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An urban metabolism and ecological footprint assessment of Metro Vancouver

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ABSTRACT

As the world urbanizes, the role of cities in determining sustainability outcomes grows in importance. Cities are the dominant form of human habitat, and most of the world's resources are either directly or indirectly consumed in cities. Sustainable city analysis and management requires understanding the demands a city places on a wider geographical area and its ecological resource base. We present a detailed, integrated urban metabolism of residential consumption and ecological footprint analysis of the Vancouver metropolitan region for the year 2006. Our overall goal is to demonstrate the application of a bottom-up ecological footprint analysis using an urban metabolism framework at a metropolitan, regional scale. Our specific objectives are: a) to quantify energy and material consumption using locally generated data and b) to relate these data to global ecological carrying capacity. Although water is the largest material flow through Metro Vancouver (424,860,000 m^3), it has the smallest ecological footprint (23,100 gha). Food (2,636,850 tonnes) contributes the largest component to the ecological footprint (4,514,400 gha) which includes crop and grazing land as well as carbon sinks required to sequester emissions from food production and distribution. Transportation fuels (3,339,000 m^3) associated with motor vehicle operation and passenger air travel comprises the second largest material flow through the region and the largest source of carbon dioxide emissions (7,577,000 tonnes). Transportation also accounts for the second largest component of the EF (2,323,200 gha). Buildings account for the largest electricity flow (17,515,150 MWh) and constitute the third largest component of the EF (1,779,240 gha). Consumables (2,400,000 tonnes) comprise the fourth largest component of the EF (1,414,440 gha). Metro Vancouver's total Ecological Footprint in 2006 was 10,071,670 gha, an area approximately 36 times larger than the region itself. The EFA reveals that cropland and carbon sinks (forested land required to sequester carbon dioxide emissions) account for 90% of Metro Vancouver's overall demand for biocapacity. The per capita ecological footprint is 4.76 gha, nearly three times the per capita global supply of biocapacity. Note that this value excludes national government services that operate outside the region and could account for up to an additional 2 gha/ca.

1. Introduction

More than 50% of the world's population live in urban regions (UNPD, 2009), and in affluent countries urbanization levels exceed 75%. Such is the case for Canada where 80% of the population lives in urban centres (Statistics Canada, 2006a). Cities and towns are perceived as the source of most states' economic wealth and the core of social and cultural activities (Jacobs, 1984). At the same time, from a biophysical perspective, cities are dissipative structures that consume vast quantities of energy and material resources (Rees, 2012, 2003). However, urban metabolism studies reveal that cities' demand for nature's goods and services is increasing over time (Browne et al., 2011; Kennedy et al., 2007; Sahely et al., 2003; Hoyer and Holden, 2003; Warren-Rhodes and Koenig, 2001; Newman and Kenworthy, 1999). This is significant because humanity's aggregate ecological footprint (Wackernagel and Rees, 1996) already exceeds the global supply of biocapacity (WWF, 2010). Humanity's ecological deficit is therefore increasing simultaneously with worldwide urbanization (Rees, 2011) even as appreciation grows that for a sustainable future, our species' demand for biocapacity must be reduced.

Urbanization has both positive and negative environmental implications. On the one hand, cities are nodes of consumption that depend utterly on a constant flow of materials and energy from around the world in order to function (Rees, 1992, 2003, 2012; Girardet, 1999; Downton, 2009). On the other hand, the economies

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of agglomeration (lower costs due to proximity of related activities)[1] and the economies of scale (lower costs due to higher volumes) associated with the city's high population density and concentration of economic activity contribute to a significant "urban sustainability multiplier" (Rees, 1997, 2009). Furthermore, the sheer wastefulness of many cities implies major opportunities for energy and material conservation. It follows that in the 21st century, cities are an appropriate focus for research into ecologically necessary, socially acceptable and politically feasible ways of reducing the overall human load on the world's ecosystems (Newman, 2006; Newman et al., 2009; Rees, 2012).

Two approaches developed in recent decades that help quantify and assess urban environmental loads are 'urban metabolism analysis' (UMA) (e.g., Wolman, 1965; Baccini, 1997; Kennedy et al., 2007) and 'ecological footprint analysis' (EFA) (Rees, 1992; Wackernagel and Rees, 1996; Chambers et al., 2000). Both use material flow analysis, predicated on the thermodynamic law of conservation of energy and the law of mass balance. Metabolism studies attempt to quantify the amounts of materials and energy that flow through a city. Analysing the material and energy metabolism of specific sectors and activities within the city allows identification of major loads and potential points of intervention for reducing urban impacts (e.g., Kennedy et al., 2010; Lenzen et al., 2003; Hendriks et al., 2000). EFA, when combined with UMA, takes the additional step of estimating the area of productive terrestrial and aquatic ecosystems required for urban metabolism to happen. This means that EFA estimates the biocapacity required to produce the energy and material resources the city consumes and to assimilate the resultant wastes (Rees, 1992; Wackernagel et al., 2006; Ewing et al., 2009). EFA also uniquely enables comparisons of demand with supply, i.e., between current urban metabolic load and available biophysical carrying capacity, both regional and global (Wackernagel and Rees, 1996; Chambers et al., 2000). For example, while world average biocapacity demand is 2.7 gha[2] per capita and global supply is only 1.8 gha per capita (WWF, 2010), the average per capita biocapacity demand in high-income cities is often much higher.

While several authors acknowledge both approaches (e.g., Hendriks et al., 2000; Sahely et al., 2003; Kennedy et al., 2007; Browne et al., 2008), most studies use only one method. Curry et al. (2011), Kennedy et al. (2010), Jones (2006), Barrett et al. (2002), Hendriks et al. (2000), Rotmans and van Asselt (2000) and Ravetz (2000) recognize UMA's usefulness in urban sustainability policy development while Collins and Flynn (2006), Mcmanus and Haughton (2006), Barrett et al. (2005), Nijkamp et al. (2004) and Holden (2004) emphasize EFA's contribution to urban policy and communication. The latter method is seen as particularly effective when local government staff is engaged in its development (Collins and Flynn, 2006; Aall and Norland, 2005).

Indeed, recently both the City of Vancouver (Vancouver, 2011) and to a lesser degree the Metro Vancouver Region (Metro Vancouver, 2007a) have indicated interest in working with EFA. It is in response to this interest, addressing local government use of EFA within a North American context, that we focus attention.

Combining UMA and EFA can build upon the strengths of each method (Curry et al., 2011). An EFA based on a UMA framework adds an additional level of insight to an already robust local-level analysis of energy and materials flows within the city. Such an approach can help local officials interpret in general terms the demands on biocapacity resulting from their city's activities and consumption by its residents. The integration of a bottom-up analysis of energy and material flows, including lifecycle assessment, to compile components of an urban metabolism and ecological footprint study can assist local governments to understand how a region's urban metabolism affects demand for ecological services.

Our objectives in this paper, therefore, are: i) to use an urban metabolism framework to quantify the energy and materials consumed by the resident population of Metro Vancouver to support their urban lifestyle patterns; and ii) to compare the ecological footprint associated with that consumption to available per capita biophysical carrying capacity globally. The study uses locally-generated, disaggregated data sources for several urban components such as: buildings, transportation, water, food, material and waste. It provides what we believe is the first integrated UMA and component based EFA study of a North American urban region. It introduces a robust data set from which to pursue further analysis pertaining to the reduction of biocapacity demand and could facilitate the integration of resource management with urban planning (Kennedy et al., 2010; Agudelo-Vera et al., 2011).

2. Evolution of ecological footprint analysis to better serve cities

To date two main approaches have been developed to calculate ecological footprints at the sub-national scale: i) an adapted compound method and ii) a component method. The compound method uses national per capita ecological footprint data that is scaled to reflect the city as much as possible (Wackernagel, 1998; Chambers et al., 2000; Ewing et al., 2010). In the crudest estimates, per capita EFs based on national data are multiplied by the population of the city in question. A more refined approach may weight certain of the national data on energy and material flows based on household consumer surveys that distinguish regional consumption preferences. Nevertheless, because it relies predominantly on national statistics, even this represents a top-down approach (e.g., Wilson and Anielski, 2005; Folke et al., 1997; Wackernagel, 1998; Onisto et al., 1998). The advantage to the compound method is that total national production, import and export data for key sectors are readily available and easier to locate than city-specific data. However, this method has limited ability to reflect the impacts of local policy and action (Levett, 1998; Chambers et al., 2000; Aall and Norland, 2005; Wilson and Grant, 2009; Xu and San Martin, 2010).

