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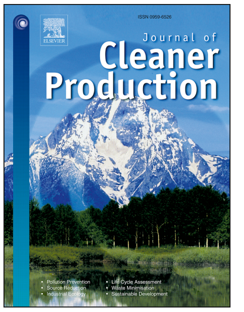

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Spatial consumption-based carbon footprint assessments - A review of recent developments in the field

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ABSTRACT. Consumption-based carbon footprint (CBCF) assessments have become increasingly important in studying the drivers of climate change from a consumer perspective. A wide range of studies and approaches for CBCF have been presented, yet a systematic and interpretative synopsis of the literature is missing. We present a comprehensive review of more than 100 CBCF studies published in Scopus-indexed journals until 2019. We analyze the methodological and conceptual development of spatially related CBCFs and provide guidance for future research. While the recent emergence of several global multi-region input-output (MRIO) models has meant remarkable development in assessment accuracy, there is space for improvement in hybrid-modeling and increasing sectoral detail. Furthermore, it was recognized that studies published under the same CBCF label actually fall into two categories with different definitions and potentially significantly different outcomes. We suggest labeling these as Areal CF (ACF) and Personal CF (PCF) in the future. ACF encompasses the CBCF of economic activities within selected geographic boundaries, and the global production and delivery chain emissions of the goods and services consumed therein, including those consumed by visitors. PCF covers the consumption of the residents of the area regardless of where the consumption takes place but excludes the consumption of visitors within the area in question. ACF analyses typically include government consumption and investments, whereas PCF analyses normally exclude these. This scope issue is seldom brought up in individual studies, and it currently takes a lot of effort and expertise to classify existing studies, which hinders their usability for policy-making. In addition, we suggest that future studies position themselves among previous studies on the same location, discuss potential reasons for differences in the results, and consider these when drawing policy conclusions.

1 Introduction

Climate change is rapidly changing the natural environment and living conditions throughout the world. It is also transforming human society. The efforts to slow down global warming are already transforming industries, business models and governance practices. Hundreds of millions of dollars are invested into decarbonization of stationary energy production alone (Bumpus & Comello 2017), which currently causes 25% of the global GHG emissions (IPCC 2014). Still, this will not be enough to achieve the goals of the 2015 Paris Climate Agreement (Bumpus & Comello 2017), nor to even reach the two-degree goal (Rogelj et al. 2016). Overall, almost 20 years after the Kyoto Protocol, global greenhouse gas (GHG) emissions are still reported to be on the rise (IPCC 2018; Myhre et al. 2017). There are several reasons for the failure of the Kyoto Protocol, one of which is the unintended problem of it allowing carbon leakage (i.e. outsourcing of emissions to other countries) (e.g. Rosen 2015). Evidence of carbon leakage has been found (e.g. Kanemoto et al. 2014; Wood et al. 2018), particularly in high growth and developed countries (; de Vries & Ferrarini 2017). Aichele & Felbermayr (2015) quantified growth of 8% in carbon imports by the countries committed to the Kyoto Protocol from non-committed countries.

Regardless of the growing awareness of carbon leakage, most current GHG emissions accounting systems are based on territorial boundaries. At the same time, the emissions embodied in trade have increased significantly, reaching nearly one-third of all global GHG emissions (Kanemoto et al. 2014; Sato 2014; Wiedmann & Lenzen 2018). And the smaller the assessed entity, the higher the reliance on imports typically is, as shown by studies of small geographic areas. On a national level Clarke et al. 2017) showed this for Iceland and Schulz (2010) for Singapore. On a sub-national level, cities and other governance units are increasingly devising GHG mitigation strategies of their own, trying to step to the forefront of climate change mitigation (C40 Cities 2018, 2019). However, this exacerbates the issue of emissions outsourcing as these sub-national units rely on other entities within their countries in addition to the national-level emissions outsourcing as discussed by e.g. Ramaswami et al. (2016) as a global theory, and shown by e.g. Chen et al. (2016) for five Australian cities, Hasegava et al. (2015) for Japan's governmental regions and Moran et al. (2018) across global cities. This suggests that any successful and truly effective GHG accounting scheme, particularly at a city, but also at any spatial scale, calls for sensitiveness to transboundary flows.

Consumption-based accounting (CBA), which allocates all the production and delivery chain emissions to the end-user, can provide information on the emissions induced by the residents and users of a certain geographic area including transboundary emissions (Baynes & Wiedmann 2009). CBA thus complements territorial assessments, and has been utilized for analyses of emissions and resources embodied in trade (e.g. Peters et al. 2010; Wiedmann & Lenzen 2018), drivers of change in emissions over time (Karstensen et al. 2018), the impacts of different local lifestyles (e.g. Bin & Dowlatabadi 2005; Baiocchi et al. 2010; Jones & Kammen 2011), rebound effects from lifestyle changes (Druckman & Jackson 2009; Thomas & Azevedo 2013; Ottelin et al. 2017; Underwood & Fremstad 2018) and urban structure - lifestyle relationships (e.g. Heinonen et al. 2013a-b; Baiocchi et al. 2015; Poom & Ahas 2016).

CBA is typically based on environmental input-output (IO) analysis (see e.g. the reviews by Wiedmann (2009), Baynes & Wiedmann (2012) and Afionis et al. (2017)) which tracks embodied environmental impacts through the production and supply chains from their origin to the final products consumed (Wiedmann et al. 2016). The outputs are typically called footprints – carbon footprints (CF) in the case of greenhouse gases (GHGs) (Gao et al. 2014; Lombardi et al. 2017). The first consumption-based carbon footprint (CBCF) assessments appeared at the end of the 90s (Murthy et al. 1997; Lenzen 1998), but the number of published studies has increased steeply during the ongoing decade, particularly within the most recent years along the emergence of openly available multi-region input-output (MRIO) models (Malik et al. 2018).

Within the last few years, MRIO models have been developed providing higher geographic resolution from country scale to different sub-national scales from regional (Tian et al. 2014; Xie et al. 2015) to particularly city (Wiedmann et al. 2015; Mi et al. 2016; C40 Cities 2018; Chen et al. 2020) and intraurban scales (Chen et al. 2017, 2018). Concurrently, city and regional scale assessments utilizing country scale models, but higher resolution input data have emerged e.g. Ala-Mantila et al. (2013) on Finland, Minx et al. (2013) on the UK, Jones & Kammen (2014) on the U.S. and Hasegava et al. (2015) on Japan).

The development from single region IO (SRIO) to MRIO models and from national level to sub-national has meant leaps in the accuracy of assessments (Wiedmann et al. 2011; Tukker & Dietzenbacher 2013). Higher-resolution spatial data assessments have provided new understanding of the impacts from different types of settlements and urban zones. At the same time, however, the field is still in many ways immature. The assessments published under the CBCF umbrella vary greatly. The scopes of both, the included consumption activities and the emission sources vary, the same terms are used to indicate different issues, different functional units (FU) are used, different models produce different outputs, etc. In addition, the assessments with essentially the same approach are labeled with varying names which do not necessarily reveal the type of assessment in question. While these issues are familiar to the practitioners of the field, they may reduce the usability of the results in policy- and decision-making.

