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Concept development and case study

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Abstract

Cities now consume resources and produce waste in amounts that are incommensurate with the populations they contain. Quantifying and benchmarking the environmental impacts of cities is essential if urbanization of the world's growing population is to occur sustainably. Urban metabolism (UM) is a promising assessment form in that it provides the annual sum material and energy inputs, and the resultant emissions of the emergent infrastructural needs of a city's sociotechnical subsystems. By fusing UM and life cycle assessment (UM–LCA) this study advances the ability to quantify environmental impacts of cities by modeling pressures embedded in the flows upstream (entering) and downstream (leaving) of the actual urban systems studied, and by introducing an advanced suite of indicators. Applied to five global cities, the developed UM–LCA model provided enhanced quantification of mass and energy flows through cities over earlier UM methods. The hybrid model approach also enabled the dominant sources of a city's different environmental footprints to be identified, making UM–LCA a novel and potentially powerful tool for policy makers in developing and monitoring urban development policies. Combining outputs with socioeconomic data hinted at how these forces influenced the footprints of the case cities, with wealthier ones more associated with personal consumption related impacts and poorer ones more affected by local burdens from archaic infrastructure.

Keywords: urban metabolism, life cycle assessment, environmental footprint, decoupling, sustainable urban development

S Online supplementary data available from stacks.iop.org/ERL/8/035024/mmedia

Nomenclature

1,4-DCB eq.	1,4-dichlorobenzene equivalents
ALO	Agricultural land occupation
EIO-LCA	Economic input–output life cycle assessment
EoL	End of life
Eq./capita yr.	Equivalents per capita per year
FE	Freshwater ecotoxicity
GDP	Gross domestic product
GHG	Greenhouse gas
GWP	Global warming potential
IP	Impact potential

ISO	International Standards Organization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
PMF	Particulate matter formation
PM_{10}	Particulate matter under 10 μm in size
UM	Urban metabolism
UM-G1	First generation urban metabolism
UM-G2	Second generation urban metabolism
UM–LCA	Urban metabolic life cycle assessment
SUD	Sustainable urban development

1. Introduction

The contribution of cities to a number of global environmental pressures such as climate change, water stress, biodiversity loss and resource scarcity is recognized to be strong [1]. These pressures will likely increase vastly, if future urban consumptive patterns follow current trends, as the percentage of urban dwellers worldwide is predicted to swell from 50% currently to 70% of total population by 2050 [2]. Much of the rural–urban migration will occur in developing economies [3], in turn compounding the negative environmental implications with a predicted large growth in economies, generally higher standards of living and increased consumption [4]. Considering that humanity's current consumptive habits already surpass the planet's carrying capacity [5, 6] it is paramount to quantify the contribution of urban areas, both mature and growing, in order to support appropriate policy interventions.

A range of methodologies designed to assess urban sustainability exist [7], however urban metabolism (UM) is one of a limited number of these to actively pursue the quantification of a city's environmental burden (another equally promising field being urban ecology [68]). UM refers to a broad range of quantitative methods that attempt to conceptualize urban areas as organisms, requiring goods and energy to maintain functionality and support growth, while emitting waste as a byproduct [8]. The framework is powerful in that it allows for an assessment of the material and energy requirements of a city's infrastructure that emerges from the sociotechnical subsystems (technical, cultural, institutional, economic, etc), even if the our current understanding of these subsystems and their interactions are murky [146]. In the last nearly 50 years the number of UM studies has been modest. A recent review by Kennedy cites at least 75 studies that implicitly or explicitly fall within UM's realm [10] with UM being applied at numerous different scales, from higher spatial resolution (neighborhoods [11]) to lower spatial resolution (cities [12] and city regions [13]). There has been little standardization of the tool, which remains a conceptual approach with large variations between studies regarding the materials, energy sources and pollutants included in the individual assessments. Furthermore, two main UM schools have arisen, one utilizing material flow accounting (MFA), the other non-mass based [14].

1.1. From first generation UM (UM-G1) to second generation UM (UM-G2)

The MFA method is the earliest and purest UM method, and thus it is termed first Generation UM (UM-G1). In applications of the UM-G1 methodology single material flows through cities (e.g. nutrient balances) [16–24] or more comprehensive lists of metabolic flows (e.g. food, water, fuels, electricity, construction materials) [11–13, 25–44] have been accounted over the period of a year. Despite its simplicity in methodology and communicability, UM-G1 has received criticism as it erroneously equates mass to environmental loading, failing to address the varying potentials for different substances to damage the receiving environment [45, 14]. Furthermore, UM-G1 only quantifies a city's direct consumption while ignoring the embedded upstream processes required to provide a city with resources and also omitting impacts from the downstream processes that handle a city's waste [145]. In all of the UM-G1 applications reviewed in this study, only direct mass and energy were measured, with the exception of a study that utilized a physical input–output table to account for material flows accounting from industrial symbiosis [43].

Developed shortly after UM-G1, UM-G2 is characterized by its attempts to move beyond mass. It interprets environmental loading predominantly using the emergy (embodied energy) concept [46–57] or on occasion, the ecological footprint (EF) method [58–60], and is usually performed under the urban ecology umbrella. UM-G2 addresses the shortcomings of UM-G1 in that both the emergy and EF metrics attempt to account for embedded environmental impacts of metabolic flows and the assimilation of some waste flows from cities [49, 61]. Moreover, urban ecology (not EF) studies open the 'black box' and attempt to map the interconnections of urban subsystems. Despite these advances the UM-G2 methodologies still have gaps that hinder their ability to fully quantify the environmental effects of cities, in that (i) the ability of emergy and EF to adequately represent all relevant environmental impacts of all flows is limited, and their conversion factors are disputed [14, 16] and (ii) the complexity of the emergy concept inhibits the communication of its results to policy makers, and consequently, its practical application [14].

1.2. The need for third generation UM

Though earlier UM methodologies provided a foundational framework for measuring the environmental impacts of cities, practitioners widely agree that current methodological faults need to be addressed [14, 61, 62]. Recently, Pincetl and colleagues [14, 63, 146] have suggested coupling UM with the life cycle assessment (LCA) framework to help mature the field of urban sustainability quantification. The benefits in coupling with LCA include (i) the ability of this technique to capture embodied environmental impacts of a metabolic flow applying a cradle to grave perspective, (ii) the quantification and communicability of model results in terms of numerous common and prescient environmental indicators, and (iii) an
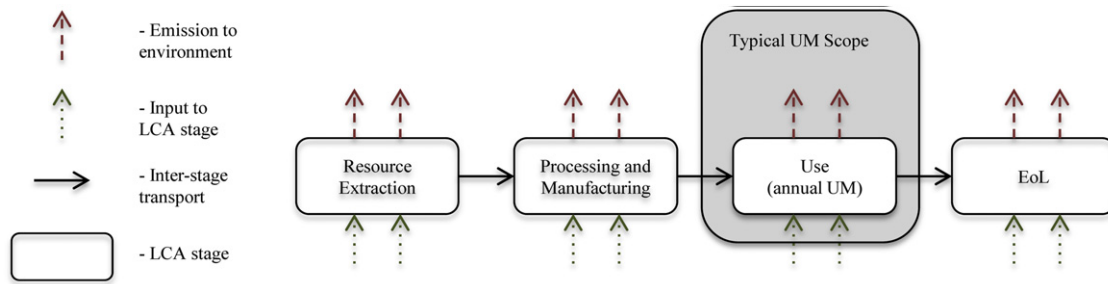
Figure 1. The different life cycle stages typically covered in an LCA each with its own associated environmental exchanges in terms of energy and mass requirements and waste and pollutant emissions. The gray box indicates that only the use stage is typically accounted for in traditional UM studies and the up- and downstream burdens tend to remain unaccounted for.

advanced method with international standards, a large user base continuously improving LCA methodology as well as the availability of inventory data for many important flows entering and exiting cities [63]. To date the coupling of UM with LCA (third generation UM or UM–LCA) has only been performed in simplistic forms, as either a partial assessment subservient to an UM-G2 study [64, 65] or to perform carbon accounting [67].

As such, this study endeavors a more comprehensive coupling of low resolution (city-scale) UM with LCA, to develop a UM–LCA model that make use of the full set of indicators available to LCA practitioners, and to utilize dedicated LCA modeling software. The aim of the study is not to develop a fully validated model, but to demonstrate the strength of this kind of UM–LCA modeling, and identify future research questions. The model is applied to five case cities in order to illustrate its applicability, robustness and ability to generate meaningful results catering to the identification of main impact sources in the urban metabolism and to the inter-city comparisons. Case cities with large variations in economic development and spatial makeup will be used in order to see if these differences yield clear distinctions regarding the scale, types and sources of environmental impacts produced. UM–LCA model outputs will be combined with basic economic data in order to explore this theme as well as to discuss the utility of UM–LCA to contribute with benchmarking indicators for SUD policy makers.

2. Method

In combining UM with the LCA framework the appropriate interface of the tools has to be identified. The basis of UM-G1 and UM-G2 studies is the determination of mass flows into the urban system over an annual period. In UM-G1, the city acts as a black box, with the interactions of the urban subsystems (see section 1) remaining outside of the model's scope [68]. Thus, UM-G1 views cities merely as users of the metabolic flows that they demand to maintain their operations and growth, and the goal of the model is simply the accounting of these demands.

