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Communication

Articulating a trans-boundary infrastructure supply chain greenhouse gas emission footprint for cities: Mathematical relationships and policy relevance

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ABSTRACT

This paper compares the policy relevance and derives mathematical relationships between three approaches for GHG emissions accounting for cities. The three approaches are: (a) Purely-Geographic Inventory, (b) Trans-boundary Community-Wide Infrastructure Footprint (CIF), and (c) Consumption-Based Footprint (CBF). Mathematical derivations coupled with case study of three US communities (Denver Colorado, Routt Colorado, and Sarasota Florida), shows that no one method provides a larger or more holistic estimate of GHG emissions associated with communities. A net-producing community (Routt) demonstrates higher CIF GHG emissions relative to the CBF, while a net-consuming community (Sarasota) yields the opposite. Trade-balanced communities (Denver) demonstrate similar numerical estimates of CIF and CBF, as predicted by the mathematical equations. Knowledge of community typology is important in understanding trans-boundary GHG emission contributions.

1. Introduction

This paper addresses the allocation of greenhouse gas (GHG) emissions to various segments of society – producers, consumers, nations and cities – using different types of GHG emission footprints. The focus is on footprints pertaining to cities where many local initiatives to mitigate GHG emissions are underway (e.g., Mayors Climate Protection Agreement (MCPA), 2009; World Mayors Summit on Climate (WMSC), 2010).

The assignment of GHGs associated with the life-cycle of a product to a unit of production has been well-understood in the industrial ecology literature. Recent efforts have incorporated such life-cycle approaches to inform GHG reporting by corporations (producers) using the concept of scopes (WRI, 2004, 2011).

Consumption-based footprints (CBF) have also been articulated, wherein GHGs in commercial/industrial sectors are not assigned to producers, but to economic final consumption represented by household expenditures, government expenditures, and business capital investments. At the national scale, GHG embodied in trade between nations has been assigned to final consumption sectors in each nation, yielding CBF of nations (Peters and Hertwich, 2008). More recently, downscaled input–output (IO) models are being tested to develop CBF at the city- and state-scales (Stanton et al., 2011). Final consumption is dominated ($>80\%$) by household expenditures; hence several CBF studies develop GHG footprints of households using readily available consumer expenditure surveys (CE) and tracing the life-cycle GHGs associated with these expenditures using nationally-aggregated EIO-LCA (e.g., Weber and Matthews, 2008; Jones and Kammen, 2011).

When nations report GHG emissions, however, territorial accounting is employed, i.e., direct GHG emissions within national boundaries are reported in national GHG inventories (e.g., EPA, 2010). These territorial accounts are often referred to as production-based accounts, but also include final household consumption of fuel (i.e., fuel combustion). Territorial or in-boundary accounts (IB) yield GHG intensity per unit productivity of nations, but are also reported on a per capita basis, although GHG^{IB}/capita does not reflect the worldwide emissions associated with the residents of any nation.

There is wide recognition that strict territorial accounting of GHGs such as that employed in national-scale GHG accounting is not by itself meaningful for the smaller spatial scale of cities (e.g., Ramaswami et al., 2008, 2011; Kennedy et al., 2009). Cities are relatively small compared to nations, and also small compared to the larger-scaled infrastructure systems in which they are embedded, e.g., transportation commutersheds, water-, power- and fuel-supply networks. Consequently, important infrastructures that provide key goods and services to cities are artificially truncated at the city's geographic boundary. Thus, GHGs from energy use in these key trans-boundary infrastructures often occurs outside the boundary of the

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city using these services (e.g., electricity or petrofuels used in a city are produced in power-plants and refineries located outside). While there is intuitive consensus that GHGs from trans-boundary power generation should be allocated to the city using that electricity (e.g., Wuppertal Institute for Climate, 2009), there is no systematic consensus on the treatment of other key infrastructures.

In recent years, several cities and associated research papers have started incorporating the embodied energy in a number of different infrastructure supply-chains serving the city as a whole (Table 1), an approach that we are formally articulating in this paper as the trans-boundary Community-Wide Infrastructure Footprint (CIF). CIF studies demonstrate that trans-boundary energy use in key infrastructures serving cities can be as large, or larger than, the direct energy use and GHGs within city boundaries (Ramaswami et al., 2008; Kennedy et al., 2009; Hillman and Ramaswami, 2010).

CIF supports cross-scale infrastructure planning for low-carbon cities addressing infrastructure provisioning for both producers (e.g., industries) and consumers (e.g., households) co-located in a community, i.e., the provision of electricity, fuel, transit, airports, water and wastewater services in a city is planned for the community as a whole–for homes, industries and businesses, together. In contrast, CBF focuses more narrowly on city resident household- and government-consumption, examining their full supply-chain impacts world-wide; local industrial/commercial activities that support visitors or export goods/services are not included in that city's CBF (see Fig. 1). Increasingly, researchers are suggesting that both a CIF and a parallel

Table 1
Examples of community-wide GHG emission studies in cities that incorporated infrastructure supply-chains serving the whole community. All studies cited here are based on local energy use and GHG data, and not derived from IO tables.