So far no comprehensive review and analysis of the technical and conceptual development of the CBCF research field has been conducted. Ottelin et al. (2019) and Afionis et al. (2017) have recently presented reviews on the CBCF literature, but both studies concentrate on the policy-making utility of CBA and policy-guidelines provided by CBCF studies. Other recent reviews have only included CBCF as one assessment approach among others to study the impacts caused by a certain consumption unit type (Zhang et al. 2015; Druckman & Jackson 2015), settlement or region Dong et al. (2016) and only included selected studies, or have focused on a certain demand component such as capital formation (Chen et al. 2019);;. The earlier reviews (Hertwich 2011; Wiedmann 2009; Kok et al. 2006) have been conducted before the majority of the current CBCF studies and before the main currently used assessment models have appeared on the market. To fill this gap, we present a systematic review of the CBCF literature searching for answers to the following research questions (RQs):

1. How has the field of literature developed and what are the main current development directions?
2. What are the main conceptual and technical differences between the studies?
3. What conclusions and future research suggestions can be drawn?

Section 3 is devoted to answering RQ1, Section 4 discusses the different perspectives to RQ2, and Section 5 ends the paper with our responses to RQ3. The scope of this review includes all spatial CBCF literature from multi-national to sub-city scale fulfilling the conditions presented in Section 2.

2 Review process

2.1 Scope definition

The scope of this review covers CBCF studies meeting the following criteria:

1. Peer-reviewed academic studies published in English in academic journals or as book chapters.
2. No review papers and discussion papers without any new empirical findings.
3. Only studies presenting full CBCF results for a certain geographic area showing emissions from different consumption categories.

Reports, conference papers, and review and policy papers that only used data from other studies were excluded. The last criterion was set to distinguish full CBCF studies from structural decomposition, industry linkage or trade flow analyses. These studies might occasionally use aggregate consumption data to assess the global embodied emissions from industries but do not present results from a consumer perspective. The last criterion also ruled out individual person carbon footprint assessments without geographic area context. We further classified studies by the method and spatial scope (Figure 1).

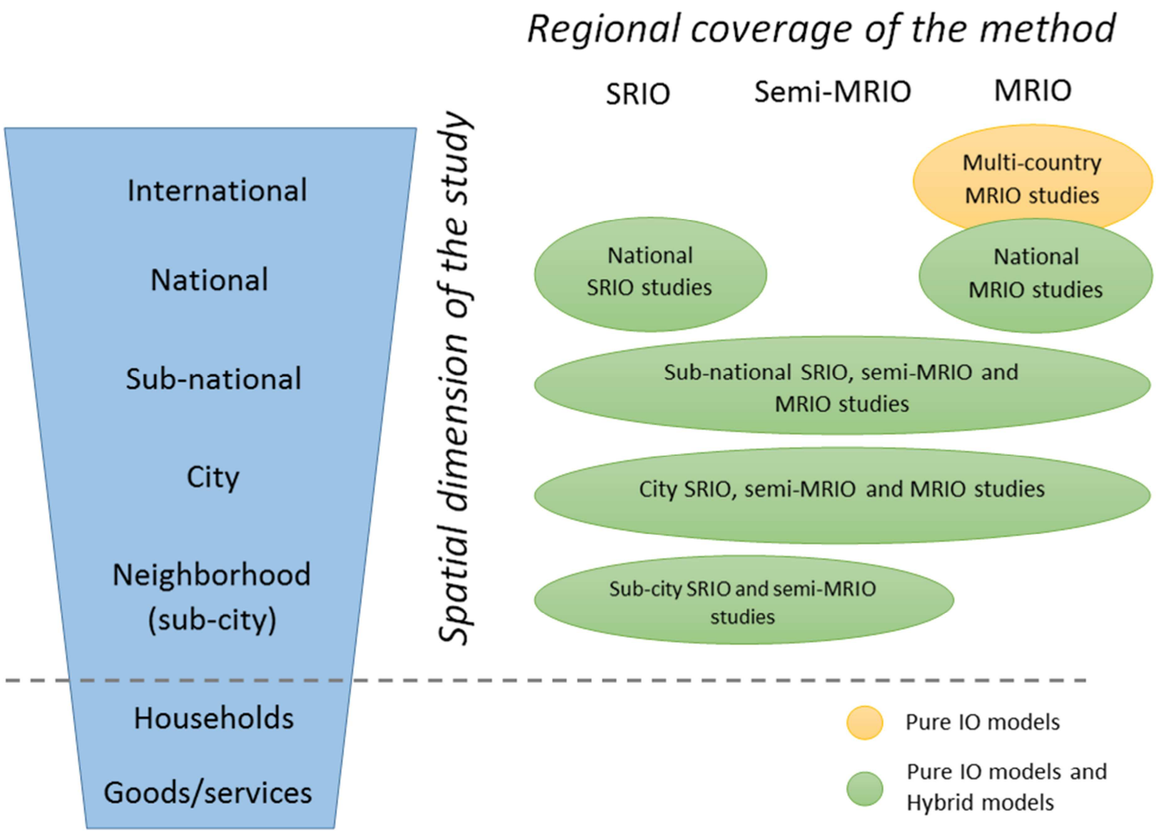

Figure 1. Scope of the review (above the dashed line) and classification of studies by method and spatial dimension. SRIO/MRIO = single/multi-region input-output model.

All partial assessments on specific consumption categories were excluded, as well as territorial or production-based (PB) assessments. Also ruled out were different assessment frameworks, including perspectives from both CB and PB approaches such as community-wide infrastructure GHG emissions footprinting (CIF) (Ramaswami & Chavez 2013), the demand-centered hybrid approach used by Ramaswami et al. (2008), the combined production and consumption approach employed by Roibas et al. (2017), the “metropolitan carbon footprint” analysis of Sovacool & Brown (2010), and urban metabolism applications (e.g. Goldstein et al. 2013; Kennedy et al. 2011; Haberl et al. 2019). All these approaches include important differences from the CBCF approach, rendering them incomparable in terms of this review.

2.2 Material selection process

Papers were systematically selected following a three-stage process. First, the snowball method was used, following the trail of references starting from an initial set of publications selected based on the authors' knowledge. Papers published up to December 2018 were included.

Second, a systematic literature search was conducted, with the additional selection criteria of only including journals that are listed in Scopus. The final search strings used in the Scopus database were:

TITLE-ABSTRACT-KEYWORD search algorithm ("consumption-based" OR "consumption based" OR "IOA" OR "MRIO" OR "input output" OR "input-output") AND ("carbon" OR "CO2" OR "GHG" OR "greenhouse gas")

Third, all papers not fulfilling the selection criteria were rejected. The initial snowball sample included 118 studies, out of which 37 were rejected, leaving a collection of 81 studies. Two Scopus searches were conducted. The first one in September 2017 led to a sample of 2,074 papers, of which 119 were screened. Out of these 119 studies, 25 were accepted and added to the snowball collection. The second Scopus search was conducted in November 2019 to add papers published until the end of 2018. This added four papers to the final review, leaving 110 papers as the overall review material collection. The full review collection with some key information from each paper is presented in the Supplementary Information (SI) Table 1.

2.3 Data collection and analysis process

To answer the RQs of the review in a systematic way, data from the literature were collected on two levels: article level and individual case level. On the article level, the particular focus was on the assessment method and model, utilized data, level of analysis, footprint type, data scope, and geographic scope. On case level, spatial scale, scope definitions, level of analysis, functional unit, utilized IO model, input data and the reported footprints were analyzed.