In the life cycle thinking applied in LCA, the accounting performed in earlier UM studies can be envisioned as the use stage inventory analysis of the material and energy flows demanded to feed a city's metabolism. This form of mass and energy accounting fits well with the philosophy of life cycle thinking which conceptualizes a product or service system as consisting of several life cycle stages; raw material extraction, manufacturing, use and end of life (EoL) [69]. When coupled with UM, the LCA attempts to account for the environmental impacts of the other life cycle stages by summing and characterizing the environmental loading of inputs and emissions of all LCA stages. Thus by modeling the extraction of resources and their processing into the multiple flows entering the urban system (the supply chain upstream of the city) and also the EoL processes downstream of the use of a metabolic flow, the UM–LCA approach attempts to cover the total impacts of the urban system as shown in figure 1. Traditionally a process-based modeling of a product system was applied in LCA [69] but it has two main drawbacks. Having to cut off recursive loops (e.g. the production of the production equipment that produces the production equipment . . .) it inherently underestimates the environmental impacts of a modeled system compared to an LCA that bases its inventory analysis on economic input–output tables to account for interdependences between industries [67]. A second drawback originates in the sheer number of individual products that enter the urban system and the impossibility of modeling each of them using a bottom-up, process-based approach. Despite these shortcomings, the developed UM–LCA is process based, as the model can still provide useful (though less complete) results and it will allow insights into fundamental methodological issues that can then be applied to the future development of more complete models that overcome process-based limitations.

The current study implemented the conceptualized scheme in figure 1 following ISO 2006 standards [70] to develop the first full UM–LCA model. Significant metabolic flows were considered for the five case cities, and the appropriate up- and downstream processes from the direct metabolism were found for each city in line with a process-based LCA approach. The UM–LCA model was developed assuming that the urban areas were at steady state with regards to mass and energy, and therefore, accumulation of metabolic flows went unaccounted. Consequently, current technologies were used in accounting for the impacts of the EoL phase of the modeled flows. The product system modeling software

GaBi 4 [71] was utilized to model the cities. Programs like GaBi allow LCA practitioners to account for exchanges between a system and its environment through built-in consistency checks and balances. The EcoInvent 2.01 [72] database was used to provide inventories of environmental exchanges (material and energy inputs, air, soil, water emissions, etc) for the modeled processes. However models were occasionally supplemented with processes from the built-in GaBi 4 PE professional database or custom built processes, when adequate processes were lacking elsewhere. Furthermore, best available representative processes were used to support the model (e.g. nuclear power generated in the United States was used to model nuclear power in Canada).

EcoInvent 2.01, though expansive in the LCIs it provides, lacks precision modeling capabilities for many processes. For instance, all meat consumption (excluding fish and seafood) was modeled as sheep production as this was the only livestock production process available in the database. Sheep represents a compromise in the level of environmental impacts resulting from livestock production as it has less impact than beef, but more than chicken [139], the two most widely consumed animals in the case cities (one case excluded, Cape Town) [91]. Due to the vagueness of the metabolic data (e.g. 'plastics', 'aluminum', etc) many flows were only modeled through the material production phase; additional processing (e.g. converting aluminum into a beverage container) was ignored, thereby having a reducing effect on the results. Further information regarding the process choices used to model the UM flows as well as their predicted impacts on the model results can be found in the supplementary material (available at stacks.iop.org/ERL/8/035024/mmedia).

The developed model was based on attributional data for the LCIs, whereby only the direct effects of the systems were accounted in the impacts. Indirect impacts were not factored in (e.g. changes to agricultural land use in response to increased first generation biofuels consumption), and thus represents a cutoff rule for the current model.

2.1. Functional unit—a basis of comparison

In LCA the functional unit is the basis of comparison for two product systems in terms of a service or function that the product or process system provides. For instance LCA could model the different beverage packaging solutions that could be used to hold an equal amount of liquid or different travel methods that can be used to transport a person a given distance. Through a comparison of the predicted environmental impacts associated with having two different means provide the same services, the LCA methodology provides a measure of relative sustainability between different product or process choices [69].

Defining a functional unit for comparing urban areas provides a unique and complex challenge in that the systems (i) support different populations with different cultures, habits, diets etc, (ii) provide varying qualities of life to residents both between and within the cities and (iii) perform functions not only for themselves but for other geographic areas through export of manufactured goods. As these systems do not provide these functions at the same level it was decided to forego the traditional functional unit of an LCA. Instead the gross annual metabolic impacts from the cities were normalized to the per capita level (much like many previous UM studies—see [58] or [76]). Thus, the results will represent the impacts of a conceptual average citizen in the case cities, and comparisons between cities will only hint at gross differences in the quality of life of the residents and the methods by which the economies of the cities are supported. Weaknesses of this choice are discussed in section 4.1.

2.2. Indicators studied

LCA results can be communicated as life cycle inventories (LCI), midpoint environmental indicators, endpoint indicators or weighted impact scores [73]. Results quantify predicted (not actual) impacts from the model system(s), and are termed impact potentials (IPs). In this study, it has been chosen to communicate the LCA results through midpoint indicators in order to strike a balance between validity and communicability of the indicator set. The midpoint indicators use (characterization) factors to convert and aggregate system–environment exchanges (from the LCI, which provides an account of the exchange of raw materials/substances between the study system and the environment) and express them relative to indicators of pressures on the environment, material resources and/or human health (e.g. climate change, (stratospheric) ozone depletion, terrestrial ecotoxicity, decreased resource concentration etc). Generally, the further an indicator moves away from the LCI the more uncertainty and subjectivity posited within the indicator [74].

Various life cycle impact assessment (LCIA) methods for generating midpoints exist but for this study the ReCiPe 2008 method has been chosen, as it is the most recent, and contrary to other LCIA methods, ReCiPe allows for multiple cultural perspectives with which to assess the impacts [75]. Three perspectives are provided by ReCiPe based on the Cultural Theory of Risk [140]; Individualist, Hierarchist and Egalitarian. The individualist is least concerned about environmental impacts of humanity's actions, the egalitarian is most concerned, and the hierarchist takes a middle ground in terms of future environmental risk. These perspectives are then reflected in ReCiPe in the models used to convert the LCIs to midpoint IPs in terms of the severity of the potential impacts (e.g. the following timeframes are used in calculating global warming potential; individualist—20 years, hierarchist—100 years, egalitarian—500 years) [75].

The 'Hierarchist' perspective is the default perspective of the applied impact assessment methodology and it was used in this study, as it is based on the most common policy principles, when viewing the severity of an environmental concern in terms of time frame and other issues [75]. Of the eighteen midpoint impact categories available in ReCiPe this study utilized four: global warming potential (GWP), freshwater ecotoxicity (FE), particulate matter formation (PMF) and agricultural land occupation (ALO) that together give comprehensive coverage (air, land and water) of the

Table 1. Characteristics of the case cities to which the UM–LCA model was applied. Data taken from various sources [76–90]. For additional information please see the supporting information (available at stacks.iop.org/ERL/8/035024/mmedia).

City (year modeled)	Beijing (2006)	Cape Town (1997)	Hong Kong (1997)	London (2000)	Toronto (1999)
Population (10^6)	17.07	3.04	6.62	7.40	5.07
Population density (residents km^{-2})	1016	1239	6480	4978	858
Gross domestic product (10^9 year 2000 United States Dollars)	85.2	18.9	169	211	165
Human development index	0.633	0.616	0.824	0.833	0.879
Average daily temperature (°C)	12	17	23	11	9
Data sources for metabolic flows	[55, 71, 72, 90–97]	[60, 98–105]	[31, 106–112]	[55, 113]	[11, 33, 114–118]

environmental impacts associated with both energy systems, chemicals use, transportation and production of biomaterials and in particular food. The latter two midpoint impacts were compared with economic measures to analyze decoupling trends. In one instance the per capita impacts for ALO and PMF were plotted against per capita GDP in order to see if relationships existed between economic factors and the types of IPs produced. Furthermore, citywide PMF IPs were divided by GDP to see relationships between the cities' economic output and their environmental pressures.

2.3. Case cities

The UM–LCA model was applied to five case cities: Beijing, Cape Town, Hong Kong, London and Toronto. A case study approach was chosen rather than a traditional sampling method in order to provide concrete and contextual insight into what the outcome such a model could be used for. The five cases were chosen on the basis of what Flyvbjerg [9] terms as a maximum variation strategy, so that a varied cross section of historical, political, social, economic, geographic and typological characteristics was represented, and the comparisons of the environmental performance of different types of cities could be elucidated. The choice of case cities was also influenced by data availability, in particular the presence of a relatively recent UM study from which metabolic flows could be extracted as input into the UM–LCA model. The definition of a 'city' varied depending on the reference UM study but consisted of either a commutershed (Cape Town, Toronto) or municipal boundaries (Beijing, Hong Kong, London). The properties of the case cities are outlined in table 1. The case studies do not aim at validating the developed model *per se*, but aim to demonstrate the usefulness of including upstream and downstream considerations in relation to urban metabolism.