The component method starts with local data that reflect the study population's consumption activities (Wiedmann et al., 2006; Barrett et al., 2002; Chambers et al., 2000). There are two sub-approaches: a) involves (monetary) input–output analysis and; b) requires direct estimates of energy and material throughput using local data. The former prevails, particularly in Europe, because of its ability to account for the embodied energy of multiple supply chain steps (Lenzen, 2001), the ease of comparing results (Bicknell et al., 1998), and the relative expediency of data collection and calculation (Barrett et al., 2002; Xu and San Martin, 2010). We refer to this approach as the 'sub-national input–output approach' (SNIO). SNIO is based on monetary input–output economic tables whose values are secondarily converted to actual energy and material flows. It typically also connects local expenditures to carbon emissions in a further extension of conventional input–output analysis. These surrogate data are then used for ecological footprint assessment. However, money-based, economy wide input–output data do not enable: a) tracking how resources flow *within* the region, and b) distinguishing between and prioritizing different types of resource flows (Wiedmann et al., 2006). Although UMA studies can

[1] Lower costs include reduced demand for energy and materials to service the built environment, e.g. reduced demand for transportation translates to fuel savings and less road repair and maintenance.

[2] A global hectare (gha) represents the world average biological productivity of land.

overcome these challenges, their full integration with EFA analysis remains impeded by what Wiedmann et al. (2006) refer to as a "black box" phenomenon associated with the input–output approach. The fact that the SNIO approach does not allow identification of major sub-flows probably contributes to the perception that EFA is constrained as a policy tool (Wiedmann and Barrett, 2010). It limits potential for local government planners and policy analysts to see how the energy and materials flows within the region that are captured by the UMA method map to the ecological footprint. Because SNIO still relies on national economic input–output tables that describe economy-wide material flows, criticisms persist that the method does not adequately reflect local situations. It also challenges local analytic capacity—regional and municipal policy and planning staff are generally unfamiliar with the method and must rely on technical experts both to do the assessment and to translate/communicate the results so they are useful for local planning and policy development purposes (Curry et al., 2011; Wiedmann et al., 2006; Aall and Norland, 2005). Moreover, Wilson and Grant (2009) observe that, in Canada, data accessibility remains an issue. Household consumer expenditure surveys are not available below the census metropolitan level, limiting cities' use of SNIO analysis.

The alternative direct approach to component EFA uses local data to capture actual energy and material flows within the city/metropolitan region. Analysts collect local data on specific sectors, for example: transportation, buildings, food, consumables and waste. They then compute the ecological footprint of each such component and sum these to produce an overall urban ecological footprint (Simmons and Chambers, 1998; Chambers et al., 2000; Barrett, 2001). The direct method is time-consuming (Xu and San Martin, 2010) and because studies tend to differ in terms of sector definition, data availability, etc., inter-city comparison is compromised. However, because the method aims to rely as much as possible on local data, the impact of local policy initiatives or actions can be measured over time with successive ecological footprint analyses (provided that the latter are structurally consistent). Cities often have access to or collect their own data on transportation (e.g., mode-split and average vehicle kilometres travelled by urban residents), buildings (e.g., total built area by type and energy use), utility services (e.g., water and sewer flows, solid waste, and related infrastructure management) all of which are required for the component analysis.

We apply a direct component approach using an urban metabolism framework that relies on access to quantitative data collected by local authorities on energy and materials consumption, e.g., data from utility meter readings for electricity and analyses of solid waste volume and composition for consumer goods.[3] This means expenditure data are not used as a proxy for energy and material throughput. This method can provide local officials with a sensitive portrayal of and valuable insights into locally unique consumption patterns. Because it uses data sets on local materials and energy flows with which local authorities are familiar, they are more readily able to understand the relationships among consumption, the resultant ecological footprint, and biocapacity supply. The method also uses lifecycle assessment to capture the hidden energy and materials flows associated with the manufacture of various products, thereby accounting for some of the indirect energy and materials embodied in trade. In short, by: i) using readily accessible and reliable data that reflect municipal energy and materials flows; ii) linking these to environmental concerns through the eco-footprint, and iii) hybridizing several methods (e.g., UMA complemented by lifecycle assessment and EFA), the direct component approach meets several important criteria identified by Wiedmann et al. (2006) for robustness and policy relevance.

3. Case study

Metro Vancouver is home to approximately 2.1 million people and spans an area of 283,183 ha (Metro Vancouver, 2006a). It comprises 22 municipalities, including the City of Vancouver.[4] The metropolitan region contains some of Canada's most fertile agricultural land; the delta of one of Canada's largest rivers, the Fraser; forested mountains; and coastal shores with crab, salmon, and other fin-fish fisheries. The region's main economic activities include: business services, tourism, agriculture, and manufacturing (BC Stats, 2010). The economy is predominantly service-based with professional, technical and other services such as public administration, retail trade and construction comprising the majority of business employment (BC Stats, 2010).

Although recognized in the literature for its commitment to advancing sustainability through regional plans and initiatives (Newman and Jennings, 2008; Wheeler and Beatley, 2009), Metro Vancouver remains characteristic of a high-consuming, first-world, urban region (Berelowitz, 2005; Rees, 2009). The majority of households, 65%, own their own home despite high unit costs averaging $C 520,397 in 2006. The majority (57%) of the region's population are between the ages of 25 and 64 years with a labour force participation rate of 67%. Sixty-five percent of this age group have some type of post-secondary education credential (BC Stats, 2010).

Approximately 60% of the region's land area is protected in the "Green Zone" comprising: agricultural land, watersheds, natural and recreational areas. Residential development occupies almost 15% and nine percent is devoted to industrial, commercial and institutional uses. Eight percent is dedicated to roads and utility right-of ways, and another nine percent is vacant, meaning it is zoned for development but has not been developed to date (Metro Vancouver, 2006a).

Metro Vancouver's electrical energy supply is 85% hydroelectricity with the remainder generated by natural gas and a small amount from other sources including incineration of municipal waste. Although the region has a relatively high percentage of electrical baseboard heating compared to the rest of Canada, space heating is predominantly through combustion of natural gas. The Province of British Columbia, in which the region is located, does not support nuclear energy and requires all public institutions including local governments to operate on a climate-neutral basis. Greenhouse gas emissions must be offset through investments in sequestration at a rate of $25 per tonne of carbon dioxide equivalent (British Columbia, 2011).

Regional utility services include three coastal mountain watersheds from which the region derives its drinking water supply; five wastewater treatment facilities; two municipal solid waste landfills (one of which is located 500 km outside the region); an incinerator that serves as a waste-to-energy facility supplying some electricity back to BC Hydro, the provincial electrical utility, and steam to nearby industries. Five waste transfer stations collect and sort recyclable materials and organize municipal waste to be

[3] Some studies refer to this as "genuine local data" (Aall and Norland, 2005). The approach can also be characterized as following a Substance Flow Analysis as a distinct method within material flow analysis (Wiedmann et al., 2006).

[4] In the 2006 study year the region comprised only 21 municipalities. On April 3, 2009, the Tsawwassen First Nation, located within Metro Vancouver, ratified the first urban treaty in British Columbia. The treaty provides "municipal-like jurisdiction over a land base of 724 ha" (Piombini, 2011).

transferred either to landfill or the waste-to-energy facility. Regional transportation services include six subsidiary companies providing: i) in-city bus and SeaBus service, ii) a regional elevated light-rapid rail system known as SkyTrain, iii) an inter-regional commuter rail service, iv) a local car ferry, and v) AirCare vehicle emissions testing facilities (GVTA, 2002).

4. Methods

This study is limited to estimating: a) energy and material consumption and waste generation by Metro Vancouver residents and the various local commercial, institutional and utility agencies serving them and; b) the ecosystem area dedicated to producing these energy and materials flows, i.e., Metro Vancouver's ecological footprint. The study excludes industrial production in the region in order to avoid double counting that portion of industrial production that is consumed locally (and already captured in the method) and to avoid counting that portion which serves the needs of consumers elsewhere. The analysis follows the original structure of EFA and what is defined by the European community as the residential principle (Eurostat, 2001)[5] or responsibility principle (Chambers et al., 2002). This means that whatever is consumed by a city's residents is counted along with the up-stream sources of energy and materials required to produce it, wherever in the world the production process occurs. This is distinct from a territorial or geographic approach that examines energy and material flows passing through a study area's territorial boundaries but a) does not account for embodied energy[6] or up-stream material inputs, and b) does not distinguish between production for trade and consumption by local residents.

The year 2006 is chosen as the base year for the study as the most recent year for which Canadian census data were available. For detailed information on specific data and their sources, calculation procedures, and assumptions, see the Supplementary materials file.

