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Three-Tier carbon accounting model for cities

Saige Wang, Bin Chen*

State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, PR China

HIGHLIGHTS

- An EIO-LCA model for urban carbon footprint accounting is presented.
- The urban carbon emissions are calculated in three tiers in context of supply chain.
- Tier 3 carbon emissions cannot be ignored for efficient urban carbon mitigation policy.

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ABSTRACT

With the rapid population and economic growth, carbon emissions in cities have been increasing due to the accelerating urbanization, which provide great potential for global climate change mitigation. To measure the carbon emissions along the urban supply chain in terms of sectoral and urban horizons, this study tries to build a systematic carbon accounting framework to quantify sectoral indirect upstream supply chain emissions for effective urban carbon mitigation. An urban Three-Tier carbon accounting model has been established based on the Economic input-output life cycle assessment (EIO-LCA) method, concerning Tier 1: direct emissions; Tier 2: emissions from purchased secondary energy resource; and Tier 3: complete supply chain emissions. A case study of Chongqing city was conducted to identify the critical sectors of three tiers that contribute most to total carbon emissions, covering 28 economic sectors during 2002–2007. The results showed that emissions of Tier 1 and Tier 2 included in most protocols only occupy a small fraction (27.8%) of the total emissions of all 3 tiers, especially for industrial sectors. It is concluded that the existing climate-control protocols have underestimated the emissions of each sector and particularly, Tier 3 emissions have to be incorporated when formulating effective urban management strategies and climate adaptation planning. By incorporating the Three-Tier carbon footprint into sectoral input–output accounting framework, this study developed carbon sector specific categorizations to pursue emissions mitigation pathways not just within their own economic activity but also across their supply chain.

1. Introduction

As the home to over half of the global population and engines of growth for national economies, cities are the major contributors to the global carbon dioxide (CO_2) emissions [1], and have been recognized as leaders to implementing carbon emission mitigation strategies [2–3]. Incorporating carbon reduction goals into urban sustainable management has become a critical issue driven by the challenge to balance economic development and carbon emissions reduction over the past decade [4]. So far, 228 global cities with around 436 million people have set carbon emission reduction goals and targets.

Carbon footprint, defined from the life-cycle perspective, has been widely proven as a useful tool for carbon measurement [5]. An important issue related to carbon footprint is joint production, which arises commonly within supply chains. Each sector in urban economic system is not only producer that provides goods and services to other sectors but also consumer of products and services that produces carbon emissions (known as indirect emissions) [6]. The “producer” sector can influence the carbon emission of “consumer” sector through providing the intermediate goods and services, which is the impact of upstream supply chain on the sectoral carbon emission. Sectoral carbon emission from urban sectoral joint production within supply chains represents a significant proportion of total emissions [7]. For example, Huang et al. found that about 75 percent of an industry sector’s carbon footprint comes from upstream supply chain emissions [8]. While the assessments of supply chain emissions can help city to identify where the best opportunities lie for climate change mitigation, regardless of whether they occur within the urban boundary or within the supply chain from

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* Corresponding author at: No. 19, Xinjiekouwai Street, Beijing 100875, PR China.
E-mail address: chenb@bnu.edu.cn (B. Chen).

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outside, little guidance is available for city to identify critical sectors and pathways to pursue emissions mitigation from entire supply chain perspective [9].

Urban carbon footprint in a supply chain differs in various system boundaries [10]. Here we defined it as the carbon emission embedded in both direct and indirect activities in specific urban economic sectors [11]. Meanwhile, there existed various carbon emission reduction protocols. The World Resources Institute and the World Council for Sustainable Development proposed the Greenhouse Gas Protocol in 2004, which has been widely accepted [12–13]. Besides, the Local Government Operation Protocol and the 2006 IPCC Guidelines for National Greenhouse Gas Inventories provided detailed and unified carbon emission accounting guidance incorporating different carbon sources and sinks into their accounting principle [14–15]. Even so, the routine reports from various institutions and existing researches on carbon emission accounting still largely ignored the supply chain carbon emissions in urban system [16–22], e.g., direct emissions and emissions from the generation of purchased electricity are often targeted with less focus on indirect emissions from sectoral upstream supply chain, and the impacts of sectoral linkage are largely neglected [6]. This results in large ‘carbon leakage’ because direct CO_2 emissions and emissions from purchased energy constitute only a small portion of the total carbon footprint [8]. Therefore, a precise estimation of the urban carbon footprint of the entire supply chain process is needed to pursue a low-carbon city.