2.4. Metabolic flows and data sources

The metabolic flows chosen for inclusion in the study were based on their importance in sustaining essential urban functions (food for residents, construction materials

for growth/maintenance of building stock and infrastructure, energy for transport, buildings and industry, and other materials commonly consumed en masse). Metabolic flows were derived predominantly from earlier UM studies [11, 31, 33, 55, 58, 60], and augmented with additional data sources, where necessary to ensure the same flows were covered for all case cities. Earlier UM studies from which data was mined generally covered the same groups of flows in the same level of detail to avoid biases between studies.

Furthermore the years studied were within a reasonable timeframe so that large shifts in the nature of societies' metabolism were avoided. Where consumptive data was completely lacking, waste statistics were used to estimate annual consumption for a limited set of goods through certain cities. Figure 2 outlines the material and energy flows considered in the current study while the data sources are referenced at the bottom of table 1. The supplementary information (available at stacks.iop.org/ERL/8/035024/mmedia) provides inventories for the annual metabolic flows for all of the cities, including sources and estimation methods for all flows.

3. Results

Despite the UM–LCA model providing results in terms of midpoint indicators, those results presented in this section were chosen based on the ability to communicate (i) how the developed model improved upon the types of quantification of earlier UM methods, and (ii) the new types of analysis of cities that the UM–LCA model can provide.

3.1. Inter-model comparisons

For all of the cities modeled it was found that embedded flows up- and downstream of the cities' direct consumption represented a significant portion of the total mass and energy usage resulting from the cities' metabolic activities. For all the cities the volumes of total mass and energy flows accounted for using UM–LCA were thus significantly larger than those that would have been quantified using the UM-G1 method. To ensure that these findings were not a consequence
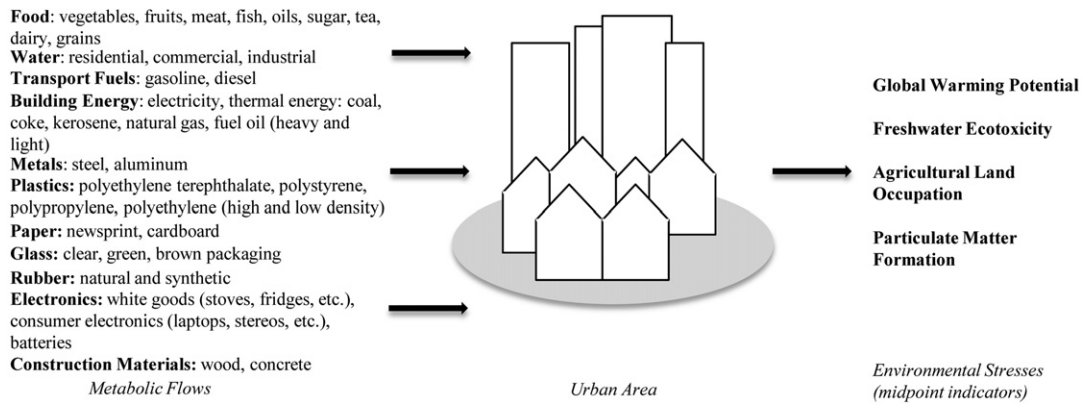
Food: vegetables, fruits, meat, fish, oils, sugar, tea, dairy, grains
Water: residential, commercial, industrial
Transport Fuels: gasoline, diesel
Building Energy: electricity, thermal energy: coal, coke, kerosene, natural gas, fuel oil (heavy and light)
Metals: steel, aluminum
Plastics: polyethylene terephthalate, polystyrene, polypropylene, polyethylene (high and low density)
Paper: newsprint, cardboard
Glass: clear, green, brown packaging
Rubber: natural and synthetic
Electronics: white goods (stoves, fridges, etc.), consumer electronics (laptops, stereos, etc.), batteries
Construction Materials: wood, concrete
Metabolic Flows

Global Warming Potential

Freshwater Ecotoxicity

Agricultural Land Occupation

Particulate Matter Formation

Urban Area

Environmental Stresses (midpoint indicators)

Figure 2. UM flows entering the case cities and resulting environmental stresses resulting from these that are included in the UM–LCA.
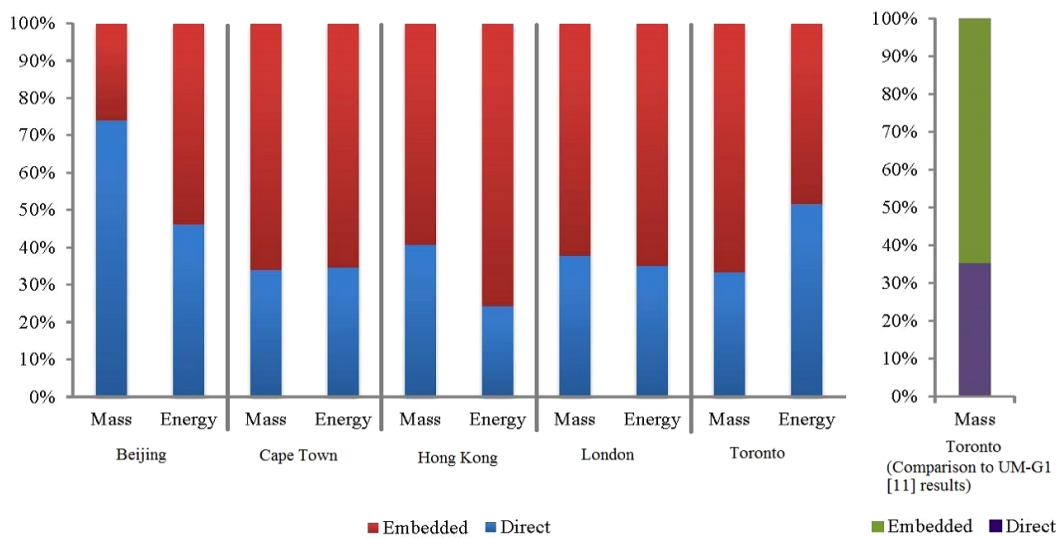

Figure 3. Contributions of embedded and direct energy to the total flows of mass and energy resulting from the metabolisms of the case cities. Direct contributions are those typically accounted for in UM-G1 studies, while the embedded flows occur up- and downstream of this. Water and air flows through the modeled systems were not included. The figure on the left shows this comparison using all flows modeled in the current study. The figure on the right performs the same comparison but only using those flows modeled in the original UM-G1 study.

of the metabolic flows modeled in this particular case, a similar comparison was performed for mass consumption in Toronto using only those flows considered in the earlier base UM-G1 study. The model proved robust, with indirect flows dominating despite the different flow regime. Figure 3 presents the relative percentages of the direct and embedded mass and energy flows as determined by the UM–LCA models of the case cities, on the left for all cities and the on the right for the Toronto confirmatory test. In the comparison of direct to embedded mass flows water and air were not included as they dwarf the scale of the other metabolic flows in the model.

For all of the cities except Beijing embedded mass flows accounted for more than 60% of the total mass flows resulting from the cities' metabolic activities, indicating that a UM-G1 study using the same flows would have underestimated the total metabolic activities by a factor of approximately 2–3. Looking at the individual flows constituting the mass and energy flows, embedded mass accounted for a significant proportion for numerous high volume metabolic flows, such as gasoline (74%), diesel (88%), natural gas (52%) and

meat (96%), explaining the discrepancy between UM-G1 and UM–LCA methods. Unlike the other cities, a majority of Beijing's total mass flows (75%) were accounted for directly, a result mainly attributed to its large concrete consumption, which consists of only 2% embedded mass.

Energy consumption through the cities showed a similar trend, with the embedded energy flows contributing between 48% (Toronto) and 76% (Hong Kong) of the cities' total life cycle energy requirements. Accordingly, UM-G1 models of the same systems would underestimate the total metabolic energy needs of the cities by factor between 2 and 4. Disagreement between the two UM methods are result of the inefficiencies in energy infrastructure [119], as well as the embedded energy in the resource extraction, manufacturing and transport of goods [120].

3.2. Inter-city comparisons of environmental performance

The five case studies illustrate that application of the UM–LCA model enables a more detailed insight into the way
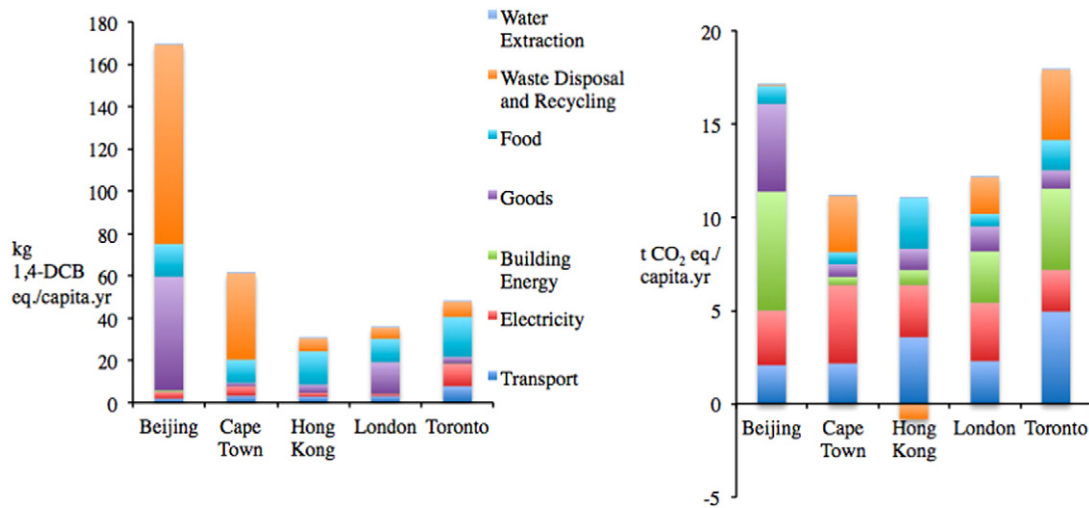
Figure 4. Predicted annual per capita GWP (tons CO_2 equivalents/person/year) and FE impacts (kilograms 1,4-dichlorobenzene equivalents/person/year) of the case cities.

that the environmental performance is distributed within each city, since there is a clear variation across the five cities due to contextual differences.