Researchers	Cities/Urban areas included in study	Trans-boundary infrastructures serving whole community						
		Electricity	Water	Fuel	Cement	Food	Air travel	Freight
Sovacool and Brown (2010)	Beijing, Delhi, Jakarta, London, Los Angeles, Manila, Mexico City, New York, Sao Paolo, Seoul, Singapore, Tokyo	✓		✓				
Ramaswami et al. (2008)	Denver	✓	✓	✓	✓	✓	✓	
Ngo and Pataki (2008)	Los Angeles	✓	✓			✓		
McGraw et al. (2010)	Chicago	✓						✓
Kennedy et al. (2009)	Bangkok, Barcelona, Cape Town, Denver, Geneva, London, Los Angeles, New York, Prague, Toronto	✓		✓			✓	
Hillman and Ramaswami (2010)	Arvada, Austin, Boulder, Denver, Fort Collins, Minneapolis Portland, Seattle	✓	✓	✓	✓	✓	✓	✓
Baynes et al. (2011)	Melbourne	✓	✓	✓	✓	✓	✓	
Chavez et al. (2012)	Delhi	✓	✓	✓	✓	✓	✓	
Mairie de Paris (2009)	Paris	✓			✓	✓	✓	
Sharma et al. (2002)	Calcutta, Delhi	✓			✓	✓		

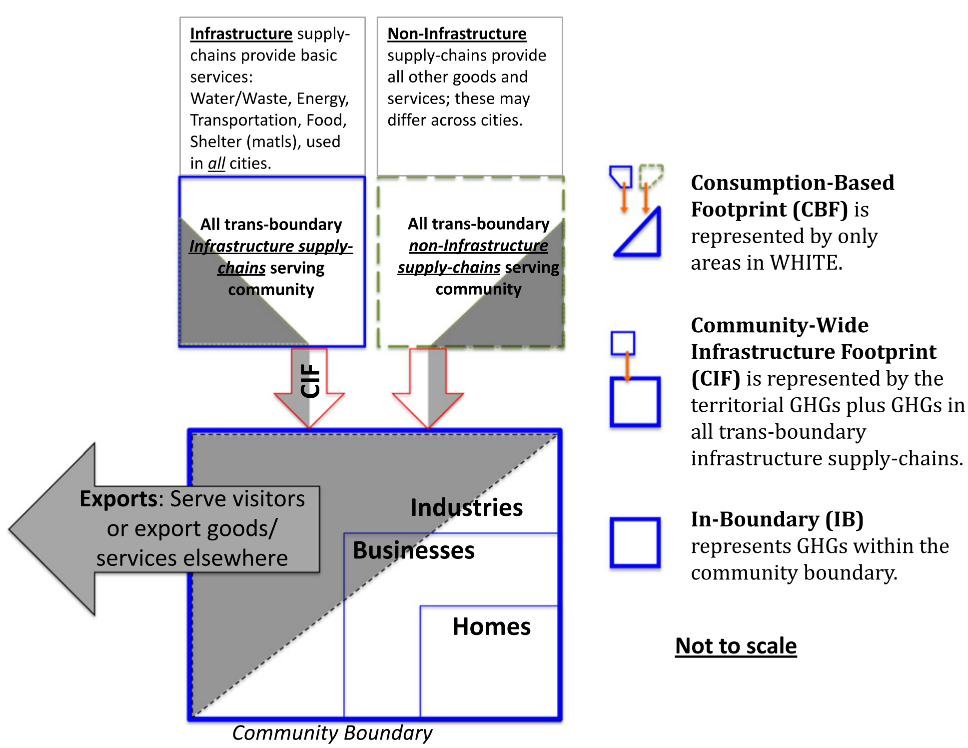

Fig. 1. In-boundary and trans-boundary components of community-wide infrastructure footprints (CIF) and consumption-based footprints (CBF) of a community. The community consists of co-located homes, commercial establishments and industries within a boundary, some of which produce locally to serve local homes (shown in white), while others serve visitors or physically export goods or services to other communities (shown in grey). Exports include infrastructure and non-infrastructure exports. Supply-chains associated with local consumption are shown in WHITE, and supply-chains associated with exports are shown in GRAY.

CBF be employed to inform a broad spectrum of GHG mitigation strategies in cities (Baynes et al., 2011; Ramaswami et al., 2011). Cities in the US and UK are also developing protocols to implement a CIF and a CBF for their communities (BSI, 2012; ICLEI, 2012) However, the two footprint approaches are often considered to be entirely separate, when in fact, they are mathematically related in important ways. The objectives of this paper are to:

- Articulate the CIF in the context of purely territorial (In-boundary, IB) and purely consumption-based (CBF) accounting, addressing the policy relevance of all three approaches.
- Elucidate mathematical relationships between the three methods, enabling approximations and simplifications between them, as appropriate.

2. Articulating an infrastructure supply-chain footprint for cities

Community-wide infrastructure footprints (CIF) overcome the shortcomings of strictly boundary-limited approaches by reporting direct community-wide energy use and GHGs within city boundaries plus trans-boundary life-cycle GHG emissions associated with essential infrastructures serving the community as a whole.

Introduced by Ramaswami et al. (2008), CIF quantifies both in-boundary and trans-boundary GHGs from essential infrastructures defined as those that provision electricity, gas, commuter- and airline-travel, transport fuels, drinking water, wastewater/waste management, food supply, and building construction materials in cities. Hillman and Ramaswami (2010) further included long-distance freight infrastructure in eight US cities. Baynes et al. (2011), and Chavez et al. (2012) evaluated most of these trans-boundary infrastructures for Melbourne and Delhi, respectively. Several others incorporated trans-boundary GHGs from a smaller subset of infrastructures (Table 1). While studies have included different infrastructure supply-chains, articulating the method explicitly as a <u>community-wide infrastructure supply-chain GHG emissions footprint</u> for cities, while elucidating its policy relevance, helps clarify the method.

