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TOPICAL REVIEW

What can we learn from consumption-based carbon footprints at different spatial scales? Review of policy implications

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Abstract

Background: Current climate change mitigation policies, including the Paris Agreement, are based on territorial greenhouse gas (GHG) accounting. This neglects the understanding of GHG emissions embodied in trade. As a solution, consumption-based accounting (CBA) that reveals the lifecycle emissions, including transboundary flows, is gaining support as a complementary information tool. CBA is particularly relevant in cities that tend to outsource a large part of their production-based emissions to their hinterlands. While CBA has so far been used relatively little in practical policymaking, it has been used widely by scientists. *Methods and design*: The purpose of this systematic review, which covers more than 100 studies, is to reflect the policy implications of consumption-based carbon footprint (CBCF) studies at different spatial scales. The review was conducted by reading through the discussion sections of the reviewed studies and systematically collecting the given policy suggestions for different spatial scales. We used both numerical and qualitative methods to organize and interpret the findings of the review. *Review results and discussion*: The motivation for the review was to investigate whether the unique consumption perspective of CBA leads to similarly unique policy features. We found that various carbon pricing policies are the most widely supported policy instrument in the relevant literature. However, overall, there is a shortage of discussion on policy instruments, since the policy discussions focus on policy outcomes, such as behavioral change or technological solutions. In addition, some policy recommendations are conflicting. Particularly, urban density and compact city policies are supported by some studies and questioned by others. To clarify the issue, we examined how the results regarding the relationship between urban development and the CBCF vary. The review provides a concise starting point for policymakers and future research by summarizing the timely policy implications.

1. Introduction

Current climate change mitigation policies are mainly based on territorial or production-based greenhouse gas (GHG) accounting, which allocate emissions according to the place of origin. Most importantly, the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol, and the Paris Agreement are based on territorial accounting that allocates GHG emissions according to national territories and excludes international aviation and shipping. Although the UNFCCC, the Kyoto Protocol, and now the Paris Agreement, have the principle of 'common but differentiated responsibilities' and an aim to place a heavier burden on developed countries, based on their historical emissions, they have been criticized for overlooking consumption-based emissions and the responsibility for transboundary flows (Peters 2008, Barrett *et al* 2013, Steininger *et al* 2014). Consumption-based accounting (CBA) allocates the GHG emissions caused by the whole supply chain of goods and services to the consumer, irrespective of where the emissions occur (Wiedmann and Lenzen 2018).

Production-based accounting (PBA) is similar to territorial accounting except that it includes the GHG emissions caused by international transportation (Barrett *et al* 2013). Several studies have revealed that while the production-based emissions of some developed countries have decreased under the Kyoto Protocol, the consumption-based carbon footprints (CBCFs) of the same countries may have increased during the same period (Peters and Hertwich 2008, Clement *et al* 2017, Isaksen and Narbel 2017). Thus, although we can detect the decoupling of production-based emissions from economic growth at country level, it does not mean that there is decoupling between total GHG emissions and economic growth at the global level. One of the main benefits of CBA is that it captures carbon leakage, including the so-called weak carbon leakage, which means the outsourcing of GHG emissions outside the territorial boundaries (Peters and Hertwich 2008, Davis and Caldeira 2010, Andrew *et al* 2013, Xie *et al* 2015). While the Paris Agreement tries to tackle the issue by involving all the countries of the world, it still relies on territorial accounting, which limits the understanding of the impact of trade on global emissions (Afionis *et al* 2017, Isaksen and Narbel 2017). CBA has the potential to prevent carbon leakage and share the responsibility for the emissions more fairly (Steininger *et al* 2014), but its political feasibility has been problematic (Afionis *et al* 2017). Yet Grasso (2016) concludes in his policy analysis that, in principle, official CBA is feasible at the national level if democratic and institutional frameworks are in place to support its implementation.

CBA is not only relevant at the national and international policy level. It has been argued that it is particularly relevant for cities, which often outsource their emissions to their hinterlands (Paloheimo and Salmi 2013, Feng *et al* 2014, Chen *et al* 2016a, 2016b, Mi *et al* 2016, Wiedmann 2016, Fry *et al* 2018, Moran *et al* 2018; see also Ramaswami *et al* 2016). Recently, there has been increasing interest among cities to adopt CBA as a complement to PBA. The C40 Cities Climate Leadership Group has estimated the CBCF for 79 of its member cities in order to broaden the mitigation targets and actions beyond the city boundaries (C40 cities 2018). They argue that by addressing the consumption-based emissions, in addition to production-based emissions, cities could potentially have a much greater impact on reducing global GHG emissions. However, CBA includes uncertainties due to the underlying assumptions inherent in the methodology, which restricts its usability for policymaking, particularly at detailed spatial scales (Afionis *et al* 2017, Owen 2017, C40 cities 2018). Thus, for example, Fry and co-authors (2018) call for investment into the development of CBCF models and underlying databases in order to increase the effectiveness of the consumption-based mitigation policies of cities. It has also been argued that consumption-based GHG emissions are difficult to address by city, and cities should rather focus on the emissions that they can directly affect (Lazarus *et al* 2013, Lin *et al* 2015, Erickson and Morgenstern 2016, Ramaswami *et al* 2017).