The per capita GWP for the cities, according to the UM–LCA model, are: 10.2 tons for Hong Kong, 11.2 tons for Cape Town, 12.2 tons for London, 17.2 tons for Beijing and 18.0 tons for Toronto, as shown in figure 3. Previously performed GHG accounting calculated London's and Toronto's emissions at 9.6 tons [141] and 16.6 tons [11] per capita, which agree with the current study to the degree that can be expected for such a method. For the other cities GHG accounting has only been performed on the energy consumption in the cities with: Beijing 11.8 tons [142], Cape Town 5.2 tons [143] and Hong Kong 5.3 [144] tons per capita, which are congruent with the GWP attributed to the building energy, electricity and transportation shown in figure 4 for those cities. By analyzing the GWP IPs it is possible to gain a more detailed insight into the contributing factors to the cities' GWP. This reveals a significant variation in GWP IPs across the five case cities. More interestingly, a pattern can be observed between the level of economic development and the main causes of greenhouse gas (GHG) emissions for the cities. Generally the more economically advanced cities (Hong Kong, London, Toronto) have GWP IPs whose origins appear to be related to the affluence and resulting private consumption of those cities' inhabitants. For GWP (and FE) IPs the potential impacts from food accumulated as biomass (determined as the difference between consumed and known disposal routes of food) has been ignored due to uncertainties in the fate and degradation processes.

For the wealthier cities, Toronto as an example, the largest contributing factors to the GWP are transport (27%) and building energy (24%), with waste disposal also playing a large role (21%) due to the city's composting activities that generate methane. GWP from transport stems primarily from the high usage rates of private automobiles in the city [121], while the building energy is a result of the reliance on distributed natural gas as a heating source, particularly of

residential buildings [122]. In Hong Kong the environmental impacts of the residents' affluence appears in the IPs from food (27%), where the air transport of perishable seafood constitutes an important factor [112]. For London, it is once again primarily the consumption by residents (not industry) that drives the important contributors to the GWP IP [55]: electricity (26%), building energy (22%) and transport (18%).

Beijing and Cape Town both differ from the wealthier case cities in that the GWP IPs related less to volume of private consumption by citizens, but more to the archaic energy infrastructure and industrial activities of the cities. In Beijing it is the building energy (37%), predominantly from industrial coal boilers [123], and the consumption of goods (27%), mainly steel for construction, which are the largest factors in the IPs. In Cape Town, the coal-based electricity system is the largest single contributor to the GWP IP (37%), with composting also playing an important role (27%). Much of the electricity consumption can be attributed to industry [100], while the remaining IP from residential activities is less due to sheer volume consumed, but more symptomatic of the generating technologies.

The relation between environmental pressure and the infrastructural shortcomings of Beijing and Cape Town are further highlighted by FE IPs in figure 3. Beijing's 169.8 kg 1,4-DCB equivalents per capita (eq./cap yr.) dwarf the other case cities. Cape Town also has an elevated FE IP (61.5 kg 1,4-DCB eq./cap yr.) compared to the other case cities, despite lower consumption by residents and a smaller relative economy. Waste management causes more than half of the FE IPs for Beijing and Cape Town; in particular, the disposal of raw sewage to surrounding waters in both cities places a large burden on the local ecosystems. In Cape Town the impoverished informal settlements dump 12.5% of the city's household wastewater into surrounding creeks and rivers [99, 124]. In Beijing 10% of residents were not connected to the water treatment system for the year studied, as the expansion of the city has outpaced the capacity of the municipal
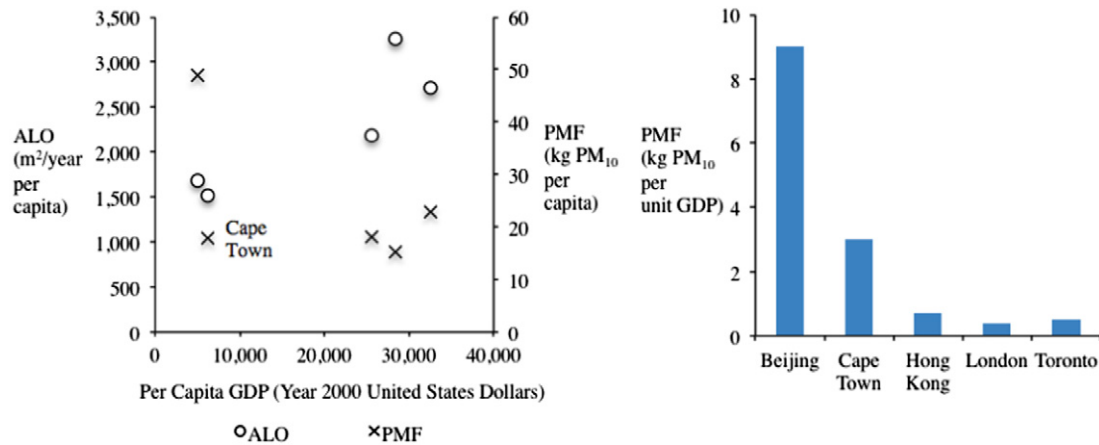
Figure 5. Per capita ALO as m^2 yr^{-1} and PMF as kg particulates <10 μm yr^{-1} are shown on the left. Local air pollution issues in Beijing and Cape Town are disproportionately high relative to the amount of economic activity, particularly when the IP per unit of economic activity is taken into account as shown on the right. Wealthier cities show a tendency to minimize air pollution while the exported environmental pressure of ALO increases with the wealth of the residents.

waterworks [125]. Furthermore, Beijing also had considerable contribution to FE from the mining activities upstream of the city's steel consumption.

Richer case cities, despite higher levels of economic activity and consumption, have lower FE IPs than Beijing and Cape Town. Furthermore, FE IPs appear to be embedded in the goods consumed in the cities and do not occur locally. Generally the wealthier case cities tend to minimize local pollution issues while the less developed study cities remain affected by pollution issues that their wealthier counterparts have long ago dealt with.

Figure 5 expands on this point by displaying the linkages between economic development and different types of IPs. Air pollution in the form of PMF is seen to be high for the level of wealth of the residents in Beijing and Cape Town. This can be regarded as a consequence of the outdated coal technology utilized for electricity, heat and industrial production in both cities [100, 126]. Wealthier case cities tend to mitigate air pollution issues through the use of cleaner technologies in energy generation, consistent with the theory that local environmental pressures are inversely related to the wealth of the potentially affected population [127, 128]. While Cape Town has similar per capita levels of PMF with wealthier cities, the PMF IP per unit of GDP shown in figure 4 reveals that, to date, only weak economic decoupling has occurred. The relatively low PMF levels in Cape Town are more a result of poverty than policy implementation; thus economic growth in Cape Town would likely result in larger marginal increases of PMF impacts compared to the wealthier cities unless compensated by the introduction of cleaner technologies.

Conversely, looking at ALO IPs for the case cities, there is a positive correlation between the growing wealth of the residents and the increase in environmental pressure from the cities' metabolic activities. The increasing ALO can be predominantly linked to the larger role that meat and dairy products play in the diets of residents in wealthier cities. As the wealth of the residents in the case cities increases, so does

the tendency to export environmental loadings of metabolic activities.

4. Discussion

The hypothesis of the current study is that the UM approach can be embedded within the process-based LCA framework, yielding a hybrid UM–LCA model that can provide a more complete measurement of the environmental pressures exerted by a city. The UM–LCA model was developed and applied to five case cities showing that (i) UM–LCA can be successfully applied to cities where the data exists, (ii) the embedded impacts from a city's metabolic activity can be large and are ignored by UM-G1 studies, and (iii) the model output allows for the identification of where in a city's supply chain environmental pressures are highest and hints at how infrastructure and socioeconomic factors relate to these. However, UM–LCA remains methodologically immature, with the current study revealing some of the basic barriers to its successful application inherent both within the model and the supporting data.

4.1. Appraisal of the UM–LCA framework

The impetus for coupling UM and LCA was the growing awareness amongst UM practitioners that both UM-G1 and UM-G2 methods failed to either properly encompass the full impacts of city's metabolism or communicate results in an effective manner [15, 64]. Gauging the developed UM–LCA's ability to address these deficiencies will provide an appraisal of its success and judge whether the UM–LCA method warrants further research effort. Furthermore, an assessment of the difficulties encountered in developing UM-G3 provides a platform to discuss ways of advancing UM–LCA and from which future research can build.