4.1. Assessing Metro Vancouver's metabolism and ecological footprint

4.1.1. Urban metabolism

We classified the materials and energy passing through the region by consumption category or associated activity and then divided the data into sub-classes to enable more refined analysis (see Fig. 1). The sub-classes are structured to capture both the weight and type of materials, embodied energy associated with producing and transporting the materials,[7] and direct operating energy. Where relevant, we further disaggregated sub-classes, attributing material flows to either the residential or 'industrial, commercial and institutional' (ICI) sectors. Both the category and sub-class taxonomy matches that used by Metro Vancouver inventories and reports (e.g., Metro Vancouver, 2008a, 2006b). While the study excluded the industrial metabolism of products manufactured in Metro Vancouver for export, light industry activities are counted, e.g. buildings and vehicle operations associated with retail warehousing that serve a predominantly commercial function. Therefore, the (I) representing industrial metabolism is bracketed in Fig. 1 to indicate this partial inclusion.

Most of the data used to compile Metro Vancouver's urban metabolism come from local and provincial government and provincially-owned corporations and include: i) Metro Vancouver reports on: common air contaminants and greenhouse gas emissions inventories, solid waste management and recycling, waste composition surveys, water management, wastewater management, and land use fact sheets; ii) Greater Vancouver Transportation Authority reports on: travel surveys that reveal vehicle kilometres travelled by vehicle type; iii) Province of British Columbia reports on: greenhouse gas emissions that include source characterization data for solid waste, motor vehicles, and building types; iv) BC Hydro reports on: electricity consumption and related greenhouse gas emission coefficients. We also obtained data from BC's largest natural gas company, Fortis BC, on natural gas consumption for residential, commercial and institutional buildings. These data are supplemented with lifecycle assessment data derived from the Athena Impact Estimator for Buildings[8] software and from the literature on various infrastructure, household and corporate consumer items including: primary building materials, e.g., wood and concrete; road construction, e.g., asphalt; personal consumables such as electronic equipment, paper and cardboard, plastics, and fibres used in clothing and upholstery. Local food consumption statistics are not collected by Metro Vancouver. Therefore, data (including relevant input–output tables) for the food component are obtained primarily from Statistics Canada and the national census. We estimate per capita food consumption in Canada from these national data then multiply by the total Metro Vancouver population of 2,116,585 people (Statistics Canada, 2006b) to provide an estimate of regional consumption.

4.1.2. Ecological footprint

Metro Vancouver's ecological footprint comprises the area, in global average hectares (gha), of biologically productive land and water ecosystems required to produce the goods, and services, consumed by the region's residents and to assimilate the carbon dioxide emissions associated with the manufacture, transport, distribution and disposal of those goods. First we estimated the ecosystem area required for each consumption category assuming global average yields provided by the United Nations Food and Agriculture Association (FAO, 2010) and equivalence factors[9] generated by the Global Footprint Network for the 2006 study year (Ewing et al., 2009). Then, for the energy land (i.e., carbon sink) estimate, we assumed a global average annual carbon sequestration value for forested land of one tonne per hectare (Kitzes and Wermer, 2006; Ewing et al., 2009; IPCC, 2001)[10] and an equivalence factor of 1.24 (Ewing et al., 2009).

To reiterate, Metro Vancouver's ecological footprint estimates, in global average hectares, the ecosystem area required on a continuous basis by the region's population to produce the food, fibre and other renewable resources it consumes and to sequester the carbon emissions it produces (i.e., emissions associated with

[5] We do not strictly adhere to the details outlined by the Eurostat Guidelines that call for an economy-wide material flow analysis to be consistent with national accounts. Because our focus is on the use of local data to generate a bottom-up urban metabolism, we give priority to locally generated data that records actual energy and materials flows versus the dollars spent on these items.

[6] Embodied energy means energy used in the manufacturing of goods consumed by Metro Vancouver residents.

[7] Embodied water, meaning water used in the manufacturing of goods consumed by Metro Vancouver residents, is outside the scope of this study. The chemicals used in the treatment of drinking water were also not considered.

[8] The Athena Institute is an internationally recognized Canadian not for profit organization that has developed a lifecycle impact assessment tool for buildings (http://www.athenasmi.org/tools/impactEstimator/).

[9] An equivalence factor is the ratio of average productivity in a given ecosystem category (e.g., cropland) to global average productivity. For example, if average cropland is approximately twice as productive as average productive land, a hectare of average cropland is equivalent to two gha.

[10] This accounts for carbon sequestration in the oceans as well.

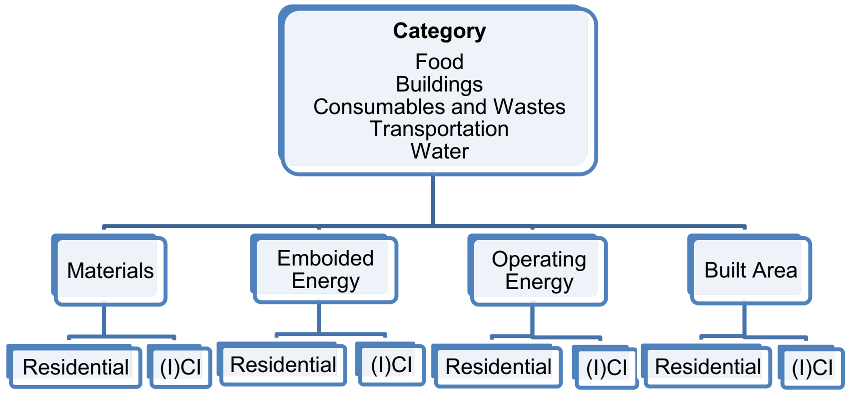

Fig. 1. Component structure of the integrated urban metabolism and ecological footprint assessment.

the production and consumption process) (see Fig. 2). Because of globalization and trade, this productive ecosystem area is scattered all over the planet. Representing the regional EF in global hectares facilitates comparison of regional demand for biocapacity to that of globally available per capita biocapacity (also measured in global hectares).

4.2. Data management

Studies of urban metabolism and the associated ecological footprint can be useful to local government planning and policy-analysts and decision-makers who seek to manage consumption and wastes. However, analysts should anticipate certain issues pertaining to data sources and data management. We describe below how we approached these challenges in the present study:

4.2.1. Accuracy

There are frequent discrepancies among data sources (Chambers et al., 2000). For example, in lifecycle analysis the same product produced by multiple countries might have varying embodied energy profiles depending on what method and energy source was used to manufacture and transport it. In this analysis, we used multiple lifecycle studies as data sources and searched for convergence among the data. We averaged the embodied energy values generated by various lifecycle assessment studies for a single product, excluding outliers.

4.2.2. Subsidiarity

When possible, we used the same data that local authorities already use to formulate their policies and management practices rather than data that has been interpolated or extrapolated from national data sets. Local authorities are more likely to trust data sources with which they are familiar and that describe actual local resource flows. Local data may also reveal important consumption-related nuances associated with the particular community being profiled.

4.2.3. Availability

Data gaps can be expected. For example, data on strictly local food consumption patterns are virtually non-existent. We therefore used national data to estimate the volumes of food and beverages consumed (both domestic and imported) and the associated demand for domestic transportation. The food miles (a.k.a. food kilometres) sub-component is probably significantly underestimated in this study.

4.2.4. Conservatism

In cases where two or more data sources meet general accuracy and subsidiarity criteria, we used the source that produced the most conservative material flows and eco-footprint estimates. When in doubt, it is better to err on the side of caution and thus avoid overstating consumption impacts (Wackernagel, 2009).

4.3. Limitations

Glass curtain walls are used extensively in Metro Vancouver high-rise architecture resulting in problems of thermal gain (summer south exposures) and loss in the City's temperate climate. The Athena Impact Estimator for Buildings software has the capacity to assess the embodied energy of glass in high-rise buildings

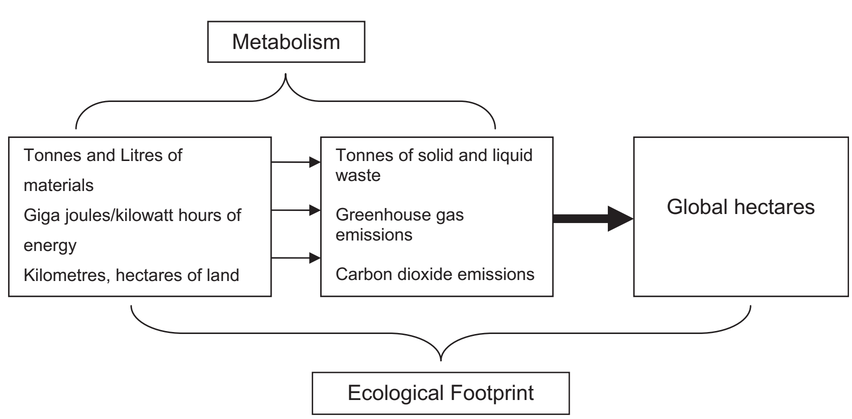

Fig. 2. Data input and output for integrated urban metabolism and ecological footprint assessment.

but we suspect that the software underestimated the total quantity of glass in Vancouver structures (and we did not undertake more sophisticated thermal modelling). Likewise, the embodied energy of concrete in the buildings, especially high-rise structures, also warrants further research given the significance of glass curtain walls. The embodied energy and operating energy requirements of buildings change over time. A more refined analysis that captures the age of the building stock could help improve future urban metabolism and ecological footprint assessments for the region (Cole, 2011).

