Supporting Information

Review on City-Level Carbon Accounting

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1. Definition of "Scope 1-3"

The definition of "Scope 1-3" originated from GHG protocol for a cooperate-scale accounting (1), and it was adopted and revised for a city-scale accounting in GPC (2). For the scope 2, besides the GHG emissions of grid-supplied electricity, if GHG emissions were generated as a consequence of the use of heat, steam and/or cooling within the city boundary, these emissions would be accounted for Scope 2 emissions as well. The other difference between two definitions is the boundary: one uses economic boundary concerning whether these sources of emissions are "controlled by the company" and the other emphasizes a geographical boundary. The definition of "Scope 1-3" is given in **Table S1** for both corporations and cities.

Table S1 the definition of scope1-3 for corporate and city

	Scope 1	Scope 2	Scope 3
GHG protocol (1)	Direct GHG emissions occur from sources that are owned or controlled by the company,	GHG emissions from the generation of purchased electricity consumed by the company.	All other indirect emissions. Scope 3 emissions are a consequence of the activities of the company, but occur from sources not owned or controlled by the company.
GPC (2)	GHG emissions from sources located within the city boundary	GHG emissions occurring as a consequence of the use of grid-supplied electricity, heat, steam and/or cooling within the city boundary	All other GHG emissions that occur outside the city boundary as a result of activities taking place within the city boundary

2. Linking various accounting methods with "Scope 1-3"

In addition to the relationship of territorial emissions(TE), community-wide infrastructure-based carbon footprinting method (CIF), and consumption-based carbon footprints (or carbon footprint, CBF), the "Scope 1-3" can also be connected with other accounting perspectives, including "final demand footprint", "controlled emissions", "purely production footprint", and "production-based footprint" (Figure S1).

The final demand footprint is in line with the scope (accounting system boundary) of CBF, according to the definition from Chen and Chen (3). The original term in the paper is "carbon emissions embodied in urban final demand", and the emissions are driven by urban final demand met by local output (household/government consumption, capital formation, and exports), domestic import and foreign import. Thus, the "final demand footprint" actually

accounts for the emissions embodied in the products of the total urban consumption.

In Chen et al.(4), the "carbon backward multiplier (CBM)" is defined as the upstream industry emissions of other regions caused by one dollar of final demand by sector i in the cities. The total amount of upstream emissions caused by urban final demand is thus the emissions embodied in imports(EEI) which is different with "final demand footprint" (see Figure S1). From a policy perspective, regional development should consider the economy and environment as a whole by paying attention to CMB and economic backward linkage (BL) in particular. In the case study of the paper, Sydney and Melbourne have strong CBM but weak BL to other regions in electricity which means the expansion of final demand in this sector in the two cities has little benefit in upstream economies but strong global warming impacts.

The "controlled carbon footprint" (originally termed as "controlled emissions") is firstly proposed by Chen and Chen (5), and then appears in subsequent papers such as Chen and Chen (6). The controlled carbon emissions consider both local CO_2 emission and that emitted elsewhere but indirectly controlled by the region due to final consumption, covering the amount of carbon emissions that can be mitigated within a region by adjusting its consumption. The quantification is realized by introducing a "regional control matrix" to the traditional Leontief model, to show the control intensity among sectors in the region. The "controlled carbon footprint" of one region should be smaller than (or a part of) its consumption-based footprint and a part of Scope 1-3, but the mathematical relationship with the Scope 1-3 according to the calculation method has yet been quantified.(5) However, this novel metrics can be used to identify the dominant carbon flows and sectors in the supply chain, and provide information on hidden pathways of carbon mitigation.

Purely production footprint (PPF) is firstly proposed in Lin et al. (7), PPF includes territorial emissions(TE) and emissions embodied in imports to industry but imports to final consumption is excluded. PPF includes the whole scope 1 and part of scope 2 and 3. The production-based footprint in Lin et al (7)'s paper covers the scope 3 emission, which is TE (Territorial Emissions) plus EEI (Emissions Embodied in Imports). These definitions can help to understand the life-cycle carbon emissions of entire urban production and consumption activities.