Although the implementation of CBA as an official information and reporting tool is in its infancy, it has been used widely in the relevant scientific literature. The CBCF literature, meaning studies that use CBA to assess GHG emissions, provides policy recommendations ranging from international policies to city and local policies. However, it is currently unknown how well the recommendations are in line with each other. Since the CBCF literature provides a unique perspective on GHG emissions, the policy implications may have unique features as well (Wiedmann and Barret 2013). In other words, our hypothesis is that the policy implications of CBCF studies are similar to each other but differ in their focus and emphasis from the implications of broader literature on climate change. This was the motivation for our systematic review on the policy implications of CBCF literature.

The review covers 103 studies that were published before July 2018. The amount of CBCF studies has increased steeply since around 2008 (Heinonen *et al* 2019), making this is a good moment to pause and reflect upon the results and policy implications. In this review, we analyze and summarize the policy implications of the studies. While Afionis *et al* (2017) provide a valuable and comprehensive policy analysis on the issue of whether CBA should be implemented as an official accounting method, particularly at national level, they do not discuss the other policy implications of the CBCF literature. In addition, we add the spatial dimension to the policy analysis. The discussed policy levels include international, national, and city levels. The focus of this review is on sub-national studies, since these provide the most relevant policy implications regarding the spatial dimension.

What we find is that the policy discussions of CBCF studies focus on wanted policy outcomes rather than on practical policy instruments. In other words, the majority of the reviewed studies provide suggestions for what should be done, but do not provide guidance on how. Shifting the emphasis of policy implications towards possible policy instruments, which could be used to achieve the wanted policy outcomes, would be helpful from the policymakers' perspective. Furthermore, policy recommendations are sometimes conflicting, even within the CBCF literature. Particularly in the case of urban density policies and urban development more generally, the policy recommendations split. Urban density and compact city policies are supported by some studies and questioned by others. The missing consensus may hinder decision-making (Zborel *et al* 2012). Thus, we review the actual results regarding the relationship between urban development and the CBCF in order to clarify this policy topic. The research questions of the review are:

RQ1: *What sort of policy implications the CBCF literature gives for different spatial scales?*

RQ2: *What do different studies find in terms of the relationship between urban structure and CBCFs?*

This paper is outlined as follows: section 2 presents the review process, section 3 the policy analysis, section 4 the review of the relationship between urban development and CBCFs, and section 5 the conclusions. Section 2.1 presents the selection procedure of the reviewed studies and the used review framework, and the following subsections describe how the analysis of the policy recommendations (RQ1) and the results of interest (RQ2) were done. Sections 3 and 4 provide the main results of the review and relevant discussion. The policy suggestions at each policy level are summarized in tables 1–3, in subsections 3.3–3.5. Although the review focuses on analyzing the policy recommendations given by the authors of the reviewed literature, we have taken a step further and provide suggestions for practical policy instruments, even if this is not done in the original sources. In the conclusions (section 5) we give guidelines for future research.

2. Review process

2.1. Selection and organization of the reviewed studies

The purpose of the review was to analyze and summarize the policy implications of the CBCF literature from a spatial point of view. Thus, the reviewed studies were selected based on the following criteria:

1. The study presents a full CBCF (not only selected consumption categories) of a certain geographic area showing the division of emissions into different consumption categories (instead of industrial sectors).
2. The study reports original research. Reviews and discussion papers were excluded.
3. The study is peer-reviewed and published in English in an academic journal or as a book chapter.

The main interest of the review were consumer carbon footprints. Thus, we excluded studies focusing on industry linkages or trade flows, which may assess consumption-based emissions but do not look at the results from a consumer's angle (Criterion 1). In addition, we excluded partial assessments, which focus on certain consumption categories instead of the full CBCF. We included only original research papers in order to organize and analyze the first-hand policy implications of the CBCF literature (Criterion 2). However, previous review and policy papers were used as additional references. We included all studies published until June 2018.

We used a systematic procedure to collect the studies for our review. We started with a snowball method, collecting all publications based on our knowledge, and adding new publications to the collection based on the references of the initial set of publications. This was followed by a systematic literature search with the Scopus database using the following string:

TITLE-ABSRACT-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')

We screened all papers to exclude those not fulfilling the above three criteria. The snowball method yielded 108 studies, out of which 30 were excluded after screening. The Scopus search resulted in 2074 studies. Majority of these were excluded after screening the titles and abstracts, leaving 119 studies for closer reading. Of these, 25 were accepted to the final review collection. Thus, the total review collection was composed of 103 studies (78 from snowball collection and 25 from Scopus). The reviewed studies and some key information are presented in the supplementary information (SI) (table S1) is available online at stacks.iop.org/ERL/14/093001/mmedia. We used the same collection of papers in our separate review on the comparability of CBCF studies, which focuses on conceptual and technical issues (Heinonen *et al* 2019).

We created a review framework to organize the reviewed studies (figure 1). We used the framework throughout the review to position the papers according to their spatial scale and policy implications. The generalizability of the results and policy implications increases with the increasing spatial scale. However, when the spatial scale is narrowed down, the level of detail of the analyzes increases. This allows more practical and individual policy implications. The spatial scale affects the research topics as well. Detailed spatial scale allows more detailed analyzes on urbanization and urban structure. The funnel of spatial scale narrows down to household level and product level carbon footprint studies. However, these were excluded from the review, which focuses on geographic spatial scales (dashed line in figure 1).