In formalizing the CIF method, Chavez (2012) proposes criteria to identify what constitutes "essential infrastructure". Similar to the case of electricity, we propose an infrastructure be considered essential when community productivity (Gross Domestic Product (GDP)) is highly correlated with community-wide use of that infrastructure, while the production/export of these services is patchy/sparse across multiple cities and hence poorly correlated with city-GDP (Fig. 2). Applying these criteria to 21 US communities affirmed that key infrastructures include provision of electricity, fuel, food, cement, and iron/steel; the water/WW sector was not highly correlated with productivity however was deemed essential, as was travel. These infrastructures, covered by CIF, are widely accepted as essential for any city to function, addressing both productivity as well as basic needs for water, energy, mobility, food and shelter. GHG emissions from the in-boundary components of these infrastructures are already being measured and reported by several cities (e.g., ICLEI). The purpose of CIF is to promote standardized accounting of these essential infrastructures in all cities to promote sustainable urban infrastructure planning, irrespective of city-size/boundary differences. In contrast, other sectors such as Furniture, Appliances and other consumables are not essential to production activities in all cities. Although the vocabulary of food production as an infrastructure sector is fuzzy, cities are indeed considering "green infrastructure" for urban food production (Grimm and Wagner, 2009). Moreover, food may also be viewed as another form of energy required to be productive.

Care must be taken to avoid double counting when incorporating supply-chains GHGs in CIF. Most infrastructures are large and visibly distinct (e.g., oil refineries, power-plants, water treatment plants), such that their GHGs can be carefully allocated based on use/demand. In the case of food production, CIF incorporates GHGs only from agriculture/livestock (i.e., farm-to-gate GHGs only) to avoid double count; any small (limited) agriculture within the city boundary can be carefully addressed avoiding double-count (Chavez et al., 2012).

Consumption-based GHG footprints (CBF) go beyond allocating infrastructure, to allocate the trade of all goods and services across cities, however, focusing only on supply-chains serving final consumption (see Fig. 1). As a result, local businesses and industries that serve visitors or produce goods and services for export are allocated out, and excluded from the city's CBF.

Both CIF and CBF provide different types of policy-relevant information. CIF is particularly relevant to future infrastructure planning for the community as a whole, because urban infrastructures are always designed to serve homes–businesses–industries in a city considered together. The potential for greening of infrastructures and supply-chains, made visible by the CIF, can be facilitated by multi-level governance (Betsill and Bulkeley, 2006) from the city- to region- to state- and national-scales, e.g., promoting alternate fueled vehicles in cities requires government facilitation at all levels including refueling stations within cities as well as adequate fuel production supply-chains outside. CIF is also effective in addressing multi-scale risks that arise from fossil energy use by all sectors in a city–homes, businesses and industries. These risks range from indoor air pollution from cook-stoves, to local-scale air pollution from traffic and industrial emissions, to regional haze and global climate change induced risks to a city's coupled water-energy system (Ramaswami et al., 2012). Thus CIF addresses trans-boundary GHG emissions, as well as local supply-chain and human health risks from community-wide infrastructure-related activities.

In contrast, CBF conceptually provides the most holistic assessment of per capita GHG emissions arising from all personal consumption activities, going beyond infrastructure. CBF can promote shifts in consumption behaviors of households and governments, and encourage purchases from cleaner producing regions, i.e., greening the supply-chain beyond the infrastructure sectors already addressed in CIF. However, because CBF excludes visitor activity and exported business–industrial output in a community, and their supply-chains (gray areas, Fig. 1), the stimulus to greening the supply-chain is limited to households and governments. Table 2 summarizes the policy relevance of the purely in-boundary accounting (IB), the CIF, and the CBF.

3. Mathematical relationships

CIF and CBF are often treated as completely separate methods, when in fact they are mathematically related. This section highlights mathematical relationships between the two using a single-region IO (SRIO) model for simplicity of illustrating the derivation. A uni-directional multi-region IO (MRIO) derivation is provided in the appendix.

3.1. SRIO derivation

Consumption-based GHG emissions, GHG^{CBF}, are computed as (Peters and Hertwich, 2008):

$$GHG^{CBF} = \underbrace{\{[B][L]+[EF^{use}]\}}_{\text{Life-cycle/Supply-chain GHG Emissions Intensity}+\text{Use Phase Emissions Factor}} \times \underbrace{\{[F]+[M_F]\}}_{\text{Total Final Consumption in Community}} \quad (1)$$