The total lifecycle demands of products consumed by residents in Metro Vancouver vary with product origin—i.e., the methods and materials used, nature of energy inputs, etc. Although we reviewed the general literature on the process energy and materials embodied in a variety of consumer products, there were few lifecycle data on products made in specific countries that export to Canada. The refinement of lifecycle data could further sharpen the analysis.

We did not assess the total weight of materials discarded on an annual basis from the transportation sector, e.g. waste oil and scrap-materials from discarded car bodies. These data would contribute to the UMA. However, we did estimate the embodied energy of private motor vehicles and roads for purposes of completing the EFA and found it to be small relative to the impacts of fuel consumption.

Finally, the role of water in urban sustainability is probably under-represented by our method. Only the energy associated with the operation of water treatment facilities and distribution systems is counted, not the energy embodied in the physical plant. Nor did we account for the chemicals used to treat drinking water (relatively low quantities in Metro Vancouver). We did estimate the energy embodied in the region's water distribution and sewer collection systems, but had to make certain assumptions about pipe diameters and lifespans where data were lacking. Only the largest of the Region's six dams was included in the analysis. However, because the impact of this dam on the ecological footprint was marginal (due to the structure's 100-year amortization period) we believe that including the remaining dams would not significantly alter our findings.

Our analysis excluded contributions from national and provincial services that benefit all Canadians, but that are exercised outside the Metro region—e.g., the operation of parliament and provincial legislatures, the operations of the treasury and supreme courts, the military, etc. These extra-regional flows are beyond the scope of a regional metabolism study yet should be included in the population's ecological footprint estimate. As data improve, future studies might account for these activities for inclusion in ecofootprint estimates. Comparing our component-based findings for Metro Vancouver to an EF estimate based on the top-down compound method would provide a crude estimate of the government services contribution.

5. Results

Fig. 3 summarizes the urban metabolism and ecological footprint of Metro Vancouver for 2006. Water represents the largest material flow through Metro Vancouver followed by transportation fuel (3,338,721,000 L or 2,373,831 tonnes).[11] Buildings account for the largest energy flow and food comprises the largest ecological footprint. Carbon dioxide output from all components is 23 million tonnes, approximately 10 tonnes per capita.

Out of a total 2,636,850[12] tonnes of food that is produced, processed, distributed and purchased for final consumption by Metro Vancouverites, approximately one-third ends up lost or wasted due to spoilage and/or plate-waste (Statistics Canada, 2007). While we used the total tonnage of consumption to calculate the ecological footprint of the food component, figure three represents net food consumed in the region, 1,753,000 tonnes (Statistics Canada, 2007). Regional food waste data, i.e. plate waste, was estimated to be 372,700 tonnes (TRI, 2008) and bio-solids were estimated at 19,770 dry tonnes (Metro Vancouver, 2012). Together these data represent a total regional material flow for food of 2,145,470 tonnes. This falls short of the gross estimate presented above. We assume the difference (491,380 tonnes) is partly attributed to discarded materials through food processing (e.g., carcass, oil seed) and partly attributed to sewage (i.e., the liquid component separated out from bio-solids which were measured in dry tonnes). Again, to avoid double counting, that portion of the regional waste stream that comprises food waste (372,715 tonnes) is not included in the EFA of the consumables and waste component.

Approximately 60% of the water consumed (424,860,000 m^3) is for residential purposes. More wastewater (462,053,500 m^3) is treated than the total amount of drinking water distributed from the region's three watersheds. This is due to storm water inflow and infiltration and to a lesser degree: combined sanitary sewers and non-watershed drinking water sources, e.g. independently owned and operated municipal reservoirs and well water.[13]

Because of the large volume of fossil fuel consumed, transportation contributes the largest share to Metro Vancouver's greenhouse gas emissions. Most of the almost 3.3 billion L of fuel consumed is for ground transportation (2.6 billion L) of which 1,178,978 privately owned vehicles account for 75% (1.9 billion L) and 28,788 commercial vehicles account for 23% (591) million L. The public transit bus fleet, comprising 3358 vehicles, consumed approximately 56 million L of fuel and 30 million kWh of electricity. The West Coast Express commuter rail service and SeaBus passenger ferry service each accounted for approximately 1 million L of fuel, and the SkyTrain elevated rail service accounted for 117 million kWh of electricity. In addition to ground oriented transportation, Metro Vancouver residents also consumed a total of 788 million L of fuel for air travel.

Buildings comprise the largest energy flow in the urban metabolism (17,515,150 MWh) for electricity consumption and 81,932,260 GJ for space and water heating. An additional 13,550,600 GJ comprises the embodied energy within the building stock. Residential buildings account for 42% of electricity demand, 60% of space conditioning and water heating demand. Total carbon dioxide emissions from building operating energy is 4,610,600 tonnes, 58% associated with residential building operations. When we add carbon dioxide emissions associated with the embodied energy of the building stock, amortized over the life of the buildings,[14] the total carbon dioxide emissions associated with the buildings component increases to 6,440,660 tonnes per year.

The residential and commercial/institutional sectors each account for approximately half of the total material goods

[11] We use a conversion factor for gasoline (the dominant fuel in the region) of 0. 711 kg/l.

[12] See the Supplementary data file for additional details, including methods and references.

[13] The oldest municipalities in the region: New Westminster, Vancouver and Burnaby have combined sanitary sewers which are being phased out.

[14] We assume a 60 year lifespan for residential buildings and 75 years for commercial and institutional buildings. These values fall within the Canadian Standards Association Guideline on Durability in Buildings referenced by Metro Vancouver's Build Smart program (GVRD, 2001).

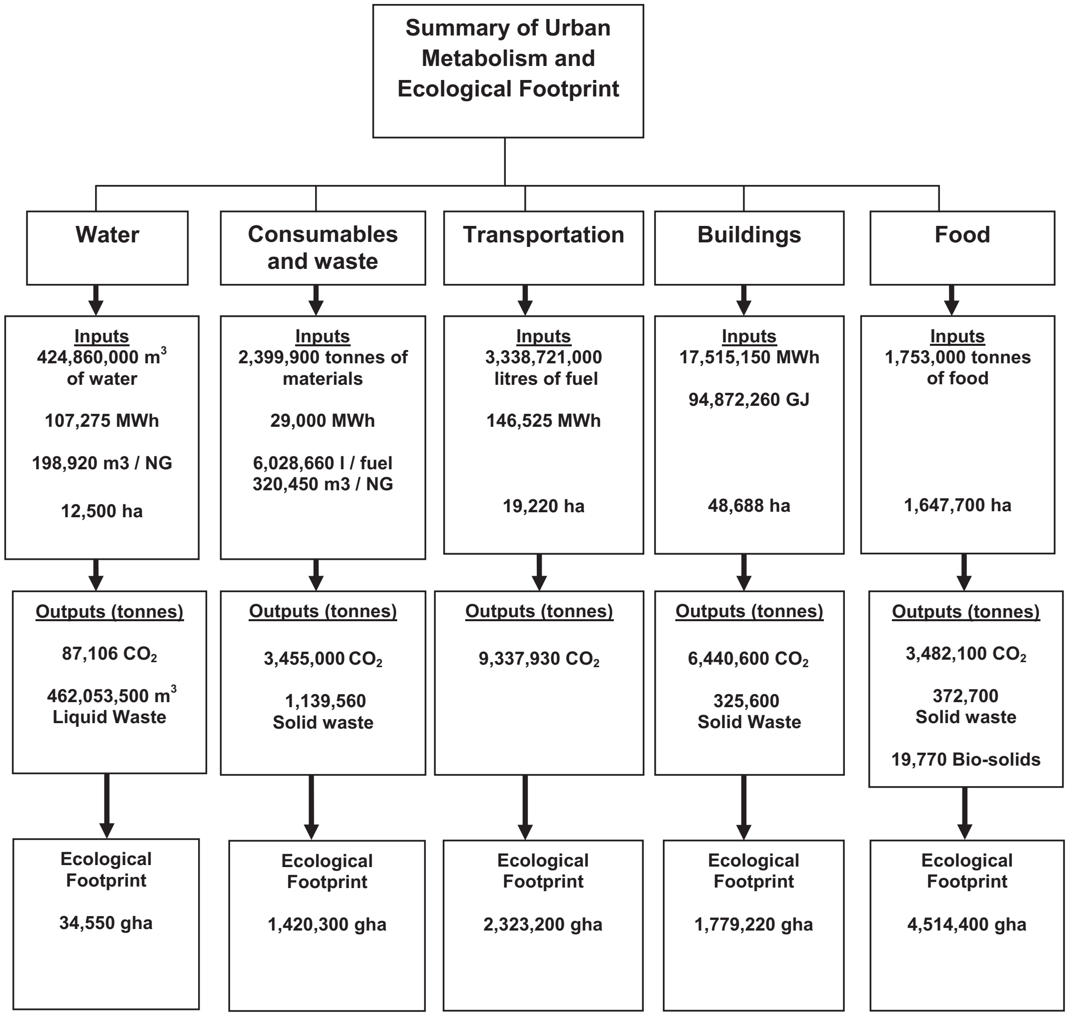

Fig. 3. Metro Vancouver metabolism and ecological footprint.

consumed. Although Metro Vancouver residents consumed approximately 2.4 million tonnes of products (more than one tonne per capita per year), they also recycled approximately 50% of their wastes. Organic wastes including: food, yard wastes, wood and paper comprise the largest portions of materials in the municipal solid waste stream.