The reviewed 110 papers reported 615 cases which were included in the review data. Only cases representing the average footprint over a certain geographic scope or area type within a certain geographic area were included, whereas, for example, income basket comparisons and family type or consumer type comparisons were left out due to the low comparability of them with other studies and low added value to this review. One exception was made for Moran et al. (2018), who present the carbon footprints of 13,000 cities, from which we included only selected areas on the case-level.

3 Development of the research field

The first CBCF studies were published in the 1990s for India (Common & Salma 1992) and Australia (Murthy et al. 1997; Lenzen 1998), but the number of published studies remained low until around 2010 (Figure 2a). Along with the emergence of several global MRIO models (Malik et al. 2018; Wiedmann & Lenzen 2018), the number of published studies has been increasing rapidly, well exceeding 100 studies published in academic peer-reviewed journals by 2019.

A total of 108 out of 110 reviewed studies used an IO or an IO-based hybrid approach. Only two papers calculate the CBCFs using a physical unit approach (Girod & de Haan, 2010; Schulz, 2010) and two using partially physical data (Froemelt et al. 2018; Dias et al. 2018). Furthermore, only Girod & de Haan (2010) provide deeper discussion about the positive and negative perspectives of using either monetary or physical data. The most widely applied global MRIO

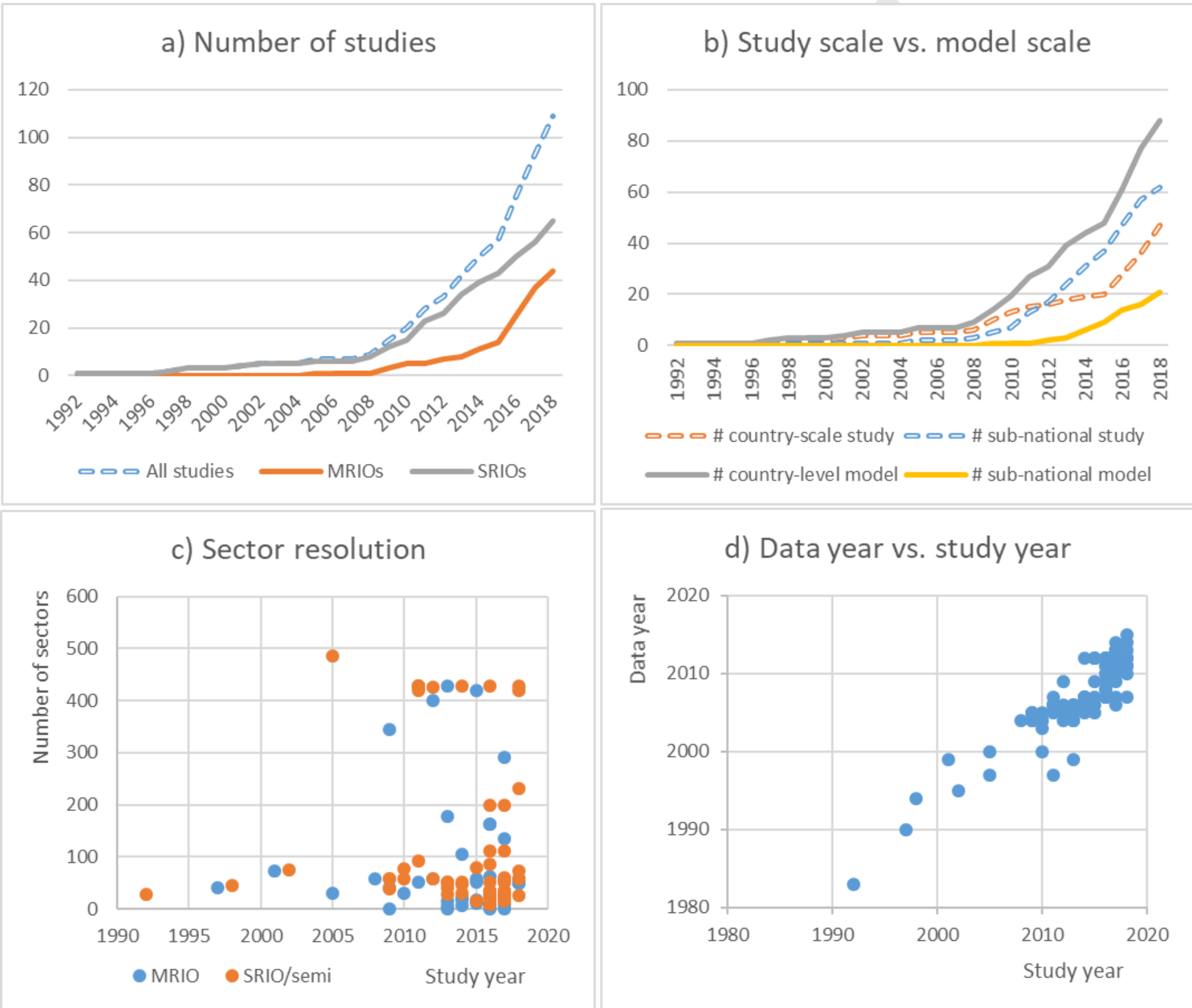

Figure 2. Illustration of the CBCF literature development: a) number of studies and their split into MRIO and SRIO -based studies; b) study scale (dashed lines) and model scale (solid lines); c) sector resolution; d) data vintage.

models in the reviewed literature include GTAP, WIOD, Eora and Exiobase. In addition, SRIO and Semi-MRIO models, such as the US EIO-LCA, China's IO-model, and Finland's ENVIMAT, have been used in several studies.

Some clear development directions could be detected. The above-mentioned emergence of MRIO models led to an increasing share of studies employing MRIO models, both at international and sub-national scales. However, it was only in 2016 that more MRIO-based than SRIO-based assessments were published for the first time, and still a considerable number have utilized SRIO models in the most recent years (Figure 2a). Another clear development has happened concerning the spatial scope. While the majority of the published studies are still based on a national scale as the highest resolution, the development towards sub-national level studies has been rapid during the past few years (Figure 2b), as called for by Chen et al. (2016) and Hasegava et al. (2015). The number of multinational studies has increased recently somewhat as well, but note that in Figure 1b the studies including more than one country, with national scale as the main unit, have been listed as country-scale studies. Following the development towards sub-national scale studies, particularly city-scale, sub-national level models have appeared, though still the majority of sub-national scale studies are performed using national-scale models (Figure 2b).

The geographic coverage is fairly wide overall, but mostly due to the few studies covering all the countries included in the main global MRIO models. The multinational studies focus predominantly on lower-income countries, but higher-income countries remain more widely studied. China has become the most-studied country, with a very rapid increase in published studies on China since 2015. Finland, Australia and the USA are the next most-studied individual countries, but the major share of the countries is covered by only one or few studies (Figure 3). Based on the affiliations of authors, China is also the most diversely studied country.

Looking at the development of the CBCF literature provides an opportunity to look at the perspective of how the main problems of the IO approach have been addressed. The most commonly acknowledged weaknesses or sources of uncertainty in IO-based assessments include the aggregation error (multiple actual production sectors with varying emissions profiles comprised into one IO model sector), linearity (linear connection between emissions and prices) and homogeneity (equal emissions intensities for all products from each IO model sector) assumptions, domestic technology assumption (SRIO model assumption of imports production with domestic emission intensities) and data vintage (and quality) (Lenzen et al. 2010; Temusho 2017; Rodrigues et al. 2018).