To track the activities across a supply chain for a specific industry and assess the embodied CO_2 in a consumer product, life cycle assessment (LCA) has been widely introduced for carbon footprint calculation in practice [23]. LCA aggregates emissions across multiple subsystems (processes/sectors) to correctly estimate system-wide (supply chain-wide) emissions [24–28]. Currently, there are two major forms of LCA, i.e., the process-based LCA and economic input-output LCA (EIO-LCA). Process-based LCA models are more precise but difficult to obtain the detailed inventory data, and might lead to significant truncation errors due to an artificial cut-off when defining the system boundaries [29]. Economic input-output (EIO) models, proposed by Leontief in 1936 to aid in manufacturing planning [30], is introduced to improve the process-based LCA framework by reflecting the inter-relationships of various sectors via the production and consumption of intermediate economic outputs [31]. By aggregating the economic activities into sectors, the EIO model has been used in carbon footprint accounting framework to facilitate the impacts of urban sectoral economic activities and sectoral linkage on the carbon emission. There is a growing number of studies on the EIO-based carbon accounting for understanding the key drivers behind countries’ growing resource use (energy consumption [32–34], energy and water [35–37], land and water use [38]) and carbon emissions [39–41]. The monetary transactions flowing among the economic sectors can be transformed to physical flows under the assumption that all outputs of a sector are produced with the same intensity of physical flow [42]. It is assumed that each industry consumes the outputs of various other industries in fixed ratios to produce its own unique and distinct output [43]. As traditional IO is constrained by aggregated sector representation, EIO-LCA has been developed to reduce the limitations of each individual approach and to increase their accuracies [44–45]. EIO-LCA methods can track all emissions across the supply chain for a specific sector and estimate all purchases and activities in a supply chain leading up to final manufacture in an industry [38]. In EIO-LCA, the environmental impact of carbon emissions is assumed to have a linear relationship with economic output in a specific sector with a steady state and conservation principle (i.e., the more products they produce, the more carbon they emit). These models have been recently applied in the accounting of carbon emissions at various scales, and related studies have been summarized in Table 1.

Considering the significant contribution of urbanization to carbon emissions, city could be used as an important handhold for carbon mitigation and adaptation practices [46–51]. There existed some

Table 1
Summary of carbon footprint related work.

Method	Scale	Results & conclusion	Study area	Authors
Inventory analysis	City level	18 typical cities that contain an average of 6.57% of the population and 7.91% of the GDP, contribute 13% of China's total CO_2 emissions.	Selected 18 cities from 6 central provinces	Xu et al. [1]
Input-output analysis	City level	Within the total carbon flow, import and export respectively accounted for 59 and 65%, highlighting the importance of emissions embodied in trade.	Xiamen	Lin et al. [18]
Top-down GHG inventories	City level	GHG emissions are mainly generated from energy use in industrial sector and coal-burning thermal power plants. Besides, the proportion of indirect GHG emission from imported energy use keeps growing, implying that big cities are further dependent on energy/material supplies from neighboring regions.	Chinese mega cites (Beijing, Tianjin, Shanghai and Chongqing)	Liu et al. [20]
Multi-scale integrated systems modelling	City level	Cross-sectoral strategies contribute an additional 15%–36% to national CO_2 mitigation, compared to conventional single-sector strategies.	637 cities of China	Ramaswami et al. [46]
EIO-LCA	National level	75 percent of an industry sector’s carbon footprint comes from upstream supply chain emissions.	U.S.	Huang et al. [8]
Three-Tier model	National level	The CO_2 emissions from industrial processes are concentrated in the nonmetal mineral products sector, instruments, meters, cultural and office machinery sector, and the construction sector.	China	Yang and Chen [47]
EIO and structural decomposition analysis	National level	How changes in China's technology, economic structure, urbanization, and lifestyles affected CO_2 emissions of China are analyzed.	China	Peters et al. [48]
EIO-LCA	Various levels	Understanding the level of geographic resolution within large industrial nations needed to reach acceptable accuracy has not been well-tested across the broad spectrum of goods and services consumed.	U.S.	Yang et al. [49]
LCA	Various levels	Spatial differentiation in life cycle impact assessment: a decade of method development to increase the environmental realism of life cycle impact assessment.	Different cases	Potting et al. [50]
Input-output analysis	National	A consistent set of carbon inventories that spans the full supply chain of global CO_2 emissions, finding that 37% of global emissions are from fossil fuels traded internationally and 23% of global emissions are embodied in traded goods.	World	Davis et al. [51]