Fig. 4 summarizes the total ecological footprint for Metro Vancouver by categories of consumption. 'Food' is the largest component of the ecological footprint because of the large area required to grow crops and fodder, and because of the energy intensity of food production, processing and distribution. Fig. 5 shows relative contributions of materials, embodied energy, operating energy and built area to each component in the ecological footprint.

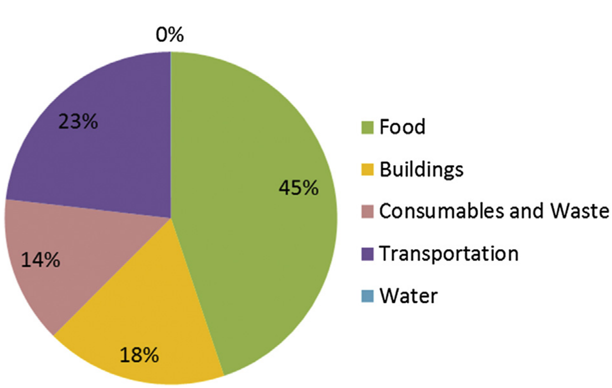

Fig. 4. Summary of Metro Vancouver's ecological footprint by component.

The second largest component in Metro Vancouver's ecological footprint is transportation. Operating energy for private, commercial and public transit fleets accounts for 6.1 million tCO_2, significantly more than the 2 million tCO_2 from the embodied energy in the vehicle fleet. Air travel by Metro Vancouver residents accounts for an additional 1.1 million tCO_2. (The regional share of the embodied energy of air craft was not estimated.) Metro Vancouverites drove a total of 1,211,124 motor vehicles (97% private vehicle, 2% commercial vehicles and 1% public transit vehicles) almost 13 billion km on approximately 6,200 km road-lanes. Private vehicles travelled an average of 10,355 km per vehicle per year, commercial vehicles an average of 16,593 km, and public transit vehicles 33,943 km (MOE, 2010).[15]

[15] Readers who are interested in other air emissions are referred to the region's Corporate Greenhouse Gas Emission Inventory (Metro Vancouver, 2008a) and Lower Fraser Valley Air Emissions Inventory Forecast and Backcast (Metro Vancouver, 2007b).

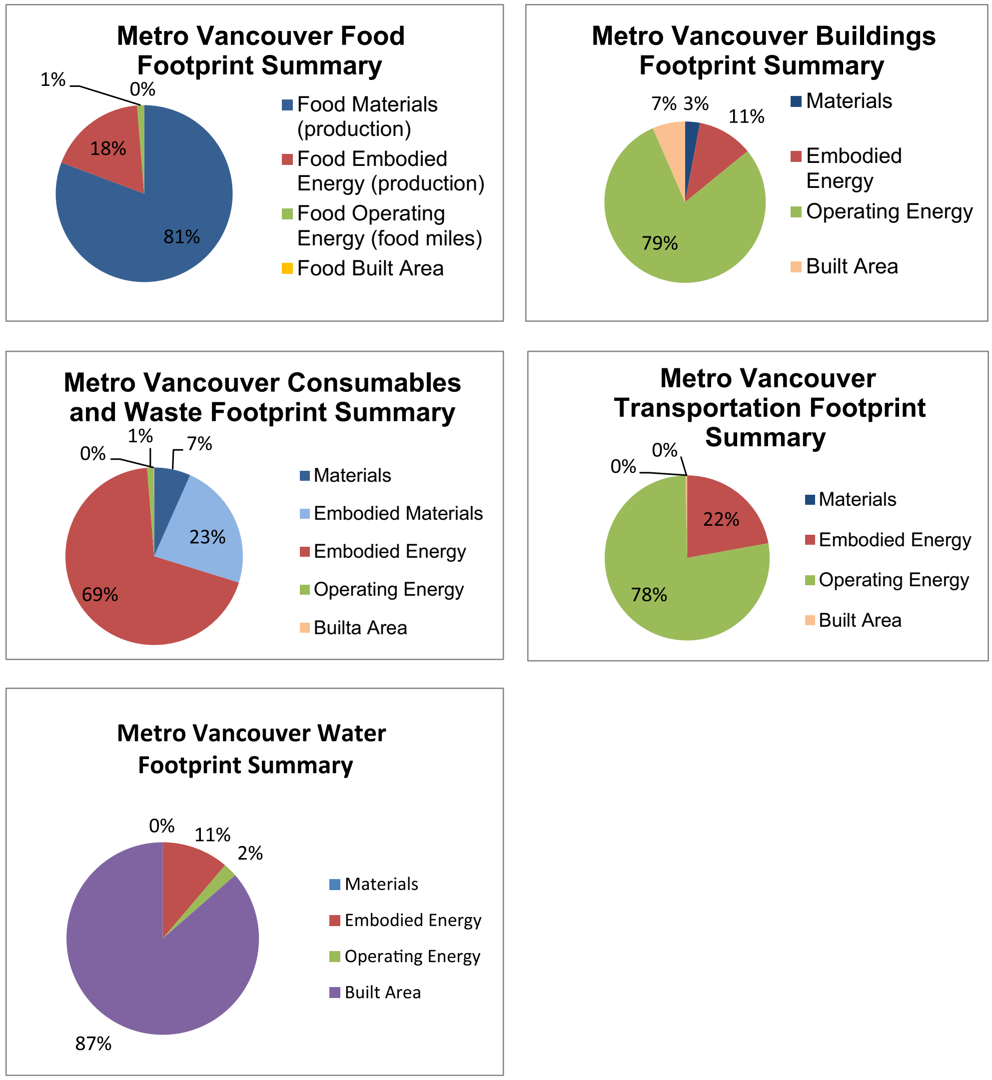

Fig. 5. Summary of Metro Vancouver's ecological footprint components.

The third largest component of Metro Vancouver's ecological footprint is buildings. Building operating energy, for both residential and commercial/institutional uses, accounts for approximately 5.6 million tCO_2. This is significantly greater than the annual amortized amount of embodied energy contained within the building stock accounting for only 793,900 tCO_2 (see Fig. 5). Approximately 7.4 billion kWh and 49 million GJ were used in residential buildings and 10 billion kWh and 32.3 million GJ were used in the institutional and commercial sector (MOE, 2010). We estimate that there are approximately 8.9 billion tonnes of materials in the regions building stock. Demolition and land clearing waste comprised 325,604 tonnes of material (Metro Vancouver, 2006b).

The fourth largest component is consumables and waste. Consumable products include such things as furniture, textiles, paper, plastic, glass, etc. The embodied energy of the products consumed accounts for the largest share of this component's footprint (69%) and approximately 3,221,957 tCO_2 (see Fig. 5). Indeed, indirect energy and material flows (i.e., embodied energy and embodied materials, meaning the up-stream material inputs used to manufacture consumable products) account for 92% of this component's ecological footprint. The remaining 8% is attributed to solid and liquid waste management, representing the consumables' end of life phase. Approximately 468,470 tCO_2 is attributed to treatment of municipal solid wastes that were either incinerated or sent to landfill. Of this amount, the majority (approximately 320,000 tCO_2) are attributed to the incineration of waste to produce heat and power at the Waste-to-Energy facility. The operating energy associated with both the management of solid and liquid wastes account for 15,000 tCO_2 and 67,133 tCO_2 respectively.