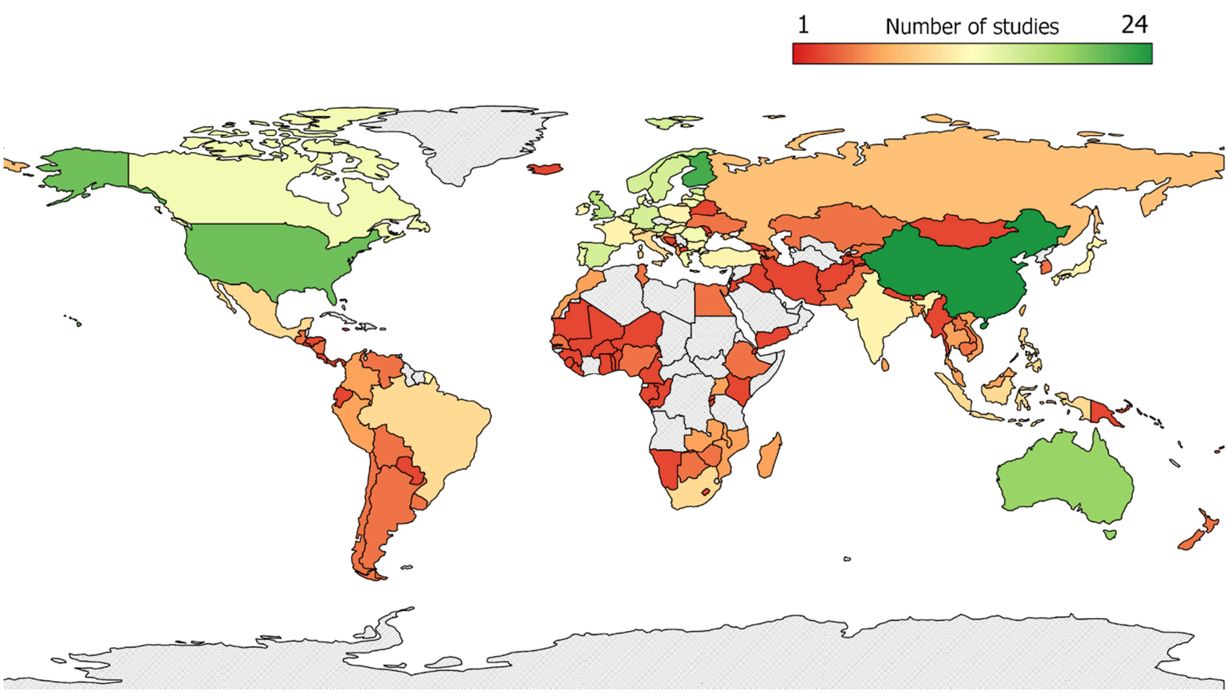

Figure 3. The geographic coverage of the reviewed CBCF literature. Moran et al. (2018) is left out due to its different nature in including 13,000 cities across the globe. Grey color = no studies have covered the country.

There has been some development towards higher sector resolutions (number of production/consumption sectors in an IO model) of the utilized models to address the aggregation error (Figure 2c). At the same time, a major share of the most recent studies has been published using models with very low sector resolutions. It actually seems that the earlier studies much more strongly made the point that the sector resolution of the utilized IO model is important and that the highest possible resolution should be selected (e.g. Lenzen et al. 2004). More recently Lenzen (2011) and Steen-Olsen et al. (2014) have provided evidence on disaggregation leading to significant accuracy improvements in IO modeling. Of the reviewed newer CBCF literature, Hasegava et al. (2015) call for higher resolution models, but still only a minor share of the most recent studies applies models reaching even 40 sectors, which Su et al. (2010) suggested as a minimum acceptable sector resolution. There also seems to be a trade-off between the spatial scope and the IO model sector resolution, particularly in sub-national scale studies.

With respect to linearity and homogeneity, the inherent assumption in the IO approach is that on average the studied populations use market average products. At the same time, it is common to study different income classes within a certain country or geographic unit, which violates this assumption. Of the reviewed studies, only one aimed at quantifying the impact of these assumptions (homogeneity and linearity). Girod & de Haan (2010) found that the quality of purchased goods increases along with affluence and that IO models likely overestimate the footprints of the more affluent consumers. Some development has taken place in addressing individual consumption patterns, particularly in the form of corrections to housing price differences (Weber & Matthews 2008; Heinonen & Junnila 2011a; Ala-Mantila et al. 2014; Ottelin et al. 2015).

Regarding the domestic technology assumption, the development towards MRIOs dominating the utilized models is a significant step towards reducing the uncertainty imposed by this assumption. However, among the sub-national scale assessments, only a few studies reach the level of within-country local technologies in their models (e.g. Wiedmann et al. 2015; Chen et al. 2016 & 2017; Fry et al. 2018). Otherwise, equal technology is assumed across the country (e.g. Hasegava et al. 2015; Mi et al. 2016; Millward-Hopkins et al. 2017). It is also common to use models with highly aggregated "rest-of-the-country" and "rest-of-the-world" regions, thus reducing the gain from sub-national scale models.

Finally, only minor improvements have been achieved with respect to data vintage. On average, analyses remain close to 10 years old when published. Only in the most recent years have more studies with a below-five-year delay appeared (Figure 2d).

4 Main conceptual and technical differences between the studies

The analyzed papers appear relatively heterogeneous in several important ways. It is important to analyze the differences and their potential impacts since the results are often compared directly, and particularly for non-professional users understanding the underlying differences in results might be difficult. Moreover, there are two different CBCF definitions that lead to different scopes and affect the assessment outcomes but are both reported as CBCFs. In the next sections, we depict the key differences which may significantly affect the assessment outcomes and the policy implications. In addition to these clearly observable differences in the published CBCF studies, it is often not clear which consumption activities are included in a specific study.

4.1 Two types of consumption-based carbon footprint assessments

The reviewed studies can be divided into two methodologically different approaches and hybrids between the two. The issue has previously been discussed in the context of MRIO modeling by Usubiaga & Acosta-Fernández (2015) and Owen et al. (2016) as ”territory and residence principles”. Lenzen et al. (2018) discuss the same issue using labels “residence-based accounting (RBA)” and “destination-based accounting (DBA)” in the context of tourism carbon footprints. However, none of the individual papers in the review collection of this study brought the issue up, and its significance for CBCF studies (beyond MRIO modeling) at different spatial scales has not been discussed before. The key difference lies in either allocating to the studied location the emissions from final purchases in the location and their global production and delivery chain emissions or allocating the emissions based on the residence of the consumers regardless of the location of final purchase (again including the indirect global emissions). Both are currently called CBCF studies without distinction, but can actually lead to very different outcomes depending on the type of the studied location.