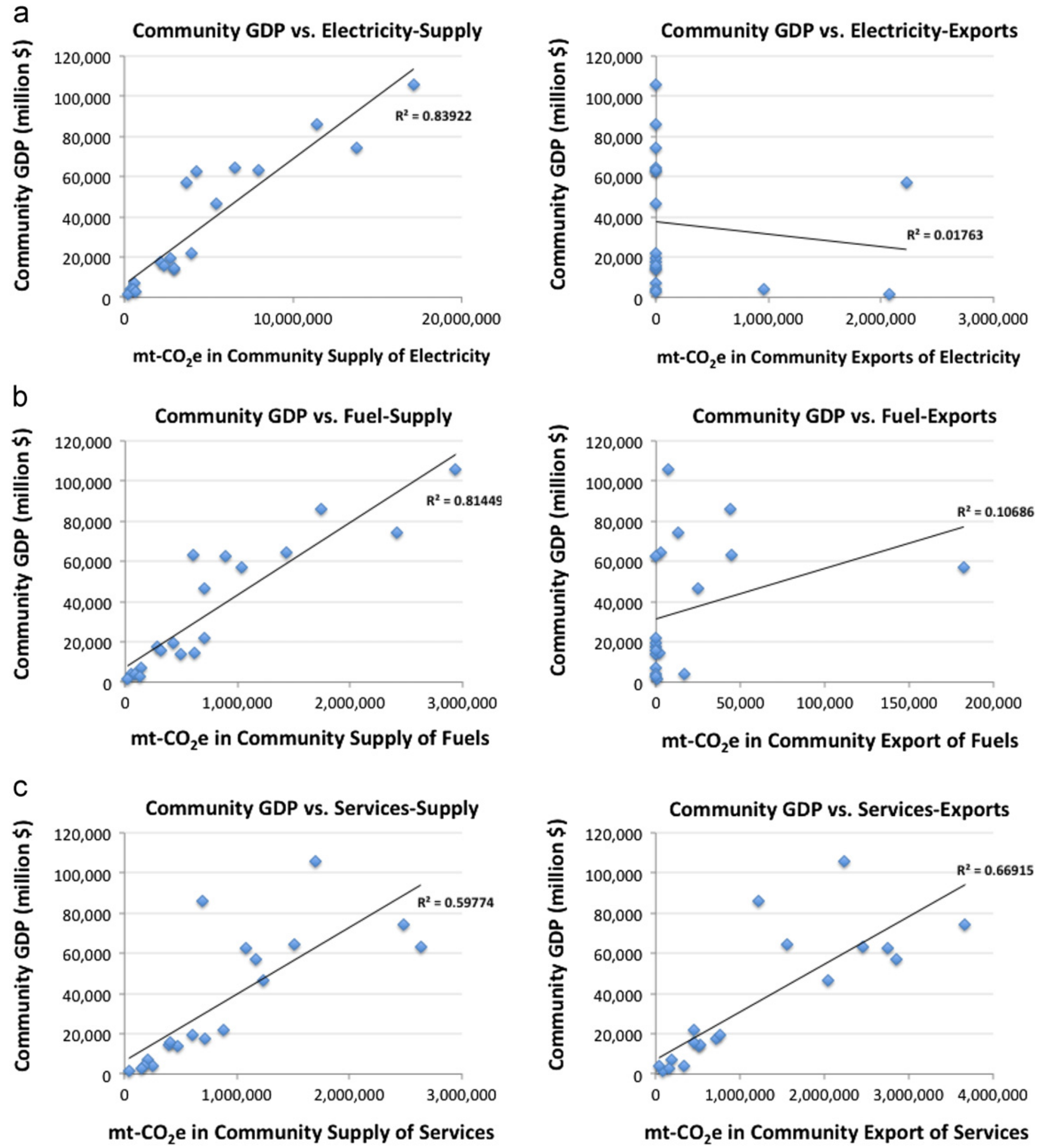

Fig. 2. Preliminary analysis of the correlation between community GDP (production) vs. community-wide Supply, and community GDP vs. community Exports of various sectors: (a) Electricity; (b) Petroleum Refining; and (c) Services. The supply of sectors such as electricity and fuel refining correlated with community productivity (GDP) for all 21 US cities studied by Chavez (2012) while the production of these important sectors occurred sparsely in very few cities. Sectors with characteristics similar to electricity and fuel refining are allocated based on their community-wide use in a community's infrastructure footprint (CIF).

where: **F** is the portion of local final consumption met by local production, and $\mathbf{M_F}$ is the portion of local final consumption met by imports. **F** plus $\mathbf{M_F}$ yields total final consumption by households, government, and capital investments in the community. **L** is the total requirements matrix *($-output/$-final demand)* representing inter-industry requirements (direct and indirect) of domestically produced and imported goods/services, which in an SRIO model, are assumed to be equal to the national ***L***. **B** is the GHG intensity vector *(mt-CO$_2$e/$-output)* (CMU, 2008), assumed the same across all regions in an SRIO. $\mathbf{EF^{use}}$ is the use phase combustion emissions factor of fuels consumed by final consumption (e.g., natural gas, transport fuels).

Next, the production balance of a community's economy is written as:

$$\underbrace{[L]\{[F]+[E]\}}_{\text{Total Requirements (TR) of Final Demand}} = \underbrace{[L][M_Z]}_{\text{TR of Imports to Local Industries}} + \underbrace{[Z]+[F]+[E]}_{\text{Total Local Output (TLO)}} = [TLO]+[L][M_Z] \quad (2)$$

where: **E** are exports, $\mathbf{M_Z}$ are imports to local industries, and **Z** are local inter-industry transactions among 440 sectors of the economy represented in the IO models (MIG, 2010). The supply-chain of M_Z is computed applying the national *L*. Total local output (TLO) represents the total local requirements of producing local final demand, and is computed as the sum of *Z* (inter-industry flows), *F* (local production consumed locally) and *E* (local production for exports). TLO reflects the local economy.