2.2. Policy analysis

The policy analysis was conducted by reading through the discussion sections of the 103 reviewed studies and systematically collecting the given policy suggestions for different spatial scales. In order to collect numerical information on how many times specific types of policies have been recommended, we selected upper-level policy categories that emerged from the whole review collection. Later we divided these into *policy instruments* and *policy outcomes*. While policy outcomes include suggestions related to the wanted

Table 1. A summary of international policy recommendations.

Main policy instrument	Policy recommendation	Benefits	Challenges
Command and control (CAC) or voluntary	Implementing CBA as an official or as a voluntary GHG accounting method complementing PBA	Makes the trans-boundary emission flows visible and enables shared responsibility between producers and consumers	– Political acceptability (requires countries to take responsibility of emissions that originate outside their borders)
			– Methodological issues
Carbon pricing	Emission trading schemes (ETS)	– Coverage	– Difficulties in setting the correct price
		– Treats all consumption equally	– Side effects, such as specious emission reductions for economic gainsa
		– Accelerates the development of clean technology	– Practical issues with coverage (national, regional or global ETS?)
			– Carbon leakage
	Border tax adjustments (BTA) to restrict GHG-intensive imports and support for local renewable energy	– Benefits for green economy within borders	– May conflict WTO rules
			– May hamper welfare development in developing countries
Voluntary	Developed countries should invest in decarbonization of their supply-chains in developing countries and/or share their technical knowledge and experiences	– Developed countries would take the responsibility	– What would be the incentive or political instrument?
		– Benefits for developing economies	– Would developing countries accept foreign investments in nationally important sectors, such as energy?
	Directing demand of specific goods and raw materials to countries, where the environmental pressure caused by the production is known to be low	Benefits for countries with sustainable production and raw material extraction practices	– What would be the incentive or political instrument?
			– May conflict WTO rules

E.g. companies selling carbon credits that do not correspond real emission reductions.

outcomes, for example changing consumption behavior or technological solutions, policy instruments are the actual policy tools or incentives to achieve the wanted outcomes. The selected policy categories for the numerical analysis were:

Policy instruments:

1. CBA should be an official accounting method (in addition to PBA)
2. Carbon pricing policies (a carbon cap and trading, emission trading schemes, carbon tax, subsidies to renewables, etc).

Policy outcomes:

3. Behavioral change, consumption patterns.
4. Technological solutions (energy efficiency, production technologies, etc).
5. Tailored policies for different groups or areas, context sensitivity.
6. The compact city, urban density policies.

In general, policy instruments include carbon pricing, command and control (CAC), meaning regulation, and voluntary incentives (Requate 2005).

Table 2. A summary of national policy recommendations.

Main policy instrument	Policy recommendation	Benefits	Challenges
Command and control (CAC) or voluntary	Implementing CBA as an official or as a voluntary GHG accounting method complementing PBA	Makes the indirect global emissions visible and brings them under climate change mitigation strategies	– Political acceptability – Methodological issues
Carbon pricing	Carbon tax	– Coverage – Treats all consumption equally – Accelerates the development of clean technology	– Carbon leakage – May affect international competitiveness negatively – Affects most strongly the lowest income groups (unless combined with additional income transfers)
	Personal carbon caps and trading	– Coverage – Fair – Accelerates the development of clean technology – Benefits for low-income groups	How to monitor and control?
CAC or voluntary	Coordination of social and climate policies	Sustainable lifestyles for all	Often in different administrative sectors
	Tailored policies for different segments of population	– Many policies do not fit for all – Allows differentiation	– Political acceptability – May seem unfair – Complexity
	Technological solutions: – Renewable energy – Energy efficiency – Cleaner production technologies (e.g. by regulation or voluntary intensives for companies)	Generally high acceptance	– Rebound effects – May be insufficient alone
	Behavioral change: – Travel behavior – Consumption behavior (e.g. by information campaigns, green product labels, increasing public transport availability)	– Immediate – Usually low-cost (for the consumer)	– Acceptance – Difficulties to change behavior – Rebound effects – May be insufficient alone
	– Reduced consumption	– Effective at the individual level	Political acceptability (How to reconcile with aspirations to economic growth and international competitiveness?)

Table 2. (Continued.)

Main policy instrument	Policy recommendation	Benefits	Challenges
	– Reduced working time	– Increasing willingness to trade money for time in developed countries	
	Replacing a part of consumption with green investments	Reduces consumption related emissions but maintains the economy	Strong green investments are not economically attractive compared to traditional investments (could be alleviated with carbon pricing policies)

However, only carbon pricing policies and CBA as an official accounting method were frequently explicitly mentioned in the reviewed literature, and thus included in the numerical analysis. Some studies highlight specific voluntary and regulatory tools, such as green labels. We discuss these in more detail in the qualitative policy analysis (subsections 3.2–3.5).

We used keywords to search for the relevant policy discussions from the papers. The used keywords were:

1. Policy discussions: 'poli*'.
2. Carbon pricing: 'pric*' or 'pricing'; 'tax'.
3. Carbon trading, emission trading schemes: 'trad*' or 'trading'; 'carbon cap'.
4. Subsidies to renewables: 'subsid*'.
5. Behavioral change, consumption patterns: 'behav*'; 'pattern'.
6. Tailored policies: 'tailor*'.
7. The compact city, urban density: 'compact'; 'dens*'.