PPF should be distinguished from production-based emissions which is debatable and unclear. For example, the case of emissions embodied in supply chains that serve local production; it is unclear which part is included or whether any at all should be in production-based emissions. This issue has also been raised by Dahal and Niemelä when comparing territorial emissions and production-based emissions.(8) Some literature describe the production-based accounting as scope 1-3.(9) Adopting a narrow meaning, other studies assume that production-based accounting excludes imports, thus equating it with pure-geographic production-based accounting, and that production-based emissions are equal to territorial emissions (TE) or direct emissions within the boundary following *IPCC guidelines* (see examples in Mi, et al.(10) and Wang, et al.(11)).

Apart from the above definition of accounting perspectives, many other literatures seek to

reveal the determinants of carbon emission growth or decrease. Various methods are developed to identify socioeconomic factors such as energy mix (12), demand or consumption(13), technical progress or intensity (13-15), population (16), carbon price (17) and economic structure (16), and evaluate how these factors will influence the carbon emissions. These researches move one step forward from calculation to application, and will provide quantified information for low-carbon urban transitions.

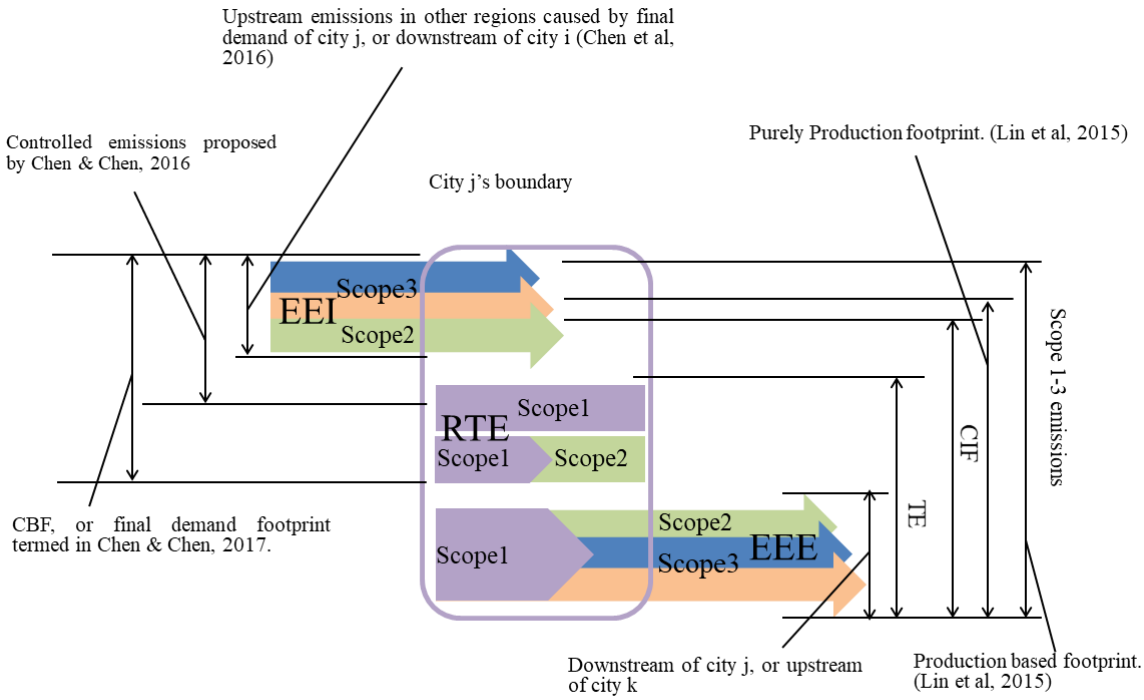

Figure S1. Detailed relationship analysis for different accounting perspectives and Scope 1-3. Also see figure 1 in manuscript for comparison