Results of the UM–LCA quantify the extent to which the metabolic activities of cities have been underestimated by the widely applied UM-G1 method. Both mass and energy flows

resulting from the modeled systems were found to be grossly higher than what would have been accounted for if only direct consumption through the cities had been considered, confirming earlier suspicions [15, 63, 64]. The considerable mass and energy amounts embedded within consumed products explained this discrepancy for many substantial flows common to all urban areas (e.g. fuels and food). The case study hinted at an increased need for UM–LCA as an assessment tool, as a city's building stock matures, since cities not undergoing significant construction activity had the majority of mass flows embedded within consumed goods. UM–LCA's expansion beyond direct consumption has also begun to quantify the extent to which cities have departed from historical ecological self-sufficiency [47, 129] and have become dependent on their hinterlands for resources and waste assimilation. Modeling the exported environmental loadings of cities will become essential as emerging economies (taken here as those cities, such as Beijing and Cape Town, with Human Development Indices below 'high' or 0.758 according to the latest index report [15]) advance and correct infrastructural deficits, thereby disconnecting urban regions from their ecological footprints, as was exhibited by the wealthy case cities in their abatement of local air and water pollution, and as observed in other cases [130, 131].

Apart from the inclusion of embedded metabolic flows in the models, UM–LCA exhibited new methods to communicate the assessment findings. The model moved beyond mass and energy as abstracted proxies of environmental loading and expressed results in terms of more common environmental indicators more easily understood by actors across different scientific disciplines. Quantification through UM–LCA also provides environmental policy makers with a potential benchmarking tool for tracking temporal shifts in a city's sustainability resulting from policy interventions. Combination of the IPs with economic data generated additional measures of relative economic decoupling for the case cities. Decoupling is viewed by many as essential in the shift towards a sustainable society [132], particularly in emerging economies where much of the urban population growth is expected [4]. UM–LCA decoupling indicators have the potential to aid in tracking economic decoupling in these cities. For instance, decoupling of industrial energy consumption is currently utilized as a proxy for assessing climate change abatement in Chinese cities [133], but with UM–LCA, officials have the potential to advance beyond proxies to using GWP IPs as a monitoring and source tracking tool. However the limitation should be kept in mind that these improved indicators can only express relative sustainability at present. Coupling UM–LCAs improved quantification with the Earth's carrying capacity, perhaps by means of the planetary boundaries approach [5], might provide measures of absolute sustainability, overcoming this current model shortcoming [138].

The abundance of indicators provided during the LCIA phase of the UM–LCA allows practitioners to quantify the relative performance of different cities over a multitude of environmental impact types/categories (e.g. air pollution,

water pollution, land use, etc). It was through this expanded indicator set that the relationship between economic development of the case cities and the exporting of their environmental loadings became clear. Furthermore, different UM–LCA studies can be compared so long as the equivalent sets of mass flows and LCIA methods are employed (the latter being easy to apply using dedicated product system modeling software). Convenient comparisons of relative environmental performance is not merely a point of interest but also of practical use in SUD; cities can look towards peers with superior environmental performance in a sector and can adapt successful practices to the local context.

The ability for UM–LCA to identify key metabolic contributors to midpoint IPs provides information to policy makers regarding hotspots in a city's metabolism that could benefit from intervention or in relation to systematic environmental conscious re-design of urban areas. The breakdown of GWP and FE IPs in this study revealed the bias towards impacts from private consumption and infrastructural deficits in wealthy and emerging cities respectively. In this sense the new method has also revealed the limitations of SUD policy, in that directly reducing the private consumption of urban residents is outside the domain of municipal policy makers, and is a difficult agenda to push in the current consumer driven, growth-based economic paradigm [131]. This echoes the findings of Heinonen and Junnila that per capita GHG emissions in Finnish cities were more correlated with the wealth of residents than the density of the cities (a popular SUD attribute) [67]. Moreover, even if reductions in manufacturing emissions occurred through cleaner production methods, the sheer volume of increased consumption is likely to eclipse the marginal benefits achieved [131].

Even with its positive aspects, the UM–LCA is only useful in the correct spatial context, taking into account the multi-level governance of urban areas. The scale of the city-scale of the current study may not be representative of the drivers and subsystems affecting metabolic flows [145]. For instance the raw-sewage releases in Cape Town are symptomatic of the informal settlements [124], and addressing this issue may be better understood through further research (UM, socioeconomic or otherwise) at the scale of the informal settlements. However, knowing the scale at which to study environmental impacts requires an initial guess, and UM–LCA can provide a quantitative compass directing researchers towards those flows that emerge as significant environmental pressures due to the subsystems embedded in the black box of the model. With this knowledge in hand, more detailed analysis can determine at what scale (sub-urban, urban, or supra-urban) is appropriate for understanding the causes and benchmarking those flows.

Inherent issues in UM studies are matters of definition, for example, where a city's geographic boundaries are delineated and what flows are to be included. Moreover some additional concerns have been introduced through the coupling of UM and LCA. Of paramount importance in the UM–LCA is how the functional unit is defined. As designed in this study the basis of comparison between the case cities does allow for comparisons of their performance, but in

an unrefined manner. Firstly some of the metabolic flows (e.g. energy and material for manufacturing) are attributable to the demands of populations outside the city with the case city benefiting from the economic activity of production but not the services the manufactured goods provide. Allocating these types of shared burdens is inherently done for materials by the MFA methodology on which the UM–LCA relies (which only quantifies material accumulation in the cities) but is ignored for the energy consumed in the cities. Thus, the current model wrongly allocated some energy impacts to the case cities, an issue that might be rectified through economic allocation using trade data on manufactured goods in a city, though this information is currently in short supply. In inter-city comparisons the different standards of living between residents in the cities has not been accounted for in the in this study, though metabolic flows have been shown by others to reflect variations in lifestyle [67]. This is not inherently at odds with the current study aim of understanding on a gross level the impacts associated with an average citizen. However, through normalization of IPs to the per capita level, relegates inter-city comparisons to the realm of abstraction, rather than a solid representation of the impacts from the compared cities' actual residents. Targeted and higher resolution UM flows might improve the method in this regard, for instance by applying the model to neighborhoods of similar income in different cities, or conversely, studying the IPs from different income neighborhoods in the same cities. These studies might better disentangle the different drivers for impacts as well as provide the contextual benefits discussed above, thus better informing policy development.

Another issue raised through the UM–LCA tool is how to model accumulated durable goods ('stocks') in cities. Researchers have already attempted UM models that account for changes in material stock assuming average durables lifetimes [37] and Kennedy has developed a mathematically rigorous methodology for tracking UM flows [134]. The difficulty in UM–LCA arises in trying to model the EoL phase of these accumulated stocks, as the uncertainty about the technology increases as the temporal scope of the model increases. For instance, what waste management strategies will be used in handling building materials that will remain in a city's stock for decades or centuries? The current study falsely assumes a steady state for EoL processes, but it is impossible to determine whether that introduces more error than trying to predict and model the future. However, this assumption has likely lead to an overestimation of IPs for durable flows, as some of these will either remain in the cities' material stock indefinitely or long enough for cleaner EoL processing to be developed. The use of uncertainty and/or sensitivity analysis may assure assessors to the importance that EoL processes play in the stability of the overall model results.

External to the UM–LCA methodology but essential to the strength of the results is data availability. As has been a theme in previous UM studies, finding reliable figures for material consumption in the case cities was difficult. Previous studies have overcome data gaps by utilizing trade statistics to perform mass balances on geographic areas [37, 58],

while others have made use of national household consumption surveys as a proxy for average consumption by city residents [33]. However, these sources are lacking for many cities [10, 14], particularly those in emerging economies where much of the urban population growth, economic development and consumption are expected to occur. Crude consumptive estimates gleaned from the limited data available in many cases do not suffice to produce robust UM–LCA models. For instance, the method of estimating consumption from waste statistics may underestimate the true metabolic volumes as the true consumption (material accumulated and output) is not accounted. Headway is being made in this direction, such as projects by the World Bank to collect UM data for a number of emerging world cities [10]. But currently, gaps in consumption data persist as a primary shortcoming in properly benchmarking SUD. In the current study these data gaps led to the exclusion of numerous important metabolic flows (e.g. clothing, copper, asphalt, etc) which may have lowered the results.

A final note regarding UM–LCA modeling is the utilization of process-based LCA, which is methodologically simple, but does not account for the interdependences amongst industries and therefore potentially underestimates IPs [66]. Economic input–output LCA (EIO-LCA) can account for inter-industry relationships using national economic inventories; however, they rest on the basic assumption that all manufacturing occurs within the country modeled, which is clearly at odds with the globalized nature of trade. To accommodate this hybrid-process-based EIO-LCAs have been developed to incorporate the strengths of both methods; (i) increased completeness of material and energy flows with the EIO-LCA and (ii) technological and geographic representativeness of the process-based LCA. The current model most likely underestimates those inter-industry material and energy dependences that strengthen the EIO-LCA, and therefore, it can only be considered a step towards the superior hybrid EIO-LCA.