Common definitions for the first CBCF approach type, following the territory principle, are “*impacts of local production minus impacts embodied in exports plus impacts embodied in imports” (e.g. Wiedmann 2016, p.163)*, “*impacts of production for domestic consumption + impacts embodied in imports”* (e.g. Steininger et al. 2018) or “CF is made up of: emissions from consumption of local products and services, interprovincial inflows and international imports, and direct household energy consumption" (Wang et al. 2018 after Zhang et al. 2014). These definitions do not explicitly define who the consumers (or importers and exporters) are. It is not necessarily the local residents who are the consumers and thus per-capita footprints of an area may include emissions of visitors or commuters to a significant extent. Similarly, it may be that the local residents actually largely make purchases outside their residential location. The Greenhouse Gas Protocol (2014, p. 115) definition for the CBCF approach in their city-scale GHG inventory standard states (the standard itself does not take a CB approach): *"Product use emissions may also be calculated according to consumption activities within the city boundary. This approach estimates emissions based on where the products are purchased and/or used, rather than where they are produced."* For example, Davis & Kaldeira (2010), using this approach, report that *"Per capita emissions associated with consumption in the United States are among the highest at 22.0 tons, surpassed only by Luxembourg, where per capita emissions of 34.7 tons are likely overstated as a result of the large fraction of the country's workforce that resides in neighboring countries."*

Another approach under the CBCF label follows the residence principle and includes only the consumption of goods and services of the residents of a certain geographic area. According to Heinonen (2012), the method allocates *"to a consumer the GHG emissions caused by his/her consumption regardless of the geographic location of the occurrence of the emissions."*. This type of CBCF is not affected in any way by the demand of commuters or other visitors but does include the consumption of the residents on their trips away from their home location. This clearly is a different definition than the above one by Wiedmann (2016, p. 163) and Steininger et al. (2018), and can potentially lead to significantly different outcomes, particularly as this type of assessment typically excludes capital formation and governmental consumption as they are not reflected in the monetary consumption of the residents of a certain area (see Section 4.2 below for further discussion). Figure 4 illustrates graphically the key qualities of these two approaches. The figure shows how visitor demand is included in the final demand in a region X, but how the demand of the residents can allocate to the same region or elsewhere making the household consumption components different in the two options.

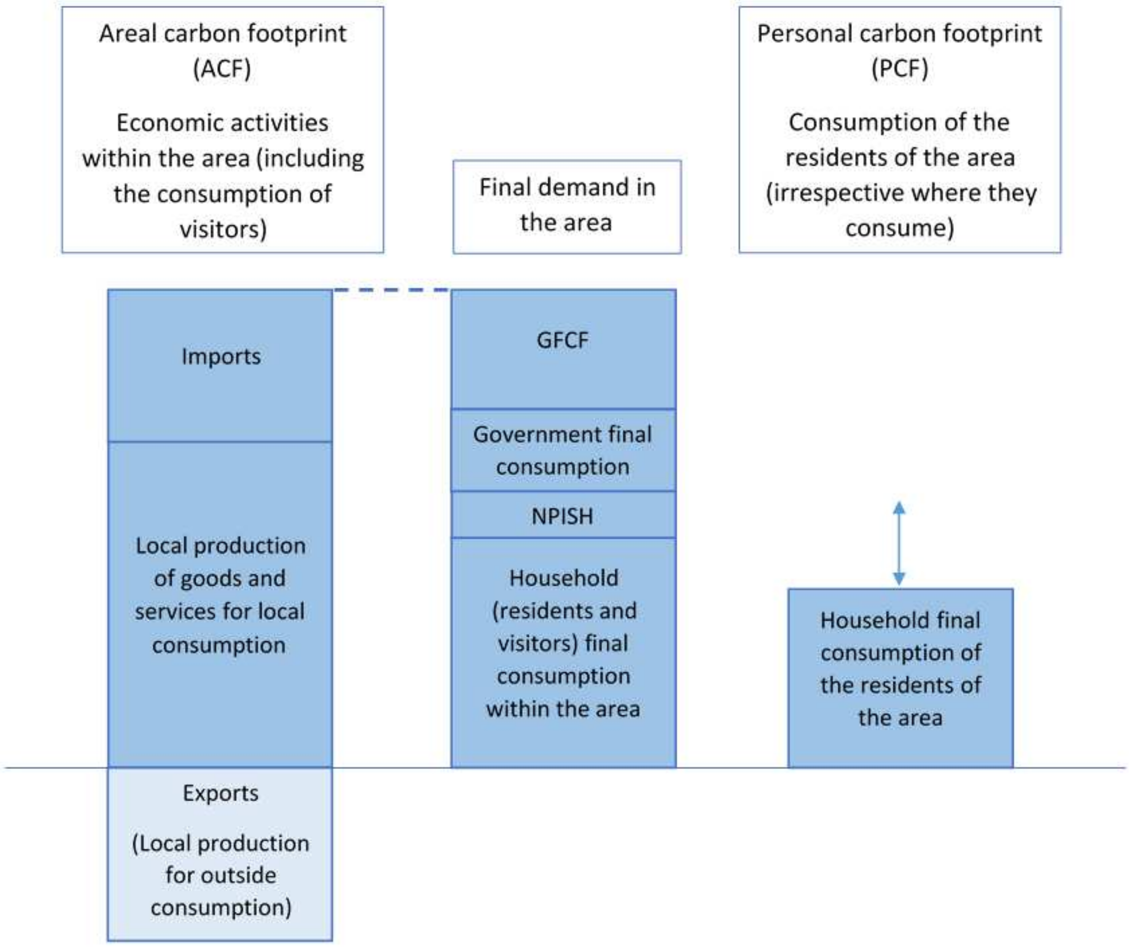

Figure 4. Illustration of the differences between the two types of CBCFs, areal and personal. In the figure GFCF means Gross Fixed Capital Formation and NPISH Non-Profit Institutions Serving Households.

There are also several hybrid approaches. The most typical in the reviewed literature (see Section 4.2) was such that personal consumption is included from the perspective of the second approach, but governmental consumption and capital formation are also included for the area under question. This approach complies with the PAS2070 standard's CB option for assessing the GHGs caused by a city, which states that: *"The CB methodology captures direct and life cycle GHG emissions for all goods and services consumed by residents of a city, i.e. GHG emissions are allocated to the final consumers of goods and services, rather than to the original producers of those GHG emissions. The CB methodology does not assess the impacts of the production of goods and services within a city that are exported for consumption outside the city boundary, visitor activities, or services provided to visitors. The CB methodology focuses solely on economic final consumption activities in a city, defined as those related to expenditures by its resident households, governments located within the boundary, and business capital expenditure."* (The British Standards Institution 2014, p. 1). This approach is a hybrid since the last two components, governmental consumption and capital formation, are allocated to the residents differently than their private consumption; many items in these two components cannot be allocated to individuals in any other way than in equal shares, and the emissions related to them relate partially to visitor-users and not only to the residents themselves. This last issue becomes particularly important when the assessed geographic area is small or thinly populated.

The same methodological issue concerns the construction of IO-models. For example, WIOD and EXIOBASE follow the residence principle, whereas GTAP and Eora apply the territorial principle (Owen, 2017). When a study uses the IO model data directly, the principle remains clear. However, in the reviewed literature, it is common to combine IO model data with other data sources, such as household budget surveys (see SI Table 1), which may change the scope again, for example, if the survey in question includes expenditures abroad.