3. Global databases for city-scale carbon accounting

Generally, there are two approaches to account for city-level territorial emissions. One is to calculate the emissions with unit-based survey data, i.e. bottom-up approach. Another approach is to downscale the national or regional statistical data to obtain the city-level data, i.e. top-down approach. Taking Chinese cities for examples, CHRED (China High Resolution Emission Database) team accounts for the emissions with each enterprise's energy consumption data, which is a bottom-up approach. Ramaswami, et al.(18) and Tong, et al.(19) also developed a emission dataset by bottom-up approach. Differently, the CEADs (China Emission Accounts and Datasets) team account for the cities' emissions using hybrid approaches. (20, 21) Part of the CEADs data are downscaled from China's national and provincial data per socioeconomic data (top-down approach), while the other part of the bottom-up data are collected based on cities' statistical documents.

Both of the two approaches have their own significant challenges and flaws. The bottom-up approach has very high data requirements, requiring a lot of workload to collect and clean the data,

thus the approach is time-consuming. Also, there might be errors during data processing, leading to an uncertainty. On the contrary, the top-down approach is easier to conduct without so much data processing work. However, the main drawback of this approach relies on pre-assumption uncertainty and data accuracy. The top-down city-level emissions are downscaled from national or sub-regional data according to socioeconomic indexes, which might have high pre-assumption uncertainty that challenges the data accuracy.

Combining top-down and bottom-up approaches, two types of databases are listed in table S2 including: 1) self-reported or statistic-based databases (SDs); 2) spatial-resolution-based databases (SRDs). The SDs is easy to assess and free to download. Global cities voluntarily report their emissions based on the GPC or GPC basic+ standards to platforms of CDP and C40. These calculations are usually based on their statistics or industry-based survey data. CEADs database focus on Chinese cities and the raw data is collected from Chinese Statistic Yearbooks.

SRDs databases provide detailed data with spatial solution but the city-scale is less assessable. Some databases need applications and further data processing. Except CHREDs, the other SRDs decompose national/subnational emission data through spatial proxies such as point-sources(22), night-time light data(23) to finer scale. The basic data of CHREDs is collected from industrial enterprises at emission sources i.e. bottom-up method with further spatial solutions.(24, 25)

Table S2 City-scale carbon emission databases

Self-reported or Statistic-based database				Spatial-resolution-based database				
	CEADs	CDP	C40	CHRED v1.0-v3.0	MEIC	ODIAC	EDGAR	PKU
Domain	China	Global	Global	China	China	Global	Global	Global
Temporal coverage	2010	2015-2018(partly cities)	2000-2016(partly cities)	2005, 2007, 2012, 2015	1990-2015	2000-2017	1970-2012	1960-2014
Time resolution	Yearly	Yearly	Yearly	Yearly	Monthly	Monthly	Yearly	Monthly
level	City	National, City, Corporate	Provincial, City	City	—	National	National	—
Spatial resolution	—	—	—	1 by 1 km, 10 by 10 km	1/4, 1/2, and 1 degree	1 by 1 km, 1 by 1 degree	0.1 by 0.1 degree	0.1 by 0.1 degree
Emission sector	17 different fossil fuels, 46 socioeconomic sectors, and 7 industrial processes	Scope 1 and 2	Energy & Buildings, Transportation & Urban Planning, Food, waste & water	Agriculture, industrial energy, service, rural household, urban household, transportation, industrial processes	Power stations, industry, residential, transportation and agriculture	fossil fuel combustion, cement production and gas flaring	energy related sectors, agricultural sectors	64 to 88 individual sources
Data accessibility	Directly downloaded	Directly downloaded	Directly downloaded	Application required	Application required	Directly downloaded; Need further data processing	Directly downloaded; Need further data processing	Directly downloaded; Need further data processing
Website	http://www.ceads.net/	https://www.cdp.net/zh/data	https://www.c40.org/research/open_data/5	http://www.cityghg.com/	http://www.meicmodel.org/dataset-meic.html	http://db.cger.nies.go.jp/dataset/ODIAC/DL_odiac2018.html	http://edgar.jrc.ec.europa.eu/overview.php?v=432_GHG&SECURE=123	http://inventory.pku.edu.cn/download/download.html

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