Upon substituting the term **[L][F]** from (2) into (1), and recognizing that total net imports are the sum of imports to industry (M_Z), plus imports to households (M_F) minus export (E) ($\mathbf{M_{net}}=\mathbf{M_Z}+\mathbf{M_F}-\mathbf{E}$), GHG$^{\text{CBF}}$ can be re-written as:

$$\text{GHG}^{CBF} = [B][TLO]+[EF^{use}] \times \{[F]+[M_F]\}+[B][L][M_Z+M_F-E]$$

Table 2
Policy relevant attributes and the degree of relevance for each of the three GHG emission accounting methods discussed in this paper. Three stars (***) represent greatest relevance; [Explanations] are provided for reduced relevance.

Desired policy-relevant attributes ↓	Utility of greenhouse gas accounting methods to policy attribute {*** represents greatest relevance; [Explanations] are provided for reduced relevance}		
	Purely geographic	Community-wide infrastructure footprint (CIF)	Consumption-based footprint (CBF)
Informs future city and regional infrastructure (multi-level) planning and policy	* [Most infrastructures transcend city boundaries]	*** [Most relevant]	* [Excludes infrastructures serving local businesses and industries that export goods.]
Linkage of energy use to local urban heat islands, local air quality, and public health	*** [Most relevant]	** [Energy use in key infrastructures is allocated based on use, not location]	* [Energy use in all industries and businesses are allocated based on consumption, not location]
Informs supply-chain vulnerability for future planning	* [Most infrastructures transcend city boundaries]	*** [Most relevant]	* [Allocates GHG after consumption occurs, but does not address future planning for local supply vulnerability]
Enables inter-city comparisons using per capita metrics to inform residents	N/A [Per capita metric is incorrectly applied]	N/A [Per capita metric is incorrectly applied]	*** [Most relevant]
Enables inter-city comparisons using economic productivity metrics	* [Most infrastructures transcend city boundaries]	*** [Most relevant]	N/A
Data availability, quality and ability to benchmark or verify energy use and GHG emissions data	** [Remote sensing (e.g., Shepson et al., 2011) may enable independent verification]	**	* [IO models are calibrated to personal consumption and other data, not separately verifiable]

Table 3
Numerical results for CIF and CBF for three U.S. communities identified by the proposed typology – net-producers, net-consumers and trade-balanced in terms of GHG embodied in imports minus exports.

County (Typology)	GHG^{CBF} (mt-CO_2e/cap): [Eq. (1)]; {Eq. (3)}	GHG^{CIF} (mt-CO_2e/cap) [Eq. (4)]	Numeric ratio: GHG^{CIF}/GHG^{CBF}	Embodied GHG in net-imports of non-infrastructures: $GHG^{non\text{-}infra}_{Mnet}$ (mt-CO_2e/cap)	Commercial–industrial electricity use per capita (kW h/cap)
Routt, CO (net-producer)	[32.2]; {31.9}	52	163%	−20 Large negative net-producer	13,271
Denver, CO (balanced)	[31.6]; {29.9}	28	94%	2 Approaches zero (∼balanced)	8,704
Sarasota, FL (net-consumer)	[28.8]; {29.7}	22	74%	8 Larger positive (net-consumer)	5,123
U.S. average [a]	28	26	93%	2 (∼Balanced)	7,704

[a] U.S. Averages have been computed by applying the methods and equations discussed in this article, using the 2008 US IO IMPLAN dataset (MIG, 2010).

$$= \underbrace{\underbrace{[B][TLO]+[EF^{use}]\times\{[F]+[M_F]\}}_{\text{Represents Geographic (Territorial) GHGEmissions Inventory }(\mathbf{GHG^{IB}})} + [B][L][M^{infra}_{net}]}_{\text{Represents CIF GHG Emissions Footprint }(\mathbf{GHG^{CIF}})}$$

$$+ \underbrace{[B][L][M^{non\text{-}infra}_{net}]}_{\text{GHG embodied in net non-infrastructure imports to city}} \quad (3)$$

In Eq. (3),

Term 1, **[B][TLO]**, represents in-boundary GHG emissions from direct energy use in all business-industrial production within the boundary. As shown in Fig. 1, these territorial GHG emissions from TLO can serve local residents (shown in white within the community boundary), as well as exports (shown in gray).

Term 2, $\mathbf{[EF^{use}][F+M_F]}$, captures use-phase GHG emissions from final consumption, e.g., GHG from natural gas combustion by households. The sum of terms 1 and 2 yields total GHG emissions from direct energy use within the community boundary, i.e., territorial (GHG^{IB}).

Term 3, $\mathbf{[B][L]}[M^{infra}_{net}]$, quantifies the supply-chain GHG emissions from net imports of key infrastructures to cities. The sum of Terms 1 and 2 (territorial) plus Term 3 (infrastructure supply-chains) yields GHG^{CIF}, also illustrated in Fig. 1. Net imports indicate that any infrastructure exports from the community are subtracted out in computing GHG^{CIF}.

Table 4
Material-energy flow analysis (M-EFA) data sources for completing GHG^{CIF} for US cities, without using IO tables. Typically GHG^{CIF} uses more locally specific data from utilities. The spatial specificity is indicated by local, regional, state or national. The data quality is indicated as low, medium, or high based on ability to track with local/regional benchmarks.