5. Conclusion

The conceptual UM–LCA model has the potential to provide an improved assessment tool for urban environmental loading beyond earlier UM methods through inclusion of the environmental pressures embedded in the goods that cities consume and by offering a clear set of communicative indicators. This initial foray into UM–LCA has highlighted a number of future research needs, including: (i) a better definition of a functional unit for cities, (ii) a need for a method to model durable goods accumulated in urban systems and (iii) the further development of the model towards the more robust hybrid EIO-LCA approach using consequential life cycle inventories. UM–LCA has the ability to generate a robust accounting of a city's emergent environmental burdens; as a black box model, however, it cannot shed light on the complex mechanisms and institutional drivers that lead to the metabolic flows a city demands. As such, UM–LCA requires socioeconomic, political and ecological observations in order to provide a truly holistic understanding

of the metabolism of cities [14, 135, 145]. Minx and others have taken in this direction by calling for the inclusion of metabolic drivers and quality of life indicators as part of a more complete UM framework [138]. Moreover, the problem of integrating UM–LCA results into the SUD policy implementation process needs to be addressed, as quantitative data has historically taken a backseat in urban policy development and monitoring [136, 137].

Conclusions regarding the relative performance of the case cities should be taken as *prima facie* considering the shortcomings in supporting data for the model. Increasing the number of studies linking urban economic activities and environmental pressure would help validate the findings here. Significant data shortcomings have plagued other UM studies, and though efforts are being made in some municipalities to collect UM data under the auspices of a number of projects [14]. The near ubiquitous lack of reliable consumption data for cities serves to highlight the uncertainty in current sustainability assessments of urban areas, and claims made by cities regarding sustainability should be viewed with caution while this data remains *in absentia*.

References

[1] Kennedy C, Baker L, Dhakal S and Ramaswami A 2012 Sustainable urban systems *J. Indust. Ecol.* **16** 775–9

[2] Price Waterhouse Cooper 2010 *Global City GDP Rankings 2008–2025* (available at: www.ukmediacentre.pwc.com, accessed 18 June 2012)

[3] UN-ESA 2011 *World Urbanization Prospects, the 2011 Revision* (available at: http://esa.un.org/unup, accessed 14 August 2012)

[4] Krausman F, Gingrich S, Eisenmenger N, Erb K, Haberl H and Fischer-Kowalski M 2009 Growth in global materials use, GDP and population during the 20th century *Ecol. Econ.* **68** 2696–705

[5] Rockstrom J *et al* 2009 A safe operating space for humanity *Nature* **461** 472–5

[6] Rees W 2008 Human nature, eco-footprints and environmental injustice *Local Environ.* **13** 685–701

[7] Haapio A 2012 Towards sustainable urban communities *Environ. Impact Assess. Rev.* **32** 165–9

[8] Kennedy C, Cuddihy J and Engel-Yan J 2007 The changing metabolism of cities *J. Indust. Ecol.* **11** 43–59

[9] Flyvbjerg B 2006 Five misunderstandings about case-study research *Qual. Inquiry* **12** 219–45

[10] Kennedy C and Hoornwg D 2012 Mainstreaming urban metabolism *J. Indust. Ecol.* **16** 780–2

[11] Codoban N and Kennedy C 2008 Metabolism of neighborhoods *J. Urban Plann. Dev.* **134** 21–31

[12] Li S, Zhang Y, Yang Z, Liu H and Zhang J 2012 Ecological relationship analysis of the urban metabolic system of Beijing, China *Environ. Pollut.* **170** 169–76

[13] Barles S 2009 Urban metabolism of Paris and its region *J. Indust. Ecol.* **13** 898–913

[14] Pincetl S, Bunje P and Holmes T 2012 An expanded urban metabolism method: towards a systems approach for assessing the urban energy processes and causes *Landsc. Urban Plann.* **107** 193–202

[15] United Nations Development Programme 2013 *Human Development Index 2013* (available at: http://hdr.undp.org/en/media/HDR_2013_EN_complete.pdf, accessed on 11 April 2013)

[16] Nilsson J 1995 A phosphorous budget for a Swedish municipality *J. Environ. Manag.* **45** 243–53

[17] Anderberg S 1998 Industrial metabolism and the linkages between economics, environment and ethics *Environ. Ecol.* **24** 311–20

[18] Hendriks C, Obermosterer R, Muller D, Kytzia S, Baccini P and Brunner P 2000 Material flow anaysis: a tool to support environmental policy decision making. Case studies on the city of Vienna and the Swiss Lowlands *Local Environ.* **5** 311–28

[19] Faerge J, Magid J and Frits P 2001 Urban nutrient balance for Bangkok *Ecol. Modelling* **139** 63–74

[20] Hedbrant J 2001 Stockhome: a spreadsheet model of urban heavy metal metabolism *Water Air Soil Pollut.* **1** 55–66

[21] Obernosterer R and Brunner P 2001 Urban metal management: the example of lead *Water Air Soil Pollut.: Focus* **1** 241–53

[22] Douglas I, Hodgson R and Lawson N 2002 Industry, environment and health through 200 years in Manchester *Ecol. Modelling* **41** 235–55

[23] Kane M and Erickson J 2007 Urban metabolism and payment for ecosystem services: history and policy analysis of the New York city water supply *Ecological Economics of Sustainable Watershed Management* (*Advances in the Economics of Environmental Resources* vol 7) ed J Erickson, F Messner and I Ring (Bingley: Emerald) pp 307–28

[24] Theiriault J and Laroch A-M 2009 Evaluation of the urban hydrologic metabolism of the greater Moncton region, New Brunswick *Can. Water Res.* **34** 255–68

[25] Wolman A 1965 The metabolism of cities *Sci. Am.* **213** 179–90

[26] Hanya T and Ambe Y 1976 *A Study on the Metabolism of Cities* (Tokyo: Science Council of Japan)

[27] Duveneaud D and Denayeyer-De S 1977 L'Ecosysteme Urbs *L'Ecosysteme Urbain Bruxellois* ed D Duveneaud and K Kestemont (Bruxelles: Traveaux de la Section Belge du Programme Biologique International) pp 581–97

[28] Baccini P 1997 A city's metabolism: toward the sustainable development of urban systems *J. Urban Technol.* **4** 213–21

[29] Stimson R, Western J, Mullins P and Simpson R 1999 Urban metabolism as a framework for investigating quality of life and sustainable development in the Brisbane-Southeast Queensland metro region *Quality of Life: Critical Issues and Options* ed L Yuan, B Yuen and C Low (Singapore: School of Building and Real Estate, National University of Singapore) pp 143–68

[30] Newman P 1999 Sustainability and cities: extending the urban metabolism model *Landsc. Urban Plann.* **44** 219–26

[31] Warren-Rhodes K and Koenig A 2001 Escalating trends in the urban metabolism of Hong Kong: 1971–1997 *Ambio* **30** 429–38

[32] Hammer M, Giljum S and Hinterberger F 2003 *Material Flow Analysis of the City of Hamburg* (available at http://tinyurl.com/a9vhhh6, accessed on 10 March 2012)

[33] Sahely H, Dudding S and Kennedy C 2003 Estimating the urban metabolism of Canadian cities: greater Toronto area case cities *Can. J. Civ. Eng.* **30** 468–83

[34] Liu J, Wang R and Yang J 2005 Metabolism and driving forces in Chinese urban household consumption *Popul. Environ.* **26** 325–41

[35] Ngo N and Pataki D 2008 The energy and mass balance of Los Angeles county *Urban Ecosyst.* **11** 121–39

[36] Ding L, Wang Y-L and Yun F 2008 The citizen's material flow consumption analysis—a case study of Chengdu *Proc. Int. Conf. on Information Management, Innovation Management and Industrial Engineering*

[37] Niza S, Rosado L and Ferrao P 2009 Urban metabolism: methodological advances in material flow accounting based on the Lisbon case study *J. Indust. Ecol.* **13** 384–405

[38] Browne D, O'Regan B and Moles R 2009 Assessment of total urban metabolism and metabolic activity in an Irish city-region *Waste Manag.* **29** 2765–71

[39] Pomazi I and Szabo E 2009 Urban metabolism: the case of Budapest *Proc. ConAccount 2008—Urban Metabolism: Measuring the Ecological City* (Prague: Charles University Environment Center) pp 351–75

[40] Liu Y, Wang W, Li X and Zhang G 2010 Eco-efficiency of urban material metabolism: a case study in Xiamen, China *Int. J. Sust. Dev. & World Ecol.* **17** 142–8

[41] SUME 2011 *Planning Resource-Efficient Cities—SUME Synthesis Report* (available at: www.sume.at/project_downloads, accessed 24 February 2012)

[42] Liang S and Tianzhu Z 2011 Urban metabolism in China: achieving dematerialization and decarbonization in Suzhou *J. Indust. Ecol.* **15** 420–34

[43] Liang S and Zhang T 2012 Comparing urban solid waste recycling from the viewpoint of urban metabolism based on physical input–output model: a case of Suzhou, China *Waste Manag.* **32** 220–5

[44] Reddy B 2013 *Metabolism of Mumbai—Expectations, Impasse and the Need for a New Beginning* (available at: www.igidr.ac.in/pdf/publication/WP-2013-002.pdf, accessed 25 January 2013)