The main focus of the policy analysis was on reading and qualitatively evaluating the policy implications of the discussion sections. We only noted down if the authors supported or questioned a specific policy. If the policy was mentioned but not commented upon by the authors, we did not note it down for the numerical analysis. For example, many authors mentioned some of the climate change mitigation policies of the case country, but neither supported nor criticized them. Nonetheless, policy analysis is vulnerable to subjective interpretations, which should be taken into account in the interpretation of the results.

In order to analyze the impact of the spatial scale on the policy recommendations, we classified the spatial scales of the studies into seven categories: *multi-national, national, sub-national* (regional), *city, sub-city* (neighborhood or similar), *urban zone*, and *settlement type* (urban–rural). *Multi-national* indicates studies that include several countries, for example, those of the EU or the whole world. However, studies that include case cities from several countries are classified as *city-scale studies*. *National studies* focus on one country. *Sub-national* indicates sub-national regions other than cities, for example provinces. *Sub-city* indicates neighborhoods or postal code areas, that is to say, areas that are generally smaller than cities. *Urban zone* indicates travel zones or similar zones within a city. *Settlement type* indicates an urban–rural comparison based on the population and/or density of the studied settlements.

2.3. Review of the results on the relationship between urban structure and CBCFs

The review of the results on the relationship between urban structure and CBCFs was conducted by reading through the results sections of the reviewed 103 studies and selecting those that included sub-national comparative analyzes on the level of urbanization. Thus, out of the larger number of studies that had a sub-national or more detailed spatial scale, only those that used clearly defined variables (such as area type or density) to describe the urban structure differences were used in this section. We found 35 such papers.

A rather substantial share of sub-national papers approach the urbanization issue by calculating average CBCFs for a wide range of different-sized spatial units—ranging from small super-output areas in London (Minx *et al* 2009), through individual cities in Finland (e.g. Heinonen and Junnila 2011a, 2011b) all the way to Chinese provinces (Yan and Minjun 2009)—or their combinations (Xie *et al* 2015). Unfortunately, these papers rarely include a rigorous description or analysis of the characteristics of each spatial unit, for example, the city in question. Thus, it is difficult to use them in the comparative analysis of the relationship between urban development and CBCFs, even though they are useful (for example, in visualizing the spatial distribution of emissions and highlighting the differences between the production- and consumption-based approaches).

3. Policy recommendations of the reviewed literature

3.1. Numerical policy analysis

The spatial scale of the study affects the policy recommendations (figure 2). For the purpose of the

Table 3. A summary of the policy recommendations for cities.

Main policy instrument	Policy recommendation	Benefits	Challenges
Command and control (CAC) or voluntary	Implementing CBA as an official or as a voluntary GHG accounting method complementing PBA	Makes the indirect global emissions of cities visible and brings them under climate change mitigation strategies	– Political acceptability – Methodological issues
Carbon pricing	City emission trading schemes (ETS)	– Coverage (in theory) – Treats all consumption equally – Accelerates the development of clean technology – Carbon offsets invested in cities and countries where the imported emissions originate may be more efficient and economical than cutting the territorial emissions of net-importing cities – Positive city image, competitiveness	– Difficulties in setting the correct price – Side effects, such as specious emission reductions for economic gains – Practical issues with coverage – May affect the economic competitiveness of the city negatively as well
CAC	Compact city and urban density policies	– Easy to reconcile with the aspirations of economic growth – Co-benefits with transit-oriented design	– Insufficient alone, the impact of urban density on CBCF is often small or insignificant – Rebound effects due to shifts in consumption – Connection to wealth generation increases CBCF
	Transit-oriented design, facilitating walking and cycling	– Generally high acceptance – Increases liveliness – Health benefits – Benefits particularly groups with otherwise high immobility, e.g. children and elderly people	Rebound effects due to lowering price of mobility
CAC or voluntary	Tailored policies for different areas	– Many policies do not fit for all areas – Allows differentiation	– Political acceptability – May seem unfair – Complexity
	Facilitating sharing economy (e.g. shared spaces and transportation)	– May benefit particularly urban areas, where small households concentrate	– Sharing should focus on GHG intensive consumption to avoid rebound effects

Table 3. (Continued.)

Main policy instrument	Policy recommendation	Benefits	Challenges
		– Supports grass root activities	– Facilitating does not guarantee that sharing takes place
		– May improve social wellbeing	
	Value from immaterial characteristics of built environment (focus on design and creating desirable atmospheres instead of heavy mass-construction)	Reduces GHG intensity of construction	May be expensive
	Creating or maintaining carbon sinks inside or outside the city boundaries	– Regenerative	Difficulties to verify the real impact
		– May benefit biodiversity as well	
	Technological solutions:	– Generally high acceptance	– Rebound effects
	– Local renewable energy	– Benefits spread outside the city as well	– May be insufficient alone
	– Energy efficiency		
	– Cleaner production technologies		