Finally, although water represents the largest material flow within the region, it has the smallest ecological footprint of all the components and represents less than 1% of Metro Vancouver's ecological footprint. This is due, in part, to the efficient design of Metro Vancouver's water distribution system that relies primarily on gravity to distribute water to the region, taking advantage of the watersheds relatively high elevation in the Coast Mountains. While only 3229 tCO_2 was generated from energy used in the treatment and supply of drinking water, the embodied energy associated with the 8000 km of pipes comprising the water distribution system account for 15,177 tCO_2 annually, assuming 305 mm cast iron pipes amortized over a lifespan of 50 years (Metro Vancouver, 2008b, also see Supplementary materials for details about method). This means that the embodied energy of the water supply system accounts for three quarters of the greenhouse gas emissions associated with the delivery of drinking water in the region on an annual basis. The estimated embodied energy of the pipes in the sewer system assumes a 50 year lifespan for concrete pipes with an average diameter of 100 mm for private, 300 mm for municipal and 1000 mm for regional pipes. The total embodied energy per year in the system accounts for 2000 tCO_2. This means that the embodied energy of the sewer system, when amortized over its lifespan, is very low. Finally, although the watershed lands surrounding the drinking water supply reservoirs are protected as ecological reserves, and therefore not counted in the ecological footprint estimate, we did include the service roads that traverse these lands. They alone account for 29,875 gha, equivalent to 87% of the water EF estimate.

The total ecological footprint estimated for Metro Vancouver was 10,054,400 gha. Recall, however, that the region spans an area of only 283,183 ha. This means that in 2006, the residents of Metro Vancouver relied on a productive land, aquatic and sea area that is approximately 36 times the size of the region itself. The ecological footprint for an average resident of Metro Vancouver is 4.75 gha (see Fig. 2). The components comprising the footprint include: food: 2.13 gha/ca, transportation 1.10 gha/ca, buildings 0.84 gha/ca, consumables and waste 0.68 gha/ca, and water 0.002 gha/ca. Again, services provided by senior governments are not included.

Fig. 6 represents Metro Vancouver's 2006 ecological footprint in terms of ecosystem type. The largest component of biocapacity demand, 59%, is for energy land (carbon sink ecosystems) and the second largest demand is for cropland. Together, energy and cropland comprise 90% of Metro's eco-footprint.

6. Discussion and conclusions

As the world urbanizes, cities must assume an ever-greater role in determining sustainability outcomes. This study introduces a detailed, bottom-up urban metabolism and ecological footprint analysis for a North American metropolitan region. We have explained why and how the methodological approach for subnational ecological footprint analysis based on economy-wide input–output calculations that are *de rigour* in Europe presents several challenges to local governments in the North American, and specifically the Canadian, context. We demonstrate the use of an alternative method, direct component approach, which we argue can work more effectively to address local government concerns and interests within the North American context.

Cities are the dominant form of human habitat, and most of the world's resources are either directly or indirectly consumed in cities. Within cities, income is highly correlated to consumption, but urban morphology and management policies also play a role. A dual approach to urban sustainability that focuses on: i) attempts to reduce overall energy and materials consumption by changes in urban morphology and management practices coupled with ii) the ethical and moral responsibility by high income consumers to reduce their personal consumption, is emerging in the urban sustainability literature (e.g., Newman and Jennings, 2008; Holden, 2004; McGranahan and Satterthwaite, 2003; Karr, 2000; von Weizsäcker et al., 1997; Haughton and Hunter, 1994). However, as representatives of some of the wealthiest economies in the world, North American cities have been slow to adopt metrics that reconcile urban consumption with available global biocapacity.

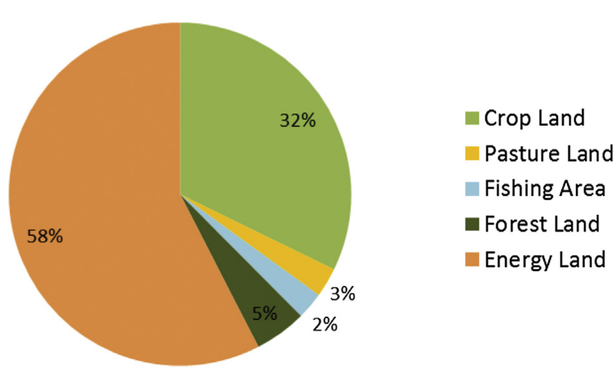

Fig. 6. Summary of Metro Vancouver ecological footprint by land type.

Urban sustainability analysis requires understanding the city's ecological resource base and the demands the city makes on an increasingly global hinterland. In North America, local government policy directed at urban sustainability is increasingly focussing on efficiency improvements coupled with demand side management strategies aimed at reducing energy and materials throughput (Roseland, 2012; Portney, 2003; Beatley, 2000). However, there are few, if any, examples in North America of cities that have policies aimed at reducing consumption to the level that science indicates would be within global ecological carrying capacity. This implies an average EF of 1.8 gha/capita (WWF, 2010). Exceptions could include Sonoma Mountain Village in the USA and the City of Vancouver (part of Metro Vancouver) that have identified one-planet living as a goal but are still in the early phases of implementation. To actually achieve this goal could require up to an 80% reduction in some consumption categories (von Weizsäcker et al., 2009). These exceptions aside, assessments of sustainability performance in North American cities seldom use metrics that situate the city in a global context, apart from attempts to raise awareness about climate change (EPA, 2010; Karlenzig et al., 2007; Portney, 2003). Inspired by the City of Vancouver's preference to use the direct approach articulated in this paper to assess their ecological footprint (Vancouver, 2011), we believe that developing a methodological approach appropriate to the North American context can help stimulate greater interest in both urban metabolism and ecological footprint analysis by North American cities.

Our objectives in this paper were to demonstrate the use of an urban metabolism framework to quantify the energy and materials consumed by the resident population of Metro Vancouver, and to compare the ecological footprint associated with that consumption to available per capita biophysical carrying capacity at the global scale. Building on Folke et al. (1997), Warren-Rhodes and Koenig (2001), Barrett et al. (2002), Aall and Norland (2005), Collins and Flynn (2006), and Dakhia and Berezowska-Azzag (2010), we have demonstrated how integrating urban metabolism analysis and ecological footprint analysis provides valuable information to local government planners and policy analysts on urban energy and material flows and on cities' appropriations of the world's shrinking biocapacity. As far as we are aware, this study is the most comprehensive assessment of Metro Vancouver's urban metabolism and ecological footprint to date and the first component-based ecological footprint analysis of a North American metropolitan region using the direct approach.

Metro Vancouver's ecological footprint in 2006 is equivalent to 10,054,400 gha. This represents an area that is 36 times the actual size of the region. Metro Vancouver residents have an average ecological footprint of 4.75 gha/ca. This is nearly double the world average biocapacity demand, estimated at 2.7 gha/ca, and almost three times the global per capita biocapacity supply, estimated at 1.8 gha/ca (WWF, 2010). In other words, if everyone consumed at a level commensurate with that of an average Metro Vancouver resident, we would need at least three additional Earth-like planets to supply the resources and assimilate the carbon dioxide emissions to support such a lifestyle. If the impacts of senior government services were also counted, the need would be greater still.

Our use of direct component ecological footprint analysis limits comparison with national level compound EF studies and component EF studies that use a sub-national input–output approach. That said, our findings are generally consistent with the results of studies elsewhere using other ecological footprint assessment methods (Scotti et al., 2009; Kissinger and Haim, 2008; Collins and Flynn, 2005; Barrett et al., 2002). Of course, our urban metabolism data can be compared freely to urban consumption data collected by similar means in other parts of the world.

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Appendix A. Supplementary material

Supplementary material related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2013.03.009.

References

Aall, C., Norland, I., 2005. The use of the ecological footprint in local politics and administration: results and implications from Norway. Local Environment 10 (2), 159–172.

Agudelo-Vera, C., Adriaan, A.M., Keesman, K., Rijnaarts, H., 2011. Resource management as a key factor for sustainable urban planning. Journal of Environmental Management 92, 2295–2303.

Baccini, P., 1997. A city's metabolism: towards the sustainable development of urban systems. Journal of Urban Technology 4 (2), 27–39.

Barrett, J., 2001. Component ecological footprint: developing sustainable scenarios. Impact Assessment and Project Appraisal 19 (2), 107–118.

Barrett, J., Vallack, H., Jones, A., Haq, G., 2002. A Material Flow Analysis and Ecological Footprint of York: Technical Report. Stockholm Environment Institute, Stockholm.

Barrett, J., Birch, R., Cherrett, N., Wiedmann, T., 2005. Exploring the application of the ecological footprint to sustainable consumption policy. Journal of Environmental Policy and Planning 7 (4), 303–316.

BC Stats, 2010. Greater Vancouver Regional District: Community Facts (BC Stats: 250-387-0327). BC Government Ministry of Citizens Services, Victoria BC. http://www.bcstats.gov.bc.ca/pubs/qrs/rd15.pdf (accessed on 24.08.10.).

Beatley, Timothy, 2000. Green Urbanism: Learning from European Cities. Island Press, Washington DC.

Berelowitz, L., 2005. Dream City: Vancouver and the Global Imagination. Douglas and McIntyre, Vancouver BC.

Bicknell, K., Ball, R., Cullen, R., Bigsby, H., 1998. New methodology for the ecological footprint with an application to the New Zealand economy. Ecological Economics 27, 149–160.

