_2 emissions by improved management of material and product use: The case of primary packaging. *Resource*, *Conservation and Recycling*, **29**, 33-64.
	941		Liu, X., Fu, Y., Xu, W. and Meng, L. (2011) Research on the carbon footprint of glass brewage packaging vessel. *Journal of Beijing Institute of Graphic Communication*, **19(4)**, 23-25.
		1250	PE Americas (2010) Environmental overview. Complete life cycle assessment of North American container glass. Glass Packaging Institute.
		1795	Edwards, D. and Shelling, J. (1999) Municipal waste life cycle assessment part 2: Transport analysis and glass case study. *Transactions of the Institution of Chemical Engineers*, **77B**, 259-274.
Aluminum		7900	PE Americas (2010) Final report. Life cycle Impact Assessment of Aluminum Beverage Cans prepared for Aluminum Association, Inc., Washington DC.
		8566	Leroy, C. (2009) Provision of LCI data in the European aluminum industry methods and examples. *International Journal of Life Cycle Assessment*, **14**, S10-S44.
	9800		International Aluminum Institute (2007) Life cycle assessment of aluminum: Inventory data for the primary aluminum industry. 2005 Update.
		9534	Althaus, H., Blaser, S., Classen, M. and Jungbluth, N. (2007) Life cycle inventories of metals. Final report eco-invent 2000. Swiss Centre for LCI, EMPA-DU, Dubendorf.
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Steel		1698	Steiner, R. and Frischknecht, R. (2007) Life cycle inventories of metal processing and compressed air supply. Final Report Ecoinvent Data v2.0, Dubendorf and Uster.
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	2010	n/a	American Iron and Steel Institute (2012) Data from report by World Steel Association, World Steel Association Life Cycle Assessment Global Hot Rolled Coil. http://www.steel.org/en/Sustainability/Life% 20Cycle% 20Information.aspx.
		2293	Steiner, R. and Frischknecht, R. (2007) Life cycle inventories of metal processing and compressed air supply. Final Report Ecoinvent Data v2.0, Dubendorf and Uster.
	2300	n/a	Norgate, T., Jahanshahi, S. and Rankin, W. (2007) Assessing the environmental impact of metal production processes. *Journal of Cleaner Production*, **15**, 838-848.
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Paper, Graphic		416	SCA Ortviken (2011) Carbon profile GrahpoCote, GraphoLux, GraphoMatt. SCA Ortviken, Sundsvall, Sweden.
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