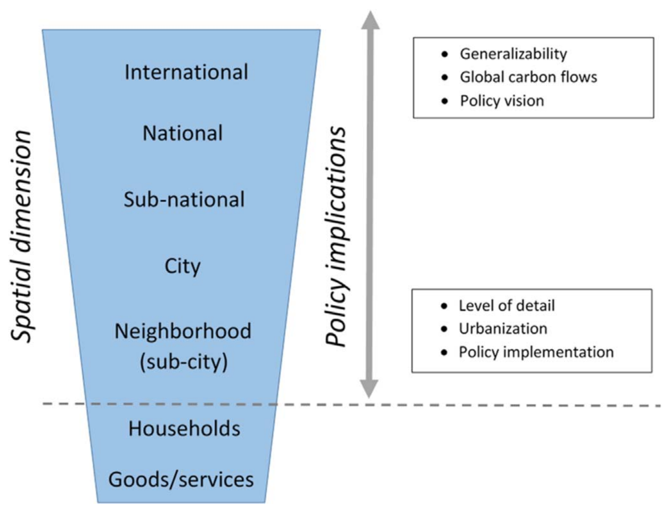

Figure 1. Review framework for positioning of the reviewed studies.

numerical analysis, we selected six upper-level policy recommendation categories that emerged from the whole review collection: carbon pricing policies, establishing CBA as an official accounting method, urban density policies, behavioral change, technological solutions, and tailored policies for different groups or areas (see the method section for details). The spatial scale of the study particularly affects the recommendations related to urban density, which are also surprisingly conflicting. The issue is discussed further in subsection 3.5 'City policies.' Otherwise, there is little criticism of any policy in the reviewed literature, only some concerns related to carbon pricing (Weber and Matthews 2008, Wood and Dey 2009) and some doubts about the sufficiency of technological solutions alone (Vringer *et al* 2010, Ivanova *et al* 2015). In general, behavioral change and technological solutions receive quite equal attention in

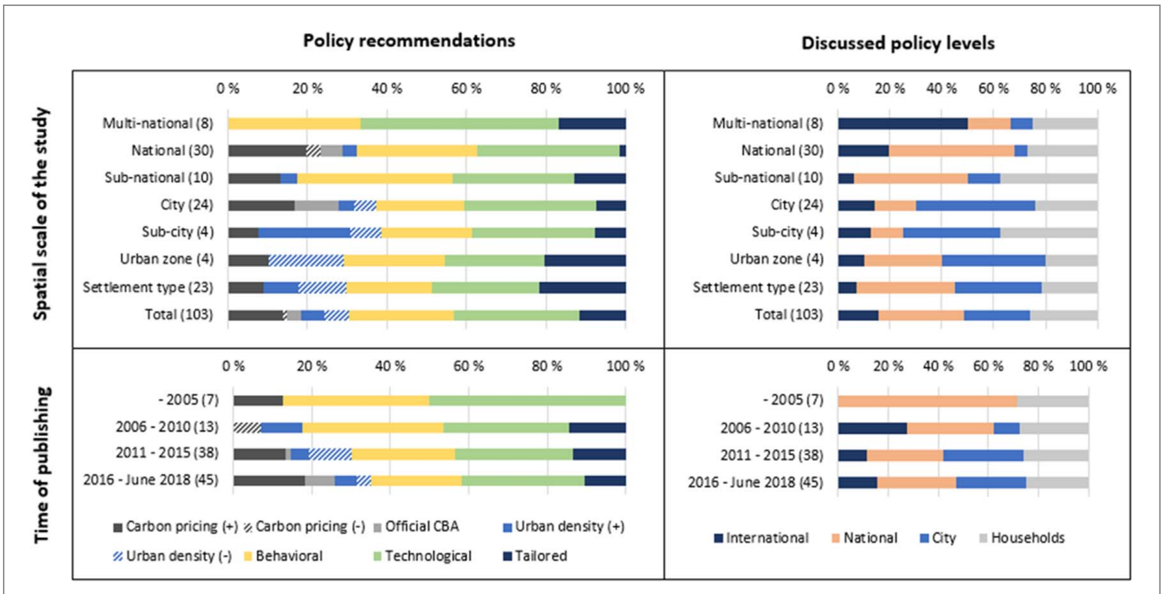

Figure 2. An overview of the numerical policy analysis. Specific policy recommendations and discussed policy levels are depicted by the spatial scale of the study and the time of publishing. The number of studies appear in parentheses. The sign (+) indicates support and (−) indicates criticism or questioning.

the reviewed literature. Policy instruments, meaning in this case carbon pricing and establishing CBA as an official information tool, are most often discussed in national- and city-scale papers, perhaps reflecting the administrative nature of the scale. In the reviewed literature, official CBA is generally seen as a complement to the current PBA, not as a method to replace it (Erickson *et al* 2012, Dolter and Victor 2016, Markaki *et al* 2017). However, the feasibility and benefits of completely switching from PBA to CBA have been discussed elsewhere (Steininger *et al* 2014, Grasso 2016).

The spatial scale of the study affects the discussed policy levels as well (figure 2). As can be expected, city-scale and more detailed scale studies emphasize city policies, whereas national and sub-national regional studies focus on national-level policies and multi-national studies emphasize international policies. However, many studies provide a policy discussion that goes beyond the spatial scale of the study. In addition, it is common in the CBCF literature to give guidelines for households and consumers, and sometimes companies, directly. Most of the studies give no priority order for the policy level. In general, the need for international cooperation is highlighted in the literature (Davis and Caldeira 2010, Levitt *et al* 2017). However, it is acknowledged that international cooperation is often slow, whereas cities, companies, and individual consumers can take more immediate action (Jones and Kammen 2011, Chen *et al* 2016a, see also policy papers by Mathur *et al* 2014, Lazarus *et al* 2013).