British Columbia (The Province of), 2011. Carbon Neutral BC, a First for North America. News Release 2011ENV0032–000805, June 30, 2011. http://www2.news.gov.bc.ca/news_releases_2009-2013/2011ENV0032-000805.htm (Viewed 30.07.12.).

Browne, D., O'Regan, B., Moles, R., 2008. Use of embodied energy and ecological footprinting to assess the global environmental impact of consumption in an Irish city-region. Journal of Environmental Planning and Management 51 (3), 447–470.

Browne, D., O'Regan, B., Moles, R., 2011. Material flow accounting in an Irish city-region 1992–2002. Journal of Cleaner Production 19 (9–10), 967–976.

Chambers, N., Simmons, C., Wackernagel, M., 2000. Sharing Nature's Interest: Ecological Footprints as an Indicator of Sustainability. Earthscan, London.

Chambers, N., Heap, R., Jenkin, N., Lewis, K., Simmons, C., Tamai, B., Vergoulas, G., Vernon, P., 2002. City Limits: a Resource Flow and Ecological Footprint Analysis of Greater London. Chartered Institute of Wastes Management, London, UK.

Cole, R., March 11, 2011. Personal Communication. Ray Cole, Professor. School of Architecture and Landscape Architecture, University of British Columbia.

Collins, A., Flynn, A., 2005. Reducing Cardiff's Ecological Footprint: a Resource Accounting Tool for Sustainable Consumption. Worldwide Fund for Nature, Surrey, UK. http://www.cardiff.gov.uk/content.asp?nav=2870, 3148, 6218, 6224&parent_directory_id=2865 (accessed 02.12.12.).

Collins, A., Flynn, A., 2006. Engaging with the ecological footprint as a decision-making tool: process and responses. Local Environment 12 (3), 295–312.

Curry, R., Maguire, C., Simmons, C., Lewis, K., 2011. The use of material flow analysis and the ecological footprint in regional policy-making: application and insights from Northern Ireland. Local Environment 16 (2), 165–179.

Dakhia, K., Berezowska-Azzag, E., 2010. Urban institutional and ecological footprint: a new urban metabolism assessment tool for planning sustainable urban ecosystems. Management of Environmental Quality: An International Journal 21 (1), 78–89.

Downton, P., 2009. Ecopolis: Architecture and Cities for a Changing Climate. Springer, Dordrecht, Netherlands.

EPA (Environmental Protection Agency), 2010. Planning for a Sustainable Future: a Guide for Local Governments. Environmental Protection Agency, United States. (Online resource). http://www.epa.gov/region02/sustainability/greencommunities/pdfs/planning_fora_sustainablefuture_nov2010.pdf (accessed 19.11.12.).

Eurostat, 2001. Economy-wide Material Flow Accounts and Derived Indicators: a Methodological Guide. European Communities, Luxembourg.

Ewing, B., Goldfinger, S., Oursler, A., Reed, A., Moore, D., Wackernagel, M., 2009. The Ecological Footprint Atlas 2009. Global Footprint Network, Oakland, CA.

Ewing, B., Reed, A., Galli, A., Kitzes, J., Wackernagel, M., 2010. Calculation Methodology for the National Footprint Accounts, 2010 Edition. Global Footprint Network, Oakland.

FAO (United Nations Food and Agriculture Organization), 2010. FAOSTAT: Production: Crops. http://faostat.fao.org/site/567/DesktopDefault.aspx.

Folke, C., Jansson, A., Larsson, J., Costanza, R., 1997. Ecosystem appropriation by cities. Ambio 26 (3), 167–172.

Girardet, H., 1999. Creating Sustainable Cities. In: Schumacher Briefing No. 2. Green Books, Devon, UK.

GVRD (Greater Vancouver Regional District), 2001. Best Practices Guide: Material Choices for Sustainable Design. Metro Vancouver, Burnaby BC.

GVTA (Greater Vancouver Transportation Authority), 2002. 2002 Program Plan Summary and Budget. Draft. March 25. TransLink, Burnaby BC. http://www.translink.ca/site-info/search-results.aspx (accessed on 14.12.10.).

Haughton, G., Hunter, C., 1994. Sustainable Cities. Jessica Kingsley Publishers Ltd, London.

Hendriks, C., Obernosterer, R., Muller, D., Kytzia, S., Baccini, P., Brunner, P., 2000. Material flow analysis: a tool to support environmental policy decision making. Case-studies on the city of Vienna and the Swiss lowlands. Local Environment 5 (3), 311–328.

Holden, E., 2004. Ecological footprints and sustainable urban form. Journal of Housing and the Built Environment 19 (1), 91–109.

Hoyer, K., Holden, E., 2003. Household consumption and ecological footprints in Norway: does urban form matter? Journal of Consumer Policy 26, 327–349.

IPCC (Intergovernmental Panel on Climate Change), 2001. Climate Change 2001: the Scientific Basis. Cambridge University Press, Cambridge, UK.

Jacobs, J., 1984. Cities and the Wealth of Nations. Vintage Books, New York.

Jones, P., 2006. The Mass Balance Movement. The Definitive Reference for Resource Flows within the UK Environmental Economy. Royal Society Wildlife Trusts. http://www.massbalance.org/resource/massbalance (accessed on 15.06.12.).

Karlenzig, W., Marquardt, F., White, P., Yaseen, R., Young, R., 2007. How Green is Your City? The SustainLane US City Rankings. New Society Publishers, Gabriola Island BC.

Karr, J., 2000. Health, integrity, and biological assessment: the importance of measuring whole things. In: Pimental, D., Westra, L., Noss, R. (Eds.), Ecological Integrity: Integrating Environment, Conservation and Health. Island Press, Washington DC.

Kennedy, C., Cuddihy, J., Engel-Yan, J., 2007. The changing metabolism of cities. Journal of Industrial Ecology 11 (2), 43–59.

Kennedy, C., Pincetl, S., Bunje, P., 2010. The study of urban metabolism and its applications to urban planning and design. Environmental Pollution 159, 1965–1973.

Kissinger, M., Haim, A., 2008. Urban Hinterlands: the case of an Israeli town ecological footprint. Environment Development and Sustainability 10 (4), 391–405.

Kitzes, J., Wermer, P., 2006. Technical Memorandum: the Carbon Conversion Factor in Ecological Footprint Accounts: Calculations and Sources of Variability. Global Footprint Network, Oakland CA.

Lenzen, M., 2001. Errors in conventional and input-output based life-cycle inventories. Journal of Industrial Ecology 4 (4), 127–148.

Lenzen, M., Lundie, S., Bransgrove, G., Charet, L., Sack, F., 2003. Assessing the ecological footprint of a large metropolitan water supplier: lessons for water management and planning towards sustainability. Journal of Environmental Planning and Management 46 (1), 113–141.

Levett, R., 1998. Footprinting: a great step forward, but tread carefully – a response to Mathis Wackernagel. Local Environment 3 (1), 67–74.

McGranahan, G., Satterthwaite, D., 2003. Urban centres: an assessment of sustainability. Annual Review of Environment and Resources 28, 243–274.

Mcmanus, P., Haughton, G., 2006. Planning with ecological footprints: a sympathetic critique of theory and practice. Environment and Urbanization 118, 113–127.

Metro Vancouver, 2006a. Metro Vancouver's 2006 Generalized Land Use by Municipality (2006 Land Use Fact Sheet). Metro Vancouver, Burnaby BC. http://