In the reviewed literature, the issue of which type of footprint is in question in a certain study is rarely brought up, and the typically utilized terminology does not reflect this issue at all. Only approximately 50% of the reviewed studies even mention the term carbon footprint, and numerous different terms have been utilized and/or suggested by different authors. These include Embedded Carbon Footprint (ECF) (Fan et al. 2012), Per-capita Household CO_2 Emissions (PHCEs) (Liu et al. 2017), Household Carbon Emissions (Serino 2017), Household Environmental Impact (HEI) (Ferguson et al. 2011), Carbon Consumption Level (CCL) (Hu et al. 2016), per-capita Household Carbon Emissions (HCE) (Maraseni et al. 2016), Consumption-Based Footprint (CBF) (Froemelt et al. 2018) and consumption-based CO_2 Emissions caused by Household consumption (CCEH) (Zhang et al. 2014). City Carbon Footprint has been employed by Chen et al. (2017) and Wiedmann et al. (2015) for an assessment following the first definition, and by Laine et al. (2017) for an assessment following the second definition. In addition, Urban Carbon Footprint (UCF) has been used by Lin et al. (2017) for a consumption-based assessment and by Lombardi et al. (2018) for a production-based assessment.

To better categorize studies, we propose that future studies label these two different approaches as *Areal carbon footprint (ACF)* and *Personal carbon footprint (PCF)* (Figure 5). CB and PB assessments form the main approaches with combined systems that fall in between (see Lombardi et al. 2018 for an overview of the different approaches). All footprints fall under the

CBA umbrella, and finally, the carbon footprint is divided according to the two CBCF types presented above, with their different hybrid applications.

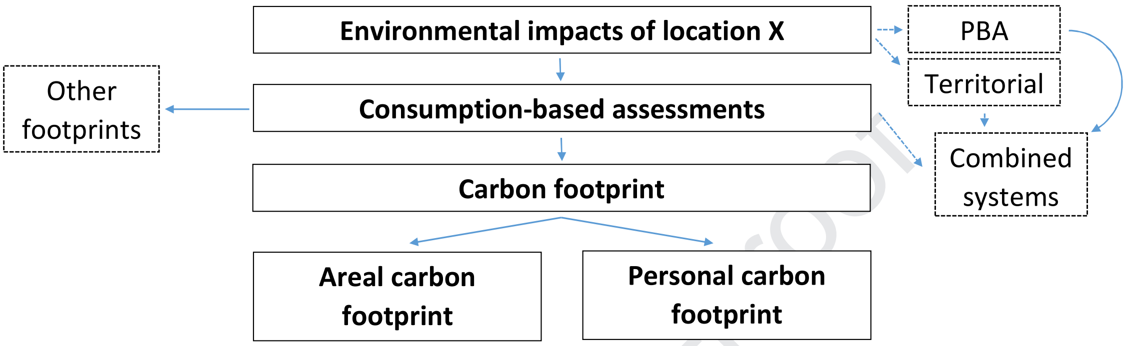

Figure 5. ACF and PCF in the assessment approach hierarchy of assessing the environmental impacts of location X.

4.2 Variation in the assessment scopes

The review revealed substantial scope differences between different CBCF studies, partially related to the different definitions discussed above, and partially to other criteria. As shown in the next sections, up to 80% of the emissions reported in one study come from sources that can be excluded from another, potentially leading to very different policy implications. While the transparent reporting of scope belongs to the key requirements of traditional process LCAs, it does not seem to be customary in the reviewed CBCF literature. In fact, many papers do not describe the study scope explicitly at all. We suggest clear and transparent scope reporting for all future studies following the topics provided in the next sub-sections.

4.2.1 Governmental consumption and capital formation

First, governmental consumption and capital formation can be either included in or excluded from a certain CF study without the label utilized reflecting these choices in any way. Typically, this is only reported as an omission, weakness or uncertainty. At the same time, some studies report capital formation, particularly for rapidly developing regions, as the most important source of emissions, potentially exceeding 50% of the overall footprints (e.g. Södersten et al. 2018a; Mi et al. 2016; Li et al. 2018). Chen et al. (2016) report construction due to economic and population growth as the most important sector for all the studied ten cities from Australia and China with shares from 21 to 41% and Steininger et al. (2018) for Austria overall with a share of over 10%. Ivanova et al. (2015) found a similar range for capital formation and governmental consumption combined for EU countries and (Ottelin et al. 2018) report these categories as making up around 20% of the CBCF. Approximately one-third of all studies include these two components and two-thirds do not (or do not mention including them) (see SI Table 1).

Governmental consumption and capital formation also potentially receive different treatment in the above-described two CBCF approaches. In ACF these categories are easily included following the same method with all types of activities within the geographic area in question. In PCF, governmental consumption and capital formation are typically not included in the assessments as they do not appear as a part of the monetary consumption of the residents of the area assessed. Similarly, as with emissions embodied in imports, this issue becomes more important along with reducing spatial scale due to increasing randomness in public services located in and capital investments allocated to the area in question. Particularly when the focus is on the behavioral differences of the residents on sub-city scales or between those living in different types of urban zones, getting reliable estimates on the use of public goods becomes difficult, and including capital formation in any other way than as equal shares for each, is virtually impossible (see Ottelin et al. (2018) for further discussion).

In the future these problems can be overcome if capital formation is included in the emissions from each production sector instead of keeping it as a separate entity in IO models (Minx et al. 2013; Södersten et al. 2018b), and if data sources are improved with information on public service use (Ottelin et al. 2018). However, as pointed out by Chen et al. (2018), the role of capital formation is typically very different in developing and developed countries, and "...*we need to be very cautious for the interpretation and comparison of the traditional emission footprint results when developing countries are involved*". It also strongly depends on the use of the assessment results if it is preferable to look at governmental consumption and capital formation components separately or combine them in with final private consumption sectors. Important as well is to notice that the capital emissions endogenized in the IO model sectors would not be the same as those in a territory principle assessment, as they would summarize global emissions based on private consumption rather than show the emissions from local capital production (see Södersten et al. 2018b for details on the endogenization).

The size of the public sector, and particularly the goods and services provided as free of charge or heavily subsidized to the residents, also vary significantly between different countries and affect the scopes of studies including personal consumption only. For example, Weber and Matthews (2008) report health care among the more important CF categories in the U.S., whereas in the Nordic countries the sector is heavily subsidized and typically almost disappears from the GHGs caused by private consumption (e.g. Heinonen et al. 2013a; Steen-Olsen et al. 2016).

4.2.2 Fossil and non-fossil CO_2 and other GHGs

Both CO_2-only assessments and those including non-CO_2 emissions are commonly called carbon footprints. In addition, non-fossil CO_2, particularly cement production, may be included or not. In the review materials, approximately 25% of studies include only CO_2 and 75% at least some non-CO_2 GHGs. Out of the CO_2-scoped papers, the majority include also non-fossil CO_2, but there are exceptions to this (e.g. Maraseni et al. 2016; Zhang et al. 2017). In the majority, the term "carbon emissions" is used to refer to either CO_2 or any GHGs.