The time dimension reveals some interesting patterns as well (figure 2). Particularly, the call for official CBA has emerged quite recently in the empirical CBCF literature, although the benefits of CBA have been discussed more generally in some early studies as well (Hertwich and Peters 2009, Davis and Caldeira 2010). In addition, city policies increase their role in the literature after 2010. This is probably directly connected to the spatial scales of the studies. The amount of studies with a sub-national and more detailed spatial scale started to increase steeply around 2010 (Heinonen *et al* 2019).

It should be noted that figure 2 only illustrates how much emphasis is given to each policy recommendation and policy level in the CBCF literature. Since one paper can discuss several policy aspects, the percentages in figure 2 illustrate the 'hits' in the whole literature instead of giving the share of studies that support or question each policy. The latter are given in tables S3–S6 (in the SI). Also, some papers do not give any policy recommendations.

The policy aspects included in the numerical policy analysis are not exhaustive, although the majority of the found policy recommendations fell under the chosen categories. In the following qualitative policy analysis, we discuss various policy aspects more broadly.

3.2. Qualitative policy analysis

Figure 3 provides an overview of the policy recommendations of the reviewed literature. We classify the policy recommendations into *policy outcomes* and *policy instruments*. *Policy outcomes* include policy recommendations that instruct what should be done, but suggest no incentives. *Policy instruments* are policy tools or incentives that can be used to achieve the wanted policy outcomes. We found that the emphasis of the policy recommendations in the reviewed literature is clearly on policy outcomes rather than policy instruments. A simple example of this is that the

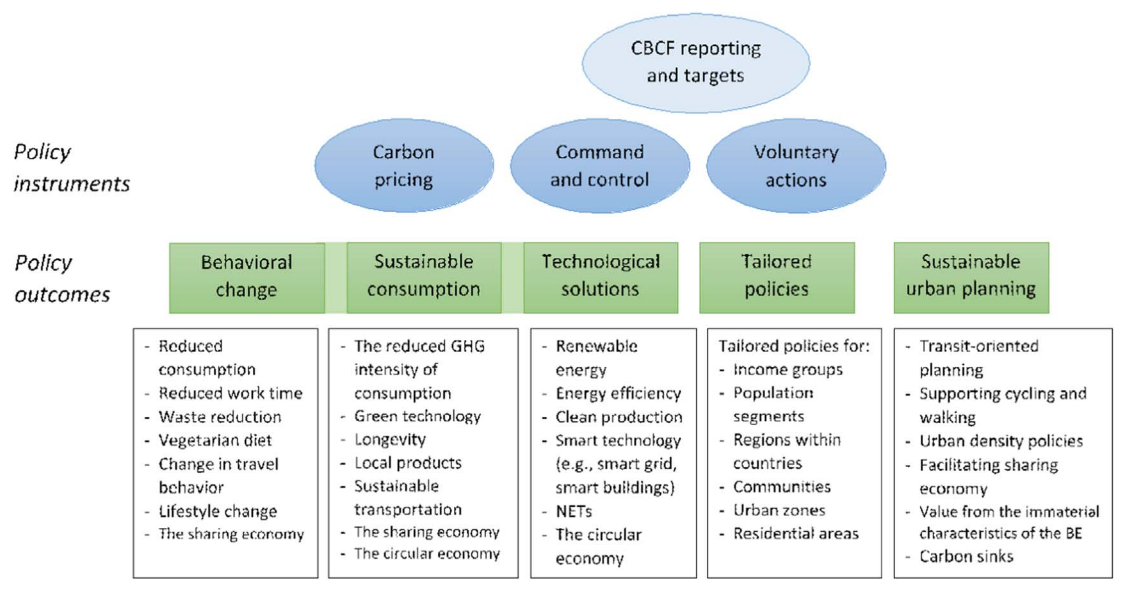

Figure 3. An overview of the policy recommendations of the CBCF literature. *Sustainable consumption* merges behavioral change and technological solutions. The lower boxes give examples of the specific policy outcomes discussed in the literature. NETs = negative emission technologies, BE = built environment.

majority of the papers suggest changing consumer behavior towards more sustainable consumption patterns, but few are concerned about how the consumers are to be persuaded to make this change. Discussion of the possible policy instruments would target this question.

We categorize the policy outcomes into *behavioral change, technological solutions, tailored policies,* and *sustainable urban planning* (figure 3). The last category is different from the one we used in the numerical analysis. In the numerical analysis, we were interested in the conflict of the recommendations related to urban density, and thus selected urban density policies as one of the examined policy category. However, in the qualitative analysis we found that the recommendations related to urban planning do not focus only on urban density, but planning more generally. Thus we use a more general 'sustainable urban planning'—category in figure 3. It should be noted that the policy outcome categories are overlapping. For example, many authors discuss sustainable consumption, which encompasses both behavioral change and technological solutions (for example, using green product labels to guide consumers). Similarly, the suggested tailored policies often include these two aspects. Tailored policies mean suggestions to target different population segments or geographic areas with different policies. In general, tailored policies can be seen as a subcategory or an overarching category for other policy outcomes. Many of the reviewed studies, 26% in total (table S3 in the SI), recommend tailored policies (e.g. Druckman and Jackson 2009, Minx *et al* 2013, Hasegawa *et al* 2015, Miehe *et al* 2016). In addition to sustainable consumption and tailored policies, there are some other broad concepts mentioned in the literature that are difficult to fit under the chosen categories, such as the sharing economy and circular economy that have been brought up in a few recent papers.