[45] Leduc W and van Kann F 2013 Spatial planning based on urban energy harvesting toward productive urban regions *J. Cleaner Prod.* **39** 180–90

[46] Zuchetto J 1975 Energy-economic theory and mathematical models for combining the systems of man and nature, case study: the urban region of Miami, Florida *Ecol. Modelling* **1** 241–68

[47] Stanhill G 1977 An urban agro-ecosystem: the example of nineteenth century Paris *Agro-Ecosystems* **3** 269–84

[48] Huang S 1998 Urban ecosystems, energetic hierarchiesm and ecological economics of Taipai metropolis *J. Environ. Manag.* **52** 39–51

[49] Huang S, Lee C and Chen C 2006 Socioeconomic metabolism in Taiwan: emergy synthesis versus material flow analysis *Resour. Conserv. Recy.* **48** 166–96

[50] Zhang Y, Yang Z and Yu Z 2006 Measurement and evaluation of interactions in complex urban ecosystem *Ecol. Modelling* **197** 77–89

[51] Zhang Y, Yang Z and Li W 2006 Analyses of urban ecosystem based on information entropy *Ecol. Modelling* **197** 1–12

[52] Zhang Y, Yang Z and Yu X 2009 Evaluation of urban metabolism based on emergy synthesis: a case study for Beijing (China) *Ecol. Modelling* **220** 1690–6

[53] Zhang Y, Yang Z, Chen B and Chen G 2009 Measurement and evaluation of the metabolic capacity of an urban ecosystem *Commun. Nonlinear Sci. Numer. Simul.* **14** 1758–65

[54] Huang S and Chen C 2009 Urbanization and socioeconomic metabolism in Taipei—an emergy synthesis *J. Indust. Ecol.* **13** 75–93

[55] Liu G, Yang Z, Chen B and Ulgiati S 2011 *Emergy-based Environmental Impact Assessment in Urban Metabolic Process: a Case Study of Beijing, 1999–2006* (available at: http://tinyurl.com/a433x8f, accessed 8 February 2012)

[56] Liu G, Yang Z and Chen B 2011 Comparison of different urban development strategy options to the urban metabolism optimal path *Procedia Environ. Sci.* **5** 178–83

[57] Liu G, Yang Z and Chen B 2011 Four angle model for the urban metabolism integrated analysis *Procedia Environ. Sci.* **5** 81–6

[58] Chartered Institute of Wastes Management 2002 *City Limits: A Resource Flow Ecological Footprint Analysis of Greater London* (London: Chartered Institution of Waste Management)

[59] Cardiff Council 2005 *Cardiff's Ecological Footprint* (Cardiff: Cardiff Council)

[60] Gasson B 2002 The ecological footprint of Cape Town: unsustainable resource use and planning implications *Proc. SAPI Int. Conf.* (Durban: Planning Africa)

[61] World Wildlife Fund 2010 *Living Planet—2010 Report: Biodiversity, Biocapacity and Development* (available at: http://wwf.panda.org/about_our_earth/all_publications/living_planet_report/, accessed 10 June 2012)

[62] Barles S 2010 Society, energy and materials: the contribution of urban metabolism studies to sustainable urban development issues *J. Environ. Plan. & Manag.* **53** 439–55

[63] Kennedy C, Pincetl S and Bunje P 2011 The study of urban metabolism and its application to urban planning and design *Environ. Pollut.* **159** 1965–73

[64] Finnveden G, Hauschild M, Ekvall T, Guinee J, Heijungs R, Hellweg S, Koehler A, Pennington D and Suh S 2009 Recent developments in life cycle assessment *J. Environ. Manag.* **91** 1–21

[65] Li D and Wang R 2009 Hybrid emergy-LCA (MEML) based metabolic evaluation of urban residential areas: the case of Beijing, China *Ecol. Comp.* **6** 484–93

[66] Ulgiati S, Ascione M, Bargigli S, Cherubini F, Franzese P, Raugei M, Viglia S and Zucaro A 2011 Material, energy and environmental performance of technological and social systems under a life cycle assessment perspective *Ecol. Modelling* **222** 176–89

[67] Heinonen J and Junnila S 2011 Implications of urban structure and carbon consumption in metropolitan areas *Environ. Res. Lett.* **6** 014018

[68] Golubiewski N 2012 Is there a metabolism of an urban ecosystem? An ecological critique *Ambio* **41** 751–64

[69] Wenzel H, Hauschild M and Alting L 1997 *Environmental Assessment of Products. Vol. 1—Methodology, Tools and Case Studies in Product Development* (London: Chapman and Hall)

[70] ISO 2006 *ISO 14040:2006 Environmental Management—Life Cycle Assessment—Principles and Framework* (Switzerland: International Standards Organization)

[71] PE International 2008 *GaBi 4, Compilation 4.4.139.1, DB Version 4.131* (Stuttgart: PE International)

[72] Swiss Centre for Life Cycle Inventories 2007 *Ecoinvent Version 2.01* (Switzerland: Swiss Centre for Life Cycle Inventories)

[73] European Commission—Joint Research Centre—Institute for Environment and Sustainability 2010 *International Reference Life Cycle Data System (ILCD) Handbook—General Guide for Life Cycle Assessment—Detailed Guidance* (Luxembourg: Publications Office of the European Union)

[74] Hauschild M 2005 Assessing environmental impacts in a life cycle perspective *Environ. Sci. Technol.* **39** 81–8

[75] Ruimte en Milieu ReCiPe 2008 *A Life Cycle Impact Assessment Method which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level* (available at: http://tinyurl.com/bzsrrn5, accessed on 1 March 2012)

[76] Environment Canada *Canadian Climate Normals 1971–2000* (available at: http://tinyurl.com/awbfjxk, cited 17 July 2012)

[77] Axelson A, Gupta K, Levy M, Lotha G, McKenna A, Parrot-Scheffer C, Singh S and Young G 2012 Cape Town *Encyclopædia Britannica* 15th edn, ed D Hoiberg (London: Encyclopædia Britannica)

[78] Leung C K *et al* 2012 Hong Kong *Encyclopædia Britannica* 15th edn, ed D Hoiberg (London: Encyclopædia Britannica)

[79] Clout H *et al* 2012 London *Encyclopædia Britannica* 15th edn, ed D Hoiberg (London: Encyclopædia Britannica)

[80] Federal Reserve Bank of New York 2012 *Historical Foreign Exchange XML Data* (available at: www.newyorkfed.org/xml/fx.html, accessed on 17 July 2012)

[81] Office of National Statistics 1999 *Regional Accounts 1999: Part 1* (London: Office of National Statistics)

[82] Price Waterhouse Cooper 2009 *Global City GDP Rankings 2008–2025* (London: Price Waterhouse Cooper)

[83] Shen J 2002 A study of the temporary population in Chinese cities *Habitat Int.* **26** 363–77

[84] Statistics Canada 2012 Toronto *Census Profile* (available at: http://tinyurl.com/a8fhrzc, accessed on 17 July 2012)

[85] City of Beijing 2007 *Olympic Games Benefit the Olympic City* (available at: http://tinyurl.com/bepny8p, accessed on 17 July 2012)

[86] Haskins C 2006 *Development Issues in Cape Town* (available at: http://tinyurl.com/b52vfte, accessed on 17 July 2012)

[87] The Government of Hong Kong Special Administrative Region of the People's Republic of China 2012 Population and vital events *Census and Statistics Department* (available at: http://tinyurl.com/amjdpc6, accessed on 17 July 2012)

[88] United Nations Development Programme 2012 *International Human Development Indicators* (available at: http://hdr.undp.org/en/data/trends/, accessed on 17 July 2012)

[89] United States Department of Labor 2012 *CPI Inflation Calculator* (available at: www.bls.gov/data/inflation_calculator.htm/, accessed on 17 July 2012)

[90] World Bank 2012 *World dataBank* (available at: http://databank.worldbank.org/ddp/home.do, accessed on 17 July 2012)

[91] Food and Agricultural Organization of the United Nations 2012 *FAOStat* (available at: http://faostat3.fao.org, accessed on 20 June 2012)

[92] Probe International 2008 *Beijing's Water Crisis 1949–2008 Olympics (2010 Update)* (available at: http://tinyurl.com/adga4ou, accessed on 19 June 2012)

[93] Lifei Z 2009 China's cement consumption expected to grow 6.3% in 2009 *China Daily* (available at: http://tinyurl.com/au68q5m, accessed on 20 June 2012)

[94] The Rubber Economist Ltd 2008 *The Rubber Economist* (available at: http://tinyurl.com/aop5cs3, accessed on 21 June 2012)

[95] Government of Beijing, Number of tourists to Beijing *Beijing International—The Official Website of the Government of Beijing* (available at: http://tinyurl.com/app6ufs, accessed on 27 July 2012)

[96] Li Z-s, Yang L, Qu X-Y and Sui Y-m 2009 Municipal solid waste management in Beijing city *Waste Manag.* **29** 2596–9

[97] 2011 Construction waste surges as recycling stagnates *China Daily* 20 October 2011 (available at: http://tinyurl.com/bkrylrw, accessed on 21 June 2012)

