comment

Carbon analytics for net-zero emissions sustainable cities

Consensus on carbon accounting approaches at city-level is lacking and analytic frameworks to systematically link carbon mitigation with the Sustainable Development Goals are limited. A new accounting approach anchored upon key physical provisioning systems can help to address these knowledge gaps and facilitate urban transitions.

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More than 500 cities worldwide have established low-carbon and net-zero carbon goals, and many are advancing climate adaptation, health and social equity, consistent with the United Nations (UN) Sustainable Development Goals (SDGs). However, there is little consensus on how to measure urban carbon emissions to achieve decarbonization. Furthermore, we lack analytic frameworks to systematically link urban carbon mitigation with other SDGs. This Comment provides a way forward on both fronts, wherein we: (1) map the different greenhouse gas (GHG) accounting approaches to specific aspects of urban decarbonization policy; and (2) highlight advances in measurement and analytics, rooted in urban infrastructure transitions, to link carbon mitigation with multiple SDGs.

Mapping carbon accounts to four aspects of decarbonization

Cities are complex due to their smaller spatial scale and embeddedness within larger-scale social, ecological and infrastructural systems[1,2]. Numerous studies have shown that a vast majority of cities import electricity, transportation fuels, water, food and construction materials needed for basic provisioning systems. Furthermore, cities are embedded in trade networks that move embodied carbon through goods and services imported/exported across city boundaries. This has motivated a transboundary urban systems perspective with four overarching GHG accounting approaches emerging over the past two decades.

Mathematical relationships have shown that no single accounting approach is both more comprehensive and locally representative[3]. Yet, despite 15 years of research, scientific papers continue to position one approach as more/less comprehensive than the others (for example, ref. [4]), often suggesting that counting more carbon leads to greater city-scale policy relevance (for example, ref. [5]), which is contested. Meanwhile, practitioners have embraced multiple accounting approaches. In the 2000s, realizing that purely territorial emissions (Scope 1) ignore substantial emissions embodied in electricity imported to cities, city networks, in consultation with scientific communities, developed improved community-scale GHG protocols that incorporated imported electricity (Scope 2) and other imports (Scope 3). However, clarity has been missing on which Scope 3 emissions are most important to urban sustainability transitions. Meanwhile, the concept of consumption-based accounting gained visibility[4,6], while new satellite data and atmospheric measurements[5] have renewed interest in Scope 1 GHGs within cities. However, what to do with these multiple accounting approaches remains unclear.

Our Comment contributes by presenting a framework that provides clarity and fosters dialogue among scientists and practitioners on urban GHG accounting. We map each of the four accounting approaches to specific aspects of urban decarbonization policy that they inform. The four aspects include: (1) monitoring carbon emission sources; (2) designing community-wide low-carbon transitions; (3) informing household actions; and (4) decarbonizing trade. Our rationale is below.

The first approach, purely territorial source-based accounting (Scope 1), tracks GHGs directly emitted within a certain geographic area, organized according to the Intergovernmental Panel on Climate Change's categories covering stationary and mobile combustion, and non-energy GHGs from local industry, agricultural/forestry and land-use change. Scope 1 emissions are often estimated using metabolic accounting of fuel-use reported by local sources[1,3], to which suitable GHG emission factors are applied. Emerging methods, which directly measure atmospheric gases using flux-towers[7] and satellite-based sensors[8], apply inverse modelling to provide an alternate method for estimating territorial GHG emissions. However, not all local GHGs are associated with local urban activities or policies; for example, emissions from aircrafts are not within the host city's purview. Furthermore, not all urban policies reduce GHG emissions locally; for example, electricity savings from more efficient buildings will be invisible in territorial accounts since most cities import electricity. This is a key drawback of purely territorial urban carbon accounting. Scope 1 accounts are therefore well-suited for the location-specific source-based monitoring aspect of decarbonization, but do not inform urban low-carbon levers like compact development and urban building efficiency that reduce use of energy and materials, often imported into cities. Indeed, systemic low-carbon transition design must link use-activities in cities with transboundary supply chains, as described next.

The second approach, community-wide infrastructure supply chain GHG footprinting (Scope 1+2+3), expands territorial accounting (Scope 1) to incorporate GHGs along transboundary supply chains of key community-wide physical provisioning systems that support residential, commercial and industrial activities in cities[1,3,9]. There are strategic reasons to focus on seven key provisioning systems that provide energy, water, shelter/buildings materials, mobility-connectivity, waste management, food and green public spaces in cities. First, globally, these seven sectors collectively contribute >90% of GHG emissions[2]. Second, they also contribute >96% of water withdrawals, and ~20 million premature deaths worldwide from inadequate access to, or pollution arising from, these sectors[2], enabling linkages

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Table 1 | Four specific aspects of urban decarbonization policy are matched with four urban carbon accounting approaches and associated tools