We divide the policy instruments in three aggregated categories: carbon pricing, command and control (CAC), and voluntary actions (following Requate 2005, Holden and Linnerud 2011). In addition, CBCF reporting and targets themselves form an information tool that can be used either voluntarily or as a mandatory steering tool (i.e. official CBA for GHG emissions). In general, any policy instrument can be used to realize any policy outcome. Implicitly the reviewed literature seems to encourage voluntary action, since command and control policies and regulation in general are rarely discussed. Some exceptions to this are presented in the following subsections. Carbon pricing—including carbon taxes, emission trading schemes, and subsidies to renewables—is the most often discussed policy instrument: it is explicitly mentioned in 33% of the reviewed papers (table S3 in the SI). However, some authors raise it only to discuss some concerns related to it. In the numerical analysis, we only report calls for official CBA and carbon pricing, since regulation and voluntary-based policy instruments are rarely mentioned explicitly. However, some papers do promote specific voluntary or regulatory tools, which are discussed in the following subsections.

The relationship between economic growth and GHG emissions underlies the policy discussions. It is explicitly mentioned in 48% of the reviewed papers (table S3 in the SI), and implicitly present in many of the rest. The need to reduce consumption is a direct policy implication of the CBCF literature, which is often lightly discussed among other policy implications. However, some authors note the political unattractiveness of the option (Weber and Matthews 2008, Ottelin et al 2018b). Reduced consumption is difficult to reconcile with the aspiration of continuous economic growth. The issue is particularly evident in the case of developing economies. Climate change mitigation policies should not jeopardize reducing the inequalities between countries and income groups (Murthy et al 1997, Hubacek et al 2017a, 2017b, Seriño 2017, Wiedenhofer et al (2017)).

In the following subsections, we present and analyze the policy implications of the reviewed literature at three policy levels: international, national, and city levels. A summary of the policy recommendations at each policy level is given at the end of each subsection (tables 1–3). In the summary tables, we aim to suggest the practical policy tools and policy instruments that are required to realize the policy recommendations—even when they are not directly suggested in the original sources. In addition, we list some of the benefits and challenges of each policy suggestion.

3.3. International policies

As discussed in the introduction, by definition the CBCF describes how the consumption of goods and services drives global GHG emissions. Due to the increasing volume of international trade, an increasing share of these emissions occur elsewhere than the location of the demand driving them (Kanemoto et al 2016, Wiedmann and Lenzen 2018). Thus, international policies are strongly present in the reviewed CBCF literature, although the emphasis of the policy implications is on the lower levels (figure 2).

The review included eight studies with a global or multi-national spatial scale. These studies discuss carbon leakage (Davis and Caldeira 2010, Ivanova et al 2017), the importance of understanding embodied emissions (Hertwich and Peters 2009), global responsibility and equity issues (Kerkhof et al 2009, Davis and Caldeira 2010, Kanemoto et al 2016, Tukker et al 2016, Hubacek et al 2017a), and the displacements of environmental pressure (Steen-Olsen et al 2012, Tukker et al 2016)—but also household actions and behavioral change (Ivanova et al 2015). Despite some policy discussion, these papers with a broad geographic scope often lack concrete advice for policies. Perhaps it is difficult to provide policy implications that would cover various countries. For example, Hertwich and Peters (2009) highlight that policy priorities depend on the country. Steen-Olsen et al (2012) present an interesting policy idea though, they note that different regions have different advantages from an environmental perspective and that international trade could actually serve to optimize the environmental impacts globally. For example, companies could direct their demand for specific goods and raw materials to countries where the environmental pressure caused by their production is known to be low (see also Chen et al 2016b, for a similar discussion on cities). However, they do not discuss what could be the policy instruments or incentives to achieve this. Hubacek et al (2017a, 2017b) raise another important international policy issue—they discuss the global inequality of carbon footprints. They examine whether the goals of the United Nations (UN) to mitigate climate change and to end poverty are in contradiction with each other. They call for policies addressing the unfair global income distribution and the carbon intensity of lifestyles in developed countries.

Studies on a more detailed spatial scale provide global and international policy implications as well. Clarke et al (2017) suggest that developed countries should invest in decarbonization of their supply chains in developing countries. Dolter and Victor (2016) make similar conclusions. Both papers include the suggestion of substituting local low-carbon production for GHG-intensive imports as well. These sort of policies could be taken into practice by border tax adjustments (BTAs). However, BTAs related to embodied emissions may contradict the international trade rules of the World Trade Organization (WTO) (Druckman and Jackson 2009, Andrew et al 2013, Afionis et al 2017). There are social justice concerns as well: the loss of export revenues in developing countries would negatively affect the welfare of the countries (Steininger et al 2014, Afionis et al 2017). In this light, clean technology investments in developing countries seem a preferable option compared to the reduced consumption of their exports. Hu et al (2016) suggest a softer approach: developed countries should share their technical knowledge and experiences of clean technologies and environmental management with developing countries. Despite the above concerns, several studies on GHG emissions embodied in trade, which are excluded from the review but have close links to the CBCF literature, advocate BTA (Izard et al 2010, Andrew et al 2013, see also the review by Sato, 2014). For example, Andrew and co-authors highlight that BTA may encourage supplying countries to regulate their GHG emissions as well. In contrast, Jakob and Marschinski (2013) and Sakai and Barrett (2016) discuss the uncertainties of BTA in reducing global GHG emissions.