Conclusions and policy implications are often drawn without reference to the GHG scope. However, the non-CO_2 GHGs form a 25% share of the global annual GHG releases (IPCC 2014) and affect very differently countries with different development levels (Hertwich and Peters 2009; Hertwich 2010; Homma et al. 2012). According to Hertwich and Peters (2009), the non-CO_2 GHGs are in a dominant role for countries up to $1000 per-capita annual expenditures and have much lower expenditure elasticity than CO_2. Hertwich (2011) states that "*The importance of food production of the overall greenhouse gas emissions from households … depends crucially on whether land use change and the emissions of methane and nitrous oxide are included in the assessment*". Furthermore, it has been suggested that the cement calcination process accounted for more than 10% of the CO_2 emissions of the whole country during the time when China surpassed the U.S. as the biggest CO_2 emitter (Gregg et al. 2008), meaning that at the city level the impact can be significant in rapidly developing places with high capital formation rates. These issues largely remain unaddressed in CBCF studies. They can also be magnified at the sub-national level due to concentration in infrastructure development.

4.2.3 Land use, land use change and forestry

Land use, land use change and forestry (LULUCF) can cause another potential important difference between the results of two different studies of the same area. Overall their global impact is close to 10% (IPCC 2014), but as with non-CO_2 GHGs, they are unequally distributed and they potentially dominate the emissions in many countries (Hertwich and Peters 2009). However, it is not clearly reported in many studies if they are included or not, and their potential impact is rarely discussed. In the included review materials only a minor share of the studies seems to include the LULUCF sector, likely due to the difficulties in assessing these emissions and particularly in reliably connecting them to IO model sectors.

4.2.4 Direct stationary energy use

Direct stationary energy use, mainly housing energy, is in the majority of the published CF studies found as one of the major GHG contributors. However, it seems that there are major differences in how housing energy is captured in different studies. First, in many places it is common to cover utility payments fully or partially as part of housing fees and rental payments. Not extracting these embedded energy payments and assessing appropriately as energy use may significantly bias an assessment towards underestimating the housing energy-related emissions in cities and particularly regarding apartment buildings where the embedded payments are the most common (Heinonen & Junnila 2011a; Ala-Mantila et al. 2014). In Finland, for example, in apartment buildings 30-40% of housing payments is embedded energy (Heinonen and Junnila 2014) and when taken into account, the energy purchases of the residents of different types of areas and those living in different types of buildings become roughly equal (Heinonen et al. 2013a). Heinonen (2016) reports a similar situation in California. In the majority of the reviewed studies, the issue is not mentioned, likely meaning that the embedded energy payments are not separated and housing energy-related emissions may thus be underestimated.

Households' direct emissions from the combustion of fuels are not included at all in some studies (e.g. Mi et al. 2016). In these studies, the bias can be significant in comparison to studies accounting for direct household combustion, and the results should not be compared, but currently, the reader bears the responsibility of finding out the scope regarding the direct emissions.

4.2.5 Durable goods

The most widely utilized input data in CBCF studies are consumer expenditure surveys (see SI Table 1). A well-known problem with such consumption data is that it does not reflect well spending on durable goods. This concerns particularly owner-occupied housing and private vehicles, but also other durable goods paid to a large extent through loans over a longer period of time. This means that without adjustments these goods don't appear similarly as other goods and services, based on purchase prices, in the assessments. The issue has not received much attention in the published studies, but some amendatory processes have been suggested. For residential buildings, Ottelin et al. (2015) present an adjustment model that annualizes the GHG load over the historical average life cycle of different types of buildings, leading to 0.6-0.8 tCO_2e emissions per capita from residential construction in the Helsinki Metropolitan Area. Weber & Matthews (2008) tested dollar-based or living-space-based estimates but found the sector contribution low (below 5%). However, these approaches still differ from the general CBCF tradition to allocate the production phase emissions of a product fully to the user based on the moment of purchase. Heinonen et al. (2012) present a model in which no annualization is used and show that for the residents of new buildings the embodied emissions are several times higher than the emissions caused by all other consumption activities for the purchase year. They also show how the construction-related emissions can dominate the carbon footprints of the residents of new buildings for decades.

In the two different types of CBCFs presented in 4.1 this issue appears again differently. Residential construction is one component of capital formation and inherently included when the capital formation is included (as typical in ACF) but does not reflect housing type differences. In PCF assessments residential construction can be allocated to the buyers of new homes but does not appear robustly using only the traditional annual consumption information. Some studies also simply leave out the residential construction component. Mach et al. (2018), for example, excluded expenditures on buying, renting or building a dwelling *"since the purchase of a dwelling is considered to be a capital investment."*

The situation is similar for vehicles, particularly for private cars. Only Ala-Mantila et al. (2014) and Heinonen (2016) address the issue, albeit in very different ways. Whereas Ala-Mantila et al. (2014) aim at splitting the impact of vehicle acquisition over time similarly as Ottelin et al. (2015) with buildings, Heinonen (2016) allocates the emissions of vehicle production directly to those purchasing new vehicles as is common with any other goods purchases. In Ala-Mantila et al.'s solution, the importance of these emissions remains low, but Heinonen's approach gives 1.0 tCO_2 per-capita emissions from vehicle production for an average Californian family with children and 0.2 tCO_2e per-capita for adult households, meaning that the issue can be somewhat important.

4.2.6 Imports

In SRIO studies imports are normally included assuming domestic GHG intensities, making them randomly over- or underestimated. However, Feng et al. (2014), Hasegava et al. (2015), Wang et al. (2018) and Long et al. (2018) only include emissions originating in the studied countries. Leaving out imports entirely leads to potentially important differences in the scopes of different studies, and should thus be transparently reported.

4.3 Other differences reducing the comparability of CBCF studies

Many other differences reduce the comparability of different assessments. For example, the unit of analysis varies, some studies employing household as the unit (e.g. Jones & Kammen 2014; Shigeto et al. 2012; Thomas & Azevedo 2013) whereas the majority operate at the per capita level. The consumption unit as defined by the OECD[1] is also utilized in several studies, but it is only used by Isaksen & Narbel (2017) as the primary unit. Some papers only report the overall areal CBCF. The unit decision can affect the outcome substantially, particularly with sub-national scale studies as the general tendency is decreasing household sizes towards more urbanized areas. Heinonen (2016) shows for California how the outcome changes radically with changing the unit from household to per capita.

Another issue is that the geographic scope affects the specificity of an assessment. Clarke et al. (2017) show an example for Iceland on how different IO model consumption data can be from local consumption surveys. Above it was discussed how important it can be to correct for utility payments embedded in housing management fees and rents, but in multi-country studies, such

[1]The first adult (aged 18 and over) is weighted as 1, the following adults 0.7, and persons under 18 as 0.5.

corrections are not done. Generally, it is evident in the review collection that there is a trade-off between the geographic coverage and the specificity of including local information into the assessment. An extreme example of this trade-off is Moran et al. (2018) who present an assessment of 13,000 cities with limited information. Fry et al. (2018) discuss in detail the issue of conducting assessments with limited information available.

4.4 Examples of inconsistent results

Overall, when looking at the published CBCF studies, it seems that there is inconsistency in the results. Particularly when it comes to less developed countries there seems to be high variation in the results when several different studies have concerned the same place using different IO models and input data. The impact of the IO model choice is seldom discussed in individual CBCF assessment papers, but many studies note that the quality of consumption data is reduced towards less developed countries. In addition, as our own observation, in many studies the scope is not defined clearly. Thus it occurs that in some studies the scope in included consumption activities is wider than in others even though in theory all consumption activities within the selected footprint type (ACF/PCF) should by default be included.