Sector	Energy/material type	M-EFA data source	{Local specificity}, and [*Relative Quality*] of M-EFA data	Frequency of data update
Buildings energy use	Electricity	Local utility billing data	{local}, [*high*]	Annual
	Natural gas	Local utility billing data	{local}, [*high*]	Annual
Transportation energy use	Surface transport (Gasoline and diesel)	VMT from regional transport models	{regional}, [*medium-high*]	Every 4–5 years
		Fleet fuel economies	{state/regional}, [*medium*]	Variable
	Air transport (Jet fuel)	Jet fuel loaded at regional airport	{local}, [*high*]	Annual
		Jet fuel allocated to cities via road trips to airport (Ramaswami et al., 2008) or airport surveys (Chavez et al., 2012)	{regional}, [*medium-high*]	Jet fuel is annual, and transport models every 4–5 years
	Long-distance freight	County-level Expenditure Data (US Census)	{local}, [*low-medium*]	Every 5 years
		County-level economic census		
Materials use and waste	Water/wastewater (WW)	Regional water utility	{local}, *[high]*	Annual
	Food	Consumer Expenditure Survey	{local}, *[medium] *compiled for only a small set of U.S. cities*	Annual
		Consumer Expenditure Microdata	{local}, *[higher]*	Annual
	Cement	County Level Economic Expenditure data (US Census)	{local}, *[low-medium]*	Every 5 years
		Portland Cement Association report[a]	{local}, *[high]*	Annual
	Waste generated	Estimated from regional, state, or national level	{state/regional}, *[low]*	Uncertain

[a] Portland cement association (PCA)—Apparent use of Portland cement and ready-mix concrete.

Term 4, $\mathbf{[B][L]}[M_{net}^{non-infra}]$, quantifies the supply-chain GHG emissions from net imports of all other, non-infrastructure sectors.

Thus, Eq. (3) can be re-written as:

$$GHG^{CBF} = GHG^{CIF} - GHG_{E_{net}}^{non\text{-}infra} \quad (4a)$$

$$= GHG^{CIF} + GHG_{M_{net}}^{non\text{-}infra} \quad (4b)$$

Eq. (4a) shows that the full supply-chain of net non-infrastructure exports ($E_{net}^{non-infra}$) from the community must be subtracted from CIF to yield CBF. This is the equivalent to adding GHGs in non-infrastructure imports to the whole community (non-infrastructure supply-chains on right side of Fig. 1), and subtracting the GHGs embodied in non-infrastructure exports from the community – which includes infrastructure (e.g., electricity) and non-infrastructure supply-chains serving exports (gray areas in the two supply-chains in Fig. 1), as well as local production serving exports (all the gray areas within the community boundary, Fig. 1).

Eq. (4) implies that:

In a trade-balanced community, where $GHG_{M_{net}}^{non\text{-}infra} \ll GHG^{CIF}$, $GHG^{CIF} \approx GHG^{CBF}$.

In a net-producer community, where $GHG_{M_{net}}^{non\text{-}infra}$ is a large negative, $GHG^{CIF} > GHG^{CBF}$.

In a net-consumer community, where $GHG_{M_{net}}^{non\text{-}infra}$ is a large positive, $GHG^{CIF} < GHG^{CBF}$.

4. Results and insights

The mathematical derivations (1–4) are tested for three US communities, Denver, Routt, and Sarasota. To compare the three methods side-by-side, downscaled IO tables for these three communities were obtained from IMPLAN (MIG, 2010) and calibrated with actual household energy use, transportation energy use and commercial–industrial energy use reported in their respective GHG inventories (Denver, 2010; Routt, 2010; Sarasota, 2008). The calibrated IO tables had to be further corrected (see following section), after which Eqs. (1–4) were evaluated; results are shown in Table 3. Note the IMPLAN tables were used to enable side-by-side comparison of all three methods with the equations. In practical applications, GHG^{IB} and GHG^{CIF} would use local utility-derived data sources shown in Table 4.

As expected, (1) and (3) yield estimates of GHG^{CBF} computed in two different ways that are in-line with each other for each of the three communities (column 2, Table 3). Moreover, GHG^{CBF} is also similar across the three communities, ranging from 29 mt-CO_2e/cap in Sarasota, to 32 mt-CO_2e/cap in Routt, and in-line with the national average GHG^{CBF} of 28 mt-CO_2e/cap. This can arise because total household expenditures in the cities ($54,000–$73,000/year) are near the US average ($55,000/year), although the distribution of goods/service consumed in the different cities varies. However, GHG^{CIF} (computed from (3)) is vastly different across the communities, ranging from 22 mt-CO_2e/cap in Sarasota, to 52 mt-CO_2e/cap in Routt (column 3, Table 3)—the latter containing a high proportion of commercial–industrial activities engaged in exports. Thus, CIF reflects the nature of each community, including the proportion of production activities relative to residential.

Table 3 shows that establishing a typology for communities as net-producers, net-consumers, and trade-balanced in terms of GHG embodied in trade – after allocating basic infrastructures – is important in understanding the relative magnitudes of GHG^{IB}, GHG^{CIF} and GHG^{CBF} in different types of cities. Both Table 3 and Fig. 3 demonstrate the mathematical relationships in (3) and (4). For a highly net-producing community GHG^{IB} and GHG^{CIF} are larger, compared to GHG^{CBF}. In contrast, for a net-consuming community, GHG^{IB} is small, and GHG^{CBF} is larger than GHG^{CIF}. In trade-balanced community, GHG^{CIF} and GHG^{CBF} are numerically similar.