[98] Palcynski R 2002 *Study on Solid Waste Management Options for Africa* (available at: http://tinyurl.com/azujflq, accessed on 14 June 2012)

[99] City of Cape Town 2001 *Service Level Indicators for the City of Cape Town* (available at: http://tinyurl.com/be7d8wm, accessed on 14 June 2012)

[100] City of Cape Town 2003 *State of Energy Report for Cape Town 2003* (available at: http://tinyurl.com/a5ayt2z, accessed on 15 June 2012)

[101] Eksom 2012 *Climate Change & COP 17* (available at: www.eskom.co.za/c/96/climate-change-cop17/, accessed on 14 June 2012)

[102] Mega-Tech Inc. 2004 *Integrated Solid Waste Management Plan* (available at: http://pdf.usaid.gov/pdf_docs/PNADD227.pdf, accessed on 14 June 2012)

[103] Roux S 2011 *Urban Agriculture as a Climate Change Mitigation and Adaptation Strategy* (available at: http://tinyurl.com/a94mogm, accessed on 15 June 2012)

[104] United Nations Environment Programme 2009 *Recycling—From E-Waste to Resources* (available at: http://tinyurl.com/yhn3gfa, accessed on 15 June 2012)

[105] Grant Thorton Kessel Feinstein 2002 *Western Cape Tourism and Investment Trends* (Cape Town: Western Cape Tourism Board)

[106] The Chinese University of Hong Kong, Department of Biochemisty 2010 *Hong Kong Population Based Food Consumption Survey 2005–2007* (available at: http://tinyurl.com/afh8898, accessed on 2 July 2012)

[107] Environmental Protection Department 1998 *Monitoring of Solid Waste in Hong Kong 1997* (available at: https://www.wastereduction.gov.hk/en/materials/info/msw1997.pdf, accessed on 2 July 2012)

[108] Environmental Protection Department 2005 *Rechargeable Battery Recycling Program Continues to Power Along* (available at: www.epd.gov.hk/epd/english/news_events/press/press_070525b.html, accessed on 3 July 2012)

[109] City of Hong Kong 2002 *Transport at a Glance 2002* (available at: http://tinyurl.com/aaghgqc, accessed on 3 July 2012)

[110] Hong Kong Tourism Board 2002 *A Statistical Review of Hong Kong Tourism 2002* (Hong Kong: Hong Kong Tourism Board)

[111] Electrical and Mechanical Services Department 2004 *Hong Kong Energy End-Use Data (1992–2002)* (available at: http://tinyurl.com/b35xymy, accessed on 2 July 2012)

[112] Yang P 2009 Food miles and sustainable consumption in Hong Kong *PhD Thesis* (available at: www.kadinst.hku.hk/PDF_file/KI_working_paper_3.pdf, accessed on 4 July 2012)

[113] Department of Energy and Climate Change 2002 *Road Transport and Energy Consumption at Regional and Local Authority Level—Experimental Regional and Local Authority Road Transport Consumption Statistics: 2002–2004* (available at: http://tinyurl.com/altcu23, accessed on 29 May 2012)

[114] City of Toronto 2007 *Premier Ranked Tourist Destination Project* (available at: www.toronto.ca/tourismstudy/final-report.htm, accessed on 23 June 2012)

[115] City of Toronto 2002 *Waste Composition Report 2000/2001* (available at: www.toronto.ca/wes/techservices/involved/swm/net/pdf/4_2_finalrep.pdf, accessed on 20 June 2012)

[116] Bentley S 2005 *Fight Global Warming at the Farmer's Market* (available at: http://tinyurl.com/ajce5sj, accessed on 23 June 2012)

[117] Recycling Council of Ontario 2005 *Let's Climb Another Molehill* (available at: http://tinyurl.com/asqavek, accessed on 20 June 2012)

[118] Saotome T 2007 Development of construction and demolition waste recycling in Ontario *Masters Thesis* (available at: http://tinyurl.com/aekf4ko, accessed on 20 June 2012)

[119] Schock R N, Sims R, Bull S, Larsen H, Likhachev V, Nagano K, Nilsson H, Vuori S, Yeager K and Zhou L 2012 Energy supply systems *Global Energy Assessment—Toward a Sustainable Future* (Cambridge: Cambridge University Press) (Laxenburg: International Institute for Applied Systems Analysis) pp 1131–72

[120] Weidmann T 2009 A first empirical comparison of energy Footprints embodied in trade—MRIO versus PLUM *Ecol. Econ.* **68** 1975–90

[121] Kennedy C 2001 *A Comparison of the Sustainability of Public and Private Transportation Systems: Study of the Greater Toronto Area* (available at: http://tinyurl.com/bezjo2j, accessed on 25 June 2012)

[122] City of Toronto 2007 *The Energy Plan for Toronto* (available at: www.toronto.ca/energy/pdf/ep4t-stakeholder-presentation-043007.pdf, accessed on 29 July 2012)

[123] Government of China 2007 *Beijing Statistical Yearbook* (Beijing: China Statistics Press)

[124] City of Cape Town 2005 *Study on the Social Profile of Residents in Three Selected Informal Settlements in Cape Town* (available at: http://tinyurl.com/bzvdznp, accessed on 14 June 2012)

[125] United Nations Environment Programme 2008 *Beijing 2008 Olympic Games—An Environmental Review* (available at: www.unep.org/publications/ebooks/beijing-report/Pdfs.aspx, accessed on 20 July 2012)

[126] Qing T 2005 *Current Status of Beijing Energy Use & the Future Development Goals* (available at: http://iis-db.stanford.edu/evnts/4164/Beijing,_Tong_Qing.pdf, accessed on 18 July 2012)

[127] Khanna H and Plassman F 2004 The demand for environmental quality and the environmental Kuznet's curve hypothesis *Ecol. Econ.* **51** 225–36

[128] Stern D, Common M and Barbier E 1996 Economic growth and environmental degradation: the environmental Kuznets curve and sustainable development *World Dev.* **24** 1151–60

[129] Kim E and Barles S 2012 The energy consumption of Paris and its supply areas from the eighteenth century to the present *Reg. Environ. Change* **12** 295–310

[130] Rees W 2009 The ecological crisis and self-delusion: implications for the building sector *Build. Res. Inform.* **37** 300–11

[131] Rees W 2012 Cities as dissipative structures: global change and the vulnerability of urban civilization *Sustainability Science: The Emerging Paradigm and the Urban Environment* ed M Weinstein and R Turner (New York: Springer) pp 247–73

[132] United Nations Environment Programme 2011 *Decoupling Natural Resource Use and Environmental Impacts from Economic Growth* (available at: http://tinyurl.com/3vahr7n, accessed on 11 January 2013)

[133] Leggett J 2011 *China's Greenhouse Gas Emissions and Mitigation Policies* (available at: www.fas.org/sgp/crs/row/R41919.pdf, accessed on 21 July 2012)

[134] Kennedy C 2012 A mathematical description of urban metabolism *Sustainability Science: The Emerging Paradigm and the Urban Environment* ed M Weinstein and R Turner (New York: Springer) pp 275–91

[135] Broto V, Allen A and Rapoport E 2012 Interdisciplinary perspectives on urban metabolism *J. Indust. Ecol.* **16** 851–61

[136] Innes J 1990 *Knowledge and Public Policy: The Search for Meaningful Indicators* (New Brunswick: Routledge)

[137] Holden M 2006 Urban inicators and the integrative ideals of cities *Cities* **23** 170–83

[138] Minx J, Creutzig F, Mdinger V, Ziegler T, Owen A and Baiocchi G 2010 *Developing a Pragmatic Approach To Assess Urban Metabolism in Europe* (available at: http://tinyurl.com/c35eosp, accessed on 9 April 2013)

[139] FAO 2006 *Livestock's Long Shadow* (available at: www.fao.org/docrep/010/a0701e/a0701e00.HTM, accessed on 16 April 2013)

[140] Thompson M, Ellis R and Wildavsky A 1990 *Cultural Theory* (Boulder, CO: Westview)

[141] Greater London Authority 2007 *Action Today to Protect Tomorrow: The Mayor's Climate Change Action Plan* (available at: http://tinyurl.com/m5of49y, accessed 19 July 2013)

[142] Geng Y, Peng C and Tian M 2011 Energy use and CO_2 inventories in the four municipalities of China *Energy Procedia* **5** 370–6

[143] City of Cape Town 2011 *Energy Scenarios for Cape Town—Exploring the Implications of Different Energy Futures for the City up to 2050* (available at: www.capetown.gov.za/en/EnvironmentalResourceManagement/publications/Documents/Energy_Scenarios_for_CT_to_2050_2011-08.pdf, accessed on 19 April 2013)

[144] Government of Hong Kong 2012 *Environment Hong Kong 1986–2011* (available at: http://tinyurl.com/lx8sucd, accessed 19 July 2013)

[145] Kennedy C, Pincetl S and Bunje P 2012 Reply to comment on 'The study of urban metabolism and its applications to urban planning and design' by Kennedy *et al* (2011) *Environ. Pollut.* **167** 186

[146] Chester M, Pincetl S and Allenby B 2012 Avoiding unintended tradeoffs by integrating life-cycle impact assessment with urban metabolism *Curr. Opin. Environ. Sustain.* **4** 451–7