www.metrovancouver.org/about/publications/Publications/KeyFacts-LandusebyMunicipality-2006.pdf (accessed on 11.08.10.).
Metro Vancouver, 2006b. Recycling and Solid Waste Management 2006 Report. Greater Vancouver Sewerage and Drainage District, Burnaby BC.
Metro Vancouver, 2007a. Minutes of the Regular Meeting of the GVRD Land Use and Transportation Committee Held on Friday, July 6, 2007. Greater Vancouver Regional District, Burnaby BC. http://www.metrovancouver.org/boards/Land%20Use%20and%20Transportation%20Committee/Land_Use_and_Transportation-July_6_2007-Minutes.pdf (Viewed on 01.08.12.).
Metro Vancouver, 2007b. 2005 Lower Fraser Valley Air Emissions Inventory and Forecast and Backcast. Metro Vancouver, Burnaby BC.
Metro Vancouver, 2008a. Metro Vancouver Corporate 2005 Greenhouse Gas Emission Inventory, Backcast and Forecast. Metro Vancouver, Burnaby BC.
Metro Vancouver, 2008b. Water Consumption Statistics Report, 2008 ed. Metro Vancouver, Burnaby BC.
Metro Vancouver, 2012. Treatment Plants. (Online resource). http://www.metrovancouver.org/services/wastewater/treatment/Pages/treatmentplants.aspx (accessed 07.12.12.).
MOE (Ministry of Environment), 2010. Community Energy and Emissions Inventory: Metro-vancouver Regional District, Updated 2007 Community Energy and Emissions Inventory. Province of British Columbia, Victoria BC. June 16, 2010, 1–8. http://www.env.gov.bc.ca/cas/mitigation/ceei/index.html (accessed 22.08.10.).
Newman, P., 2006. The environmental impacts of cities. Environment and Urbanization 18 (2), 275–295.
Newman, P., Jennings, I., 2008. Cities as Sustainable Ecosystems: Principles and Practice. Island Press, Washington DC.
Newman, P., Kenworthy, J., 1999. Sustainability and Cities: Overcoming Automobile Dependence. Island Press, Washington DC.
Newman, P., Beatley, T., Boyer, H., 2009. Resilient Cities: Responding to Peak Oil and Climate Change. Island Press, Washington DC.
Nijkamp, P., Rossi, E., Vindign, G., 2004. Ecological footprints in plural: a meta-analytic comparison of empirical results. Regional Studies 38 (7), 747–765.
Onisto, L., Krause, E., Wackernagel, M., 1998. How Big is Toronto's Ecological Footprint? Centre for Sustainable Studies and City of Toronto, Toronto, Ont.
Piombini, M., 2011. A Profile of First Nations, Tribal Councils, Treaty Groups and Alliances with Interests Within Metro Vancouver and its Member Municipalities. On-table Information Item 4.1: Mayors Committee Meeting: March 16, 2011. Metro Vancouver, Burnaby BC. http://www.metrovancouver.org/boards/Mayors%20Committee/Mayors_Committee-March_16_2011-On_Table_Items.pdf (accessed 24.06.11.).
Portney, K., 2003. Taking Sustainable Cities Seriously: Economic Development, the Environment, and Quality of Life in American Cities. Massachusetts Institute of Technology Press, Cambridge Massachusetts.
Ravetz, J., 2000. Integrated assessment for sustainability appraisal in cities and regions. Environmental Impact Assessment Review 20 (1), 31–64.
Rees, W.E., 1992. Ecological footprints and appropriate carrying capacity: what urban economics leaves out. Environment and Urbanization 4 (2), 121–130.
Rees, W.E., 1997. Is "Sustainable city" an oxymoron? Local Environment 2, 303–310.
Rees, W.E., 2003. Understanding urban ecosystems: an ecological economics perspective (Chapter 8). In: Berkowitz, A., Nilon, C., Howleg, K. (Eds.), Understanding Urban Ecosystems. Springer-Verlag, New York, pp. 115–136.
Rees, W.E., 2009. The ecological crisis and self delusion: implications for the building sector. Building Research and Information 37 (3), 300–311.
Rees, W.E., 2011. Getting serious about urban sustainability: eco-footprints and the vulnerability of twenty-first-century cities (Chapter 5). In: Bunting, T., Filion, P., Walker, R. (Eds.), Canadian Cities in Transition: New Directions in the Twenty-first Century. Oxford University Press, Toronto, pp. 70–86.
Rees, W.E., 2012. Cities as dissipative STRUCTURES: global change and the vulnerability of cities. In: Weinstein, M.P., Turner, R.E. (Eds.), Sustainability Science: the Emerging Paradigm and the Urban Environment. Springer, New York.
Roseland, Mark, 2012. Toward Sustainable Communities: Solutions for Citizens and Their Governments, fourth ed. New Society Publishers, Gabriola Island, BC.
Rotmans, J., van Asselt, M., 2000. Towards an integrated approach for sustainable city planning. Journal of Multi-criteria Decision Analysis 9, 110–124.
Sahely, H.R., Dudding, S., Kennedy, C.A., 2003. Estimating the urban metabolism of Canadian cities: Greater Toronto Area case study. Canadian Journal of Civil Engineering 30 (2), 468–483.
Scotti, M., Bondavalli, C., Bodini, A., 2009. Ecological footprint as a tool for local sustainability: the municipality of Piacenza (Italy) as a case study. Environmental Impact Assessment Review 29, 39–50.
Simmons, C., Chambers, N., 1998. Footprinting UK households: how big is your ecological garden? Local Environment 3, 355–362.
Sonoma Mountain Village, 2012. SOMO Living. One Planet. One Place. (Online resource). http://www.sonomamountainvillage.com/community/index.php (accessed on 07.12.12.).
Statistics Canada, 2006a. Census Data: Population, Urban and Rural, by Province and by Territory. http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/demo62a-eng.htm.
Statistics Canada, 2006b. Census Data: Community Profiles. Vancouver, British Columbia (Census Metropolitan Area). http://www12.statcan.ca/census-recensement/2006/dp-pd/prof/92-591/details/page.cfm?Lang=E&Geo1=CMA&Code1=933__&Geo2=PR&Code2=59&Data=Count&SearchText=Vancouver&SearchType=Begins&SearchPR=01&B1=All&GeoLevel=&GeoCode=933.
Statistics Canada, 2007. Food Statistics 2006 Catalog No. 21-020-X. http://www.statcan.gc.ca/bsolc/olc-cel/olc-cel?catno=21-020-X&CHROPG=1&lang=eng.
TRI (Technology Resource Inc.), 2008. Solid Waste Composition Study. Metro Vancouver, Burnaby BC.
UNPD (United Nations Department of Economics and Social Affairs, Population Division), 2009. World Urbanization Prospects: the 2009 Revision: File 2: Percentage of Population Residing in Urban Areas by Major Area, Region and Country, 1950–2050. http://esa.un.org/unpd/wup/index.htm.
Vancouver (City of), 2011. Achieve a One-planet Ecological Footprint in Greenest City 2020 Action Plan. Vancouver, City of Vancouver, pp. 48–53. http://vancouver.ca/greenestcity/PDF/GC2020ActionPlan-Goal7.pdf (accessed on June 17, 2012).
von Weizsäcker, E., Lovins, A., Lovins, H., 1997. Factor Four: Doubling Wealth Halving Resource Use: the New Report to the Club of Rome. Earthscan, London.
von Weizsäcker, E., Hargroves, C., Smith, M., Desha, C., Stasinopoulos, P., 2009. Factor 5: Transforming the Global Economy Through 80% Increase in Resource Productivity. Earthscan, London.
Wackernagel, M., 1998. The ecological footprint of Santiago de Chile. Local Environment 3 (1), 7–25.
Wackernagel, M., 2009. Methodological advances in footprint analysis. Ecological Economics 68 (7), 1925–1927.
Wackernagel, M., Rees, W.E., 1996. Our Ecological Footprint: Reducing Human Impact on the Earth. New Society Publishers, Gabriola Island, BC.
Wackernagel, M., Kitzes, J., Moran, D., Goldfinger, S., Thomas, M., 2006. The ecological footprint of cities and regions: comparing resource availability with resource demand. Environment and Urbanization 18 (1), 103–112.
Warren-Rhodes, K., Koenig, A., 2001. Ecosystem appropriation by Hong Kong and its implications for sustainable development. Ecological Economics 39, 347–359.
Wiedmann, T., Barrett, J., 2010. A review of the ecological footprint indicator – perceptions and methods. Sustainability 2 (6), 1645–1693.
Wiedmann, T., Minx, J., Barrett, J., Vanner, R., Ekins, P., 2006. Sustainable Consumption and Production – Development of an Evidence Base. Project Reference SCP001-Resource Flows. Project Code CTX0505/SCP1.1. Department of Environment, Food and Rural Affairs (DEFRA). http://www.resource-accounting.org.uk/uploads/Reports/scp001.pdf (Viewed 30.07.12.).
Wheeler, S., Beatley, T. (Eds.), 2009. The Sustainable Urban Development Reader, second ed. Routledge: Taylor and Francis Group, London.
Wilson, M., Anielski, M., 2005. Ecological Footprints of Canadian Municipalities and Regions. Federation of Canadian Municipalities, Ottawa. http://www.fcm.ca/Documents/reports/Ecological_Footprints_of_Canadian_Municipalities_and_Regions_EN.pdf (Viewed on 28.05.12.).
Wilson, J., Grant, J., 2009. Calculating ecological footprints at the municipal level: what is a reasonable approach for Canada? Local Environment 14 (10), 963–979.
Wolman, A., 1965. The metabolism of cities. Scientific American 213 (3), 179–190.
WWF (World Wide Fund for Nature), 2010. Living Planet Report. World Wide Fund for Nature, Gland Switzerland.
Xu, S., San Martin, I., 2010. Ecological Footprint for the Twin Cities: Impacts of Consumption in the 7-county Metro Area. Metropolitan Design Centre, College of Design, University of Minnesota, Minnesota. http://www.designcenter.umn.edu/research/documents/TCFPwebfinal.pdf (Viewed on 28.05.12.).