These results indicate than no one method offers a more holistic (larger number) for GHG accounting. The data also highlight that per capita metrics applied to GHG^{CIF} can present a misleading picture, wherein cities with disproportionately large commercial-industrial production activities relative to residential activity report

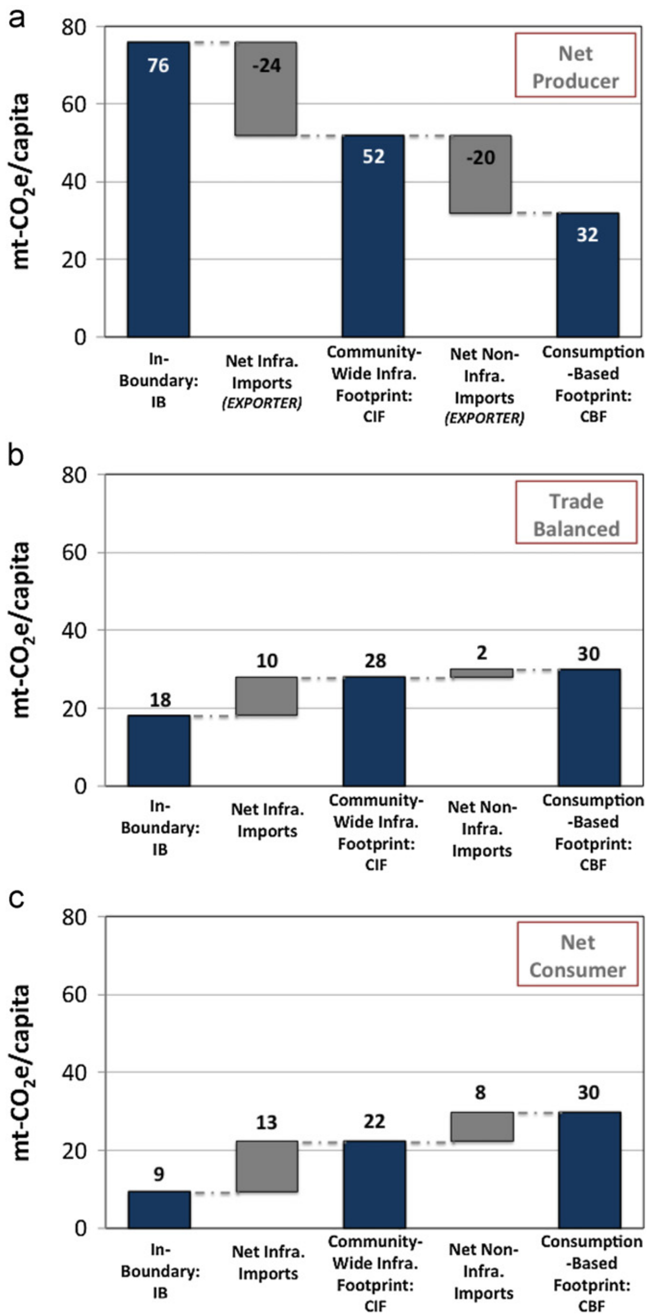

Fig. 3. Graphical illustration of mathematical relationships derived in this article. (a) Routt, a net-producing community reports $GHG^{CIF} > GHG^{CBF}$. (b) Denver, a larger metro community, estimated to be roughly trade-balanced reports $GHG^{CIF} \approx GHG^{CBF}$. (c) Sarasota, a community dominated by residences (net-consumer) reports $GHG^{CIF} < GHG^{CBF}$.

substantially larger GHG^{CIF}/cap, while their GHG^{CBF} are similar to the US average.

5. Data challenges

Computing GHG^{CBF} for the three communities in this paper using downscaled IO data revealed significant data challenges. Downscaled IO tables are primarily used for economic development planning and do not match actual energy flows associated with electricity and fossil fuel use in local communities (e.g., Table 5). Nationally downscaled home energy use did not match locally observed data and had to be corrected therewith (Denver, 2010; Routt, 2010; Sarasota, 2008). Further, the local electricity generation as projected by IMPLAN, significantly deviated from that reported by eGRID (EPA, 2011) in the three communities (Table 5). This mismatch became visible for electricity because comparison with eGRID was possible; however, such mismatches in representing local production may also exist in other sectors, but remain unverifiable.

Other mismatches between monetary and physical flows were also observed when large corporate headquarters are situated in a city, or when self-employed persons in a city operate energy assets located elsewhere. For example, Denver's IO table reported high *Oil & Natural Gas Sector* exports from residents who have a stake in the business; however, there are no oil and gas wells located in the city. More collaboration with developers of IO models such as IMPLAN can help flag these mismatches and develop tools specific for city-scale energy use and GHG analysis, as the IO models are not currently designed to represent energy/material flows.

The challenges of downscaling IO tables are particularly relevant only to CBF computations (GHG^{IB} and GHG^{CIF} use mostly local-scale data, see Table 4). Consequently, many researchers prefer to use Consumer Expenditure Surveys with national EIO-LCA to compute GHG^{CBF}. However, this alternate approach does not capture efficiencies in the local production system that serves local consumption.

6. Conclusion

Our preliminary case study of 3 cities suggests using caution in applying downscaled IO data to city-scale GHG accounting because current IO downscaling methods do not incorporate energy-materials mapping/verification capabilities that are essential to show the percent local consumption that is being met by local production.