Aspect of urban decarbonization policy	Carbon accounting approach	Associated accounting tools and example application	Associated concept of net-zero carbon emissions
Monitoring location-specific sources of GHG and air pollutants	Purely territorial source-based accounting (only focuses on direct emission sources of GHG)	Very few cities do only Scope 1 accounting: eight cities in ref. [11]	Net-zero territorial emissions (without supply chains)
Designing community-wide integrated urban infrastructure transitions (multi-sector integration for net-zero carbon city, resilient city, healthy city, smart city and so on)	Community-wide infrastructure supply-chain footprinting of key provisioning systems[a]: energy, mobility, buildings, water, waste/sewage management, green infrastructure and food systems (transboundary; links production of these sectors to consumption by homes and to exporting businesses)	(Scope 1 and 2): 27 cities in ref. [11] GPC and ICLEI Basic Protocol[b] (Scopes 1±2±3): energy, mobility, wastewater and waste: 73 cities in ref. [11] GPC Basic+ and ICLEI-USA Advanced (Scopes 1+2+3): all provisioning systems > 20 US cities[9]; and additional cities in Australia, China and India	Net-zero carbon community-wide infrastructure and food provisioning systems[c] (including nexus interactions and supply chains)
Informing households on carbon footprint mitigation (analysing all consumer expenditures beyond those for key provisioning systems)	Purely consumption-based carbon footprint (transboundary; links production of all sectors to consumption by homes; excludes exporting businesses)	Household consumption carbon calculators, for example, in ref. [6]	Net-zero carbon household expenditures
Decarbonizing trade: understanding local-to-global trade linkages (beyond the key provisioning systems)	Total supply-chain footprinting (transboundary; links production-to-consumption and exports; all sectors)	Research study of 79 C-40 cities in ref. [4]	Net-zero carbon trade

[a]Seven key physical provisioning systems contribute >90% of global GHGs; excluded are deforestation and industrial processes for chemical and petrochemical production. [b]ICLEI–USA's basic protocol includes reporting GHGs associated with water supply. [c]Decarbonizing the key physical provisioning systems will result in decarbonized trade.

of low-carbon transitions with multiple SDGs of health, equity and well-being[10]. Indeed, social systems like education and healthcare also require these physical systems to function. Third, the seven physical systems form the core of several urban infrastructure transition agendas — smart city, compact city, electric mobility, nature-based solutions, food-action and climate adaptation planning — all of which recognize that infrastructure and land-use planning are interlinked and undertaken for households and businesses together. Thus, a community-wide perspective encompassing all seven sectors is particularly well-suited to the design aspect of low-carbon transitions, leveraging nexus interactions among sectors, and aligning local transitions with larger-scale efforts in decarbonizing energy, mobility and agriculture.

Community-wide transboundary footprinting has been institutionalized in city GHG accounting protocols (for example, the ICLEI–USA Community GHG Protocol and Global Protocol for Cities (GPC)), with varying sectoral coverage (Table 1). Basic protocols, incorporating transboundary powerplant emissions from imported electricity (Scope 2) and waste-emissions, have been adopted widely[1,11]. Some argue that focusing on these basic/core sectors may be more tractable for cities[12]. More advanced protocols incorporate lifecycle Scope 3 GHGs from petroleum refining for community mobility, water supply and wastewater treatment, cement and steel for construction, transboundary agricultural emissions for community food supply, as well as biogenic carbon from land-use changes and sequestration by greenery, thus covering all the seven sectors[3,9].

The third GHG accounting approach, consumption-based footprinting, assigns GHG emissions from the production of all goods and services wherever they occur globally to final consumption, dominated by households, within a city[6]. It thus informs households on low-carbon actions beyond the seven infrastructure and food sectors already addressed in community GHG protocols. Examples include purchases of clothing, furniture and other goods. However, local operational energy use by businesses (for example, hotels, restaurants and industries) that serve tourists or export goods and services are excluded. Thus, consumption-based accounting is not a community-wide account and does not inform the design of community-wide transitions.

The fourth accounting approach, total community-wide GHG footprinting, is an emerging method that uses economic input–output accounts to track total supply chain GHG emissions of all urban activities, including both consumption and exports[4]. Thus, it aligns with the aspect of decarbonizing local-to-global trade, well beyond the scope of community-scale planning. The method requires high-quality input–output data that are currently available only for a few cities worldwide, with uncertainty in mapping physical flows to economic data.

The above discussion demonstrates that each of the four accounting approaches aligns with a specific aspect of urban decarbonization (Table 1) and should not be conflated with another aspect. Each approach is complete within the context of its stated purpose; thus, counting 'more carbon' will not advance that specific purpose. Table 1 also illustrates what a net-zero carbon city means for the different approaches; that is, net-zero territorial emissions, net-zero community-wide physical provisioning systems, net-zero household expenditures and net-zero trade, respectively, for the four carbon accounting approaches. Few would argue that a net-zero carbon city is merely a net-zero carbon parcel of land (territorial perspective); indeed, this will create perverse incentives to move industry outside cities. Likewise, a net-zero city is not merely a collection of net-zero carbon households. Thus, articulating a net-zero carbon city as