In Figure 6 the high- and low-end estimates from different studies are shown to some selected locations. In many cases, in between the extremes, there are several estimations without any clear uniformity. For example for China, Ivanova et al. (2017) recently estimated an average per capita CBCF of 1.8 tCO_2e, Hubacek et al. (2017) 4.8 tCO_2e and Fry et al. 7.6 tCO_2e. All these studies also include both capital formation and governmental consumption and include non-CO2 GHGs. Similar problematic issues exist for other locations as well. Even for the USA, the spread is wide: from 10 tons (Wiedenhofer et al. 2017) to 28 tons (Hertwich and Peters 2009) and for EU27 Wiedenhofer et al. (2017) give an estimate of 6.7 tons, Steen-Olsen et al. 13.0 tons and Ivanova et al. ~10 tons. On a city-level, the estimates fall similarly far apart, although few city-locations have been studied by different groups of researchers. A good example is Beijing, which has been studied extensively. For it, e.g. Moran et al. (2018) report the CBCF per capita as 4.2 tCO2e, whereas Lin et al. (2017), Hu et al. (2016) and Chen et al. (2016) all report CBCFs of over 17 tons.

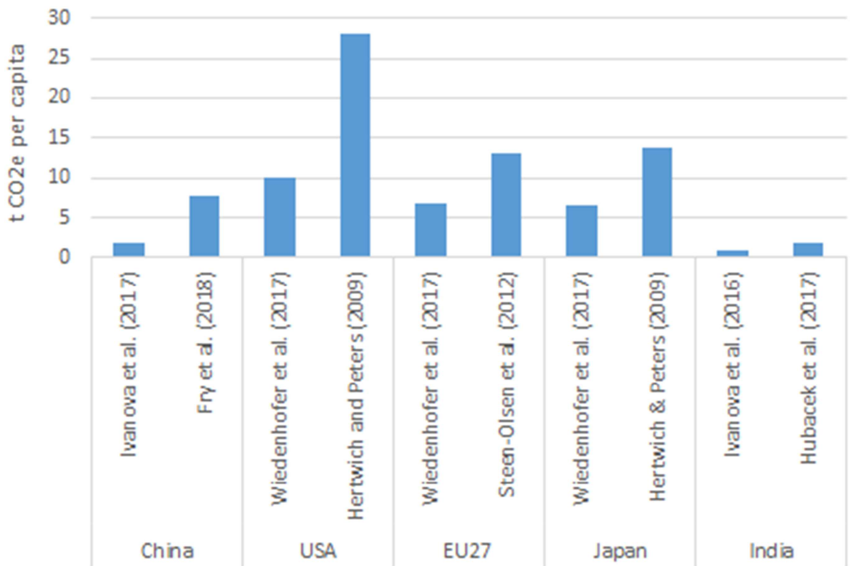

Figure 6. The high- and low-end estimates from different studies on some selected locations.

The observations are in line with previous literature about the CBCF uncertainty ranges increasing towards lower development level countries. Rodrigues et al. (2018) suggest uncertainty ranges of 5-10% in OECD countries and 10-20% in non-OECD countries on a country level - and significantly higher at the sectoral level. Similarly, Moran & Wood (2014) find significant result variation between different MRIO models, but also that over time the different models reveal similar patterns of change. Owen et al. (2016) and Peters et al. (2012) suggest that the differences between the MRIO models are to a large extent explained by methodological model construction choices rather than arising from uncontrolled uncertainty factors such as data for sectoral emissions. Owen et al. (2016) actually find the above-discussed residence or territory principle issue in MRIO-models as one of the key sources for the differences in results. Overall the uncertainty is also likely much higher in sub-national scale assessments.

5 Conclusions

5.1 Main findings and suggestions for conceptual improvement

In this review on the CBCF literature, we have concentrated on the development of the CBCF field and on the technical and conceptual heterogeneity of the assessments. We have shown several findings important for the academic community, CBCF practitioners and users of such studies. Below we present the three key findings we think should be noted and a suggestion for improvement related to each one.

1. CBCF studies fall into two methodologically different categories (and their hybrids), which we suggest to label as *Areal CF* and *Personal CF*. The first one includes the final demand in an area in question regardless of who the consumers are, and typically includes capital formation and other final demand categories. The second one includes

the consumption of the residents of the area in question regardless of where the consumption activities take place and typically excludes investments and demand by governments.

2. Scope reporting should be improved. Currently, it takes a lot of effort and expertise to classify studies under the CBCF label by their different scopes. We suggest clear and transparent reporting of both the GHG scope and the system boundaries (particularly potentially omitted consumption components) following the categories presented in Section 5.2:

    a. Governmental consumption and capital formation
    b. Greenhouse gases included
    c. LULUCF
    d. Direct energy use
    e. Durable goods
    f. Imports.

3. There is significant variation in the results of the studies published on the same location. We suggest paying more attention to this issue in future studies by positioning each study among the previous studies of the same location and discussing the potential reasons for the differences in the results and considering the issue when drawing policy-implications.

5.2 Directions of future research

We reviewed the recommendations for further research from the CF literature published in 2015-2018. In addition, we suggest some new research directions based on the findings of this review.

First, most studies recommend increasing the accuracy, coverage, and applicability of CBCF assessments by using bottom-up data to refine top-down estimates from IO data (e.g. Athanassiadis et al., 2018). Such survey-based data can help to increase the number of sectors and regions in the model and the carbon intensity coefficients assigned to each region (Hasegawa et al., 2015; Chen et al., 2016a; Chen et al., 2017; Chen et al., 2018; Lin et al., 2017; Zhang et al., 2016).

Second, multi-model (and multi-year) comparisons – as have been carried out for global MRIO models (Owen, 2017; Moran & Wood, 2014), for example – would shed more light on the reliability of city-scale models (Athanassiadis et al., 2018; Miehe et al., 2016). Relaxing the linearity assumption in standard IO models by adjusting trade flows with prices has also been suggested (Heinonen, 2016; Chen et al., 2018) and partly implemented (Ala-Mantila et al. 2014).

Third, most CBCF studies only take into account activities over a one-year period. However, a deeper understanding of the full life-cycle emissions of buildings and infrastructure is also required (Ottelin et al., 2015; Ottelin et al., 2018). Similarly, the lifestyles of people vary significantly depending on their age and life situation, and therefore personal longitudinal assessments would provide valuable new information about the carbon performance of different urban regions.

In addition, three gaps or under-investigated areas requiring further work arise based on the findings of this review. First, research should take place comparing the differences in the outcomes of the Areal and Personal approaches to CF: under which conditions do they return similar estimates and when the results are not comparable? Second, future works should aim at endogenizing capital production and governmental consumption into personal final consumption to give a choice for the researcher to look at them in both ways, as globally spread emissions related to consumption of goods and services or as separate local sectors. This development would also bring ACF and PCF closer to one another. Third, future studies should address the issue of quality and errors when comparing consumers at different affluence levels.

Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

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Highlights

1. Review of over 100 consumption-based carbon footprint (CBCF) studies is presented
2. Studies with the same CBCF label fall into two methodically different categories
3. Results between the two categories can vary significantly
4. Study scopes are often weakly reported which hinders the usability in policy-making
5. Research space exists in the fields of hybrid models and model sectoral detail