Analysis of the IO tables, however, provided a useful side-by-side theoretical comparison of GHG^{IB}, GHG^{CIF}, and GHG^{CBF} for net-producing, net-consuming and trade-balanced communities based on GHGs embodied in trade of non-infrastructure sectors. Along with the mathematical relationships (3 and 4), the data offer the following insights:

- No one method among IB, CIF or CBF provides a larger or "more holistic" account of GHG emissions associated with communities.
- For high net-producing communities, CIF will yield a larger GHG footprint compared to the CBF. In such cities, focusing GHG mitigation on production activities is likely to be more important than focusing on household consumption.
- For high net-consuming communities, CIF will yield a lower GHG footprint compared to CBF. Here household consumption levers will be the largest.
- For large metro communities that are likely to be trade-balanced, attention should be given to both production and consumption.

Understanding the nature of communities as highly producing, highly net-consuming and net-GHG trade-balanced, after allocating out basic infrastructures, is essential for an improved scientific understanding of their trans-boundary impacts and better prioritization of mitigation strategies.

Table 5
Differences in electricity use between Unadjusted IMPLAN and Community GHG Inventory reports for three US communities. Monetary energy purchases retrieved from IO tables were converted to physical units using state average prices (EIA, 2011).

		Electricity use		Total local electricity generation		
		From unadjusted IMPLAN[a]	From each community's GHG inventory[b]	Unadjusted IMPLAN (GW h/yr)	EPA eGRID (GW h/yr)[c]	% error
Routt	Residential intensity	980 kW h/HH/mo	833 kW h/HH/mo	1280	3654	−65%
	Total commercial–industrial use	287 GW h	251 GW h			
Denver	Residential intensity	1,284 kW h/HH/mo	546 kW h/HH/mo	19,296	1269	1421%
	Total commercial–industrial use	11,313 GW h	5038 GW h			
Sarasota	Residential intensity	952 kW h/HH/mo	1403 kW h/HH/mo	1671	0	Very large
	Total commercial–industrial use	1,730 GW h	1861 GW h			

[a] Unadjusted IMPLAN data was retrieved from each of the communities input–output data file, provided by MIG, Inc. (2010).
[b] Each of the three communities GHG inventory report are used to extract geographic (in-boundary) energy use.
[c] Local electricity generation retrieved from EPA eGRID (EPA, 2011).

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Appendix. MRIO Equation Derivations

MRIO Derivation

We now derive mathematical relationships between GHG^{CIF} and GHG^{CBF} using a uni-directional MRIO model. A uni-directional MRIO assumes that direct trade to local industries dominates. For details on uni-directional MRIO, the reader is referred to Lenzen et al. (2004), Peters and Hertwich (2008), and Weber and Matthews (2008). MRIO attempts to attribute impacts to a particular region by considering a number of trade partners with different production characteristics (i.e., L-matrix). For simplicity, we begin by writing MRIO GHG^{CBF}, using a two-region model where Region 1 is the local community, and Region 2 is the rest-of-world (ROW).

$$GHG^{CBF} = [B][L_1][F] + [B][L_2][M_F] + [EF^{use}][F + M_F] \quad (A1)$$

where: $\mathbf{L_1} = (I - A_1)^{-1} = (I - [A_{11} + A_{21}])^{-1}$ and is the full production matrix of the local/base economy, $\mathbf{L_2}$ is the ROW production matrix in which following uni-direction MRIO, is assumed equal to the national (US) production matrix ($\mathbf{L}$).

The production balance of an economy in the MRIO framework is written:

$$[L_1]\{[F] + [E]\} = A_{11}x_1 + A_{21}x_1 + F + E = TLO + A_{21}x_1 \quad (A2)$$

where: $\mathbf{A_{11}}$ are the direct requirements on local production, $\mathbf{A_{21}}$ are the direct requirements on production of industrial imports from region 2 to 1, and $\mathbf{x_1}$ is region's 1 output. Further, $A_{11}x_1 = Z$, and $A_{21}x_1$ equals the total industrial imports into the local economy, region 1.

Next we assume that all industrial imports into region 1 are exclusive of region 1 exports, and that $\mathbf{A_{21}x_1} \approx \mathbf{[L_2][M_Z]}$. Then, upon substituting $\mathbf{[L_1][F]}$ from (Eq. A2) into (Eq. A1), MRIO GHG^{CBF} are shown as:

$$\begin{aligned} GHG^{CBF} = {} & [B][TLO] + [EF^{use}][F + M_F] \\ & + \{[B][L_2][M_Z^{infra} + M_F^{infra}] - [B][L_1][E^{infra}]\} \\ & + \{[B][L_2][M_Z^{non\text{-}infra} + M_F^{non\text{-}infra}] - [B][L_1][E^{non\text{-}infra}]\} \quad (A3) \end{aligned}$$

where,

$[B][TLO] + [EF^{use}][F + M_F] + \{[B][L_2][M^{infra}] - [B][L_1][E^{infra}]\}$ should approximate GHG^{CIF}, and

$\mathbf{\{[B][L_2][M^{non\text{-}infra}] - [B][L_1][E^{non\text{-}infra}]\}}$ are the GHG embodied in net imports of non-infrastructures to the city.

These relationships can be directly related to those obtained from (4) in the manuscript.

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