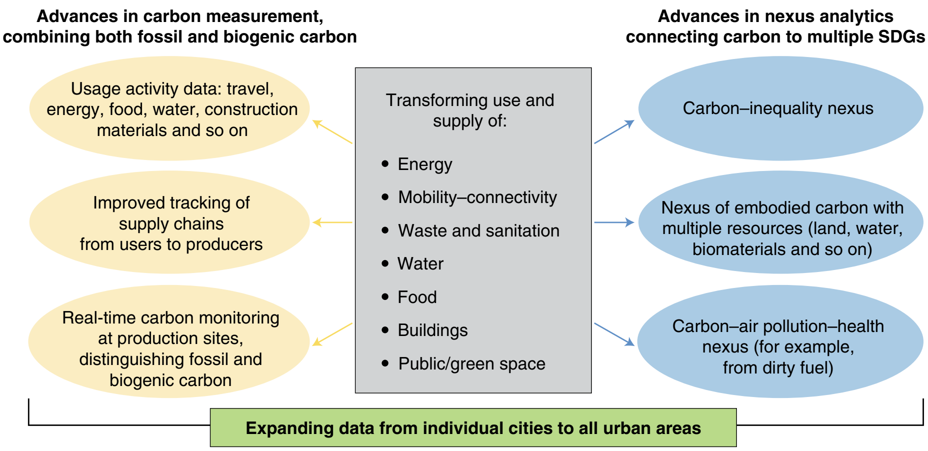

Fig. 1 | Key advances required in urban carbon analysis. Carbon measurements (left) and carbon-SDG nexus analytics (right).

one with net-zero carbon community-wide physical provisioning systems can provide an ambitious yet realistic decarbonization agenda. Furthermore, decarbonizing these key sectors will automatically decarbonize carbon embodied in global trade, thereby transcending the need for total supply-chain accounting of the whole urban economy.

Thus, the centrality of the key provisioning systems in sustainability frameworks[10] provides clear rationale for cities to focus on mainstreaming community-wide Scope 1+2+3 GHG accounting, consistently incorporating all seven infrastructure and food systems to achieve a net-zero sustainable future — locally, nationally and globally.

The path forward for urban carbon measurement and analytics

Achieving this vision will require three main advances (Fig. 1).

First, cities urgently need better usage-activity data; that is, use of energy, water, construction materials, food, mobility- and waste-services. While water, sewerage and electric utilities are providing increasingly high-quality data that can be benchmarked[1,9], there is much uncertainty in estimating physical flows of construction materials, food, and fuel-use in mobility. Here, the emerging urban data revolution offers several innovations; for example, estimating electricity use and disruptions via satellite data[13], remote sensing of thermal combustion and mobility data from mobile phones[14]. Three-dimensional imaging of cities[15] enables fine-grained assessments of construction materials, while novel wastewater analyses[16] help quantify nutrition and food flows. Such data enable detailed urban metabolic assessments that link human activities with material inflows/outflows from cities. These data innovations inform how urban actions, such as compact growth and healthy diets programmes, can reduce unsustainable urban resource draws, which are critical for achieving a net-zero carbon future. Second, advances in physically based input–output modelling[17] and blockchain technologies can better map urban supply chains for spatially granular assessment of transboundary carbon flows. Last, new methods at the intersection of remote sensing and atmospheric sciences (described earlier) are enabling location-specific source-based monitoring of GHG emissions at production locations[8]. Connecting usage-activity, supply chains and production-site data will be necessary to decarbonize transboundary provisioning systems, requiring integration across urban metabolism studies, atmospheric sciences, remote sensing and social sciences to understand human activities on the ground. Indeed, human activities data are the foundation for both urban metabolic and atmospheric modelling methods of carbon accounting, and the first step for monitoring policy effectiveness; for example, reduced travel or energy use. Carbon accounting must include both fossil and biogenic carbon, the latter associated with land-use change, agriculture, and biomaterial use.

Alongside measurements, advanced analytics are needed to link decarbonization and the SDGs. Here, city data on inequality in access to and consumption of the key provisioning systems are critical for designing transitions that are just (SDG 10) and low-carbon (SDG 13). Tracking fossil fuels along with other resources, such as land, water, biomaterials and minerals embedded in transboundary supply chains[18], is important to ensure urban transitions benefit climate as well as other SDGs related to water (SDG 6) and land (SDG 15). Likewise, models that link transitions in food systems (SDG 2), electric mobility and circular economy[19] with carbon and air pollution will be critical to the nexus with health (SDG 3).

Finally, carbon measurements and multi-SDG analytics must have capacity to cover all urban areas consistent with national energy- and material-use, demonstrated recently in the United States, China[19] and India[20]. Such efforts will support measurement and analysis toward a net-zero, sustainable and equitable future, in small and large cities worldwide, consistent with national/global goals. Advancing this new carbon science will require developing common frameworks and vocabularies across practitioners and scientists, transcending disciplinary boundaries, and fostering international partnerships across cities worldwide. ❐

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