3.4. National policies

National-level policies are a popular topic in the reviewed CBCF literature (figure 2). In particular, the national and sub-national regional scale studies focus on national-level policy implications. Similar to multinational studies, carbon leakage (Markaki et al 2017), responsibility for emissions (Clarke et al 2017, Steininger et al 2018), and the importance of understanding the emissions embodied in trade (Bin and Dowlatabadi 2005, Levitt et al 2017, Isaksen and Narbel 2017) are discussed. In addition to global responsibility and the allocation of emissions, responsibility within a country receives attention. Druckman and Jackson

(2009) and Mach *et al* (2018) suggest policies that would target the segments of society responsible for the highest carbon footprints, which often means the highest income groups. More subtle policy suggestions touching upon the issue of income differences are provided as well. In a study on China by Wiedenhofer *et al* (2017) they highlight that social and redistributive policies interact with climate and energy policy. They call for efforts enabling sustainable lifestyles for all and promote the coordination of social and environmental policies. Ottelin *et al* (2018b) give support for such a policy strategy by revealing how the redistributive policies of welfare states improve carbon equity between the different income groups. Regional equality is discussed in the literature as well. Sub-national regional studies highlight the need to take regional characteristics into account in local and national decision-making (Erickson *et al* 2012, Miehe *et al* 2016).

The policy suggestions cover behavioral change and technological solutions quite equally. Many authors specifically highlight the need for both (Kim 2002, Vringer *et al* 2010, Ferguson and MacLean 2011, Duarte *et al* 2013). Regarding technological solutions, renewable energy production and energy efficiency are supported in several papers (Underwood and Zahran 2015, Brizga *et al* 2017, Markaki *et al* 2017, Özbaş *et al* 2017). However, Markaki and co-authors also discuss possible rebound effects related to energy efficiency measures. Rebound effects occur when energy efficiency decreases the price of the energy service, for example, the price of heating. Due to the lower price, the consumption of the energy service (or other goods and services) may actually increase, which counteracts the original energy-saving purpose.

Thomas and Azevedo (2013) specifically study the rebound effects of residential energy efficiency investments. Based on their findings, they promote carbon pricing: enacting pollution taxes or auctioned permits that internalize the externalities of energy use. Carbon pricing is supported by many other authors as well (Common and Salma 1992, Zhang 2013, Zhang *et al* 2014, Seriño and Klasen 2015, Underwood and Zahran 2015, Xie *et al* 2015, Miehe *et al* 2016, Clarke *et al* 2017, Wiedenhofer *et al* 2017). In addition, Maraseni *et al* (2016b) remind us that the subsidies for coal and oil must be cut. However, some concerns about carbon pricing policies are raised in the literature as well. Weber and Matthews (2008) discuss the problematics of carbon taxes. If carbon taxes are implemented at national level, they will not cover imported goods, which is particularly problematic in low-carbon economies. BTAs could solve the problem, but as discussed above, they have their own downsides. Similarly, Wood and Dey (2009) discuss the possible negative impacts of emission trading schemes on Australian industries, although they do not oppose carbon pricing directly. In addition, some authors remind us that carbon pricing affects lower-income groups more than others, since many basic needs (such as heating and daily transportation) have a relatively high GFG intensity (Gill and Moeller 2018). As a solution, Ottelin *et al* (2018b) suggest combining carbon pricing with additional income transfers to lower-income groups.

In addition to various carbon pricing policies, information dissemination programs are suggested as a policy instrument, particularly in order to change consumer behavior (Bin and Dowlatabadi 2005, Nässén *et al* 2015, Özbaş *et al* 2017). Curiously, Nässén and co-authors highlight that promoting pro-environmental attitudes may actually be more important regarding support for climate policy than for consumer behavior, since the impact of the latter is limited. Sustainable consumption choices may have rebound effects as well. For example, giving up car ownership and other actions that save money in addition to emissions, may lead to shifts in consumption that counteract the intended emission savings (Lenzen and Dey 2002, Ornetzeder *et al* 2008, Ottelin *et al* 2017). In addition, they may lead to changes in time use, which also have GHG implications (Heinonen *et al* 2013a, Wiedenhofer *et al* 2018).

Some recent papers suggest a sharing economy (Ala-Mantila *et al* 2014, 2016, Underwood and Zahran 2015, Fremstad *et al* 2018, Jones *et al* 2018) or circular economy (Zhang 2013, Athanassiadis *et al* 2016) as policy strategies. However, a deeper discussion on how to implement such policies and what would be the impact on CBCFs is missing from the literature.

3.5. City policies

Around half of the reviewed papers (53%) have a more detailed spatial scale than the national or sub-national regional level. For the purpose of the review, we further divided these studies into four classes according to the scale: *city*, *sub-city*, *urban zone*, and *settlement type*. These studies often focus on city policies in their policy discussion (figure 2).

The city-scale studies highlight the benefits of CBA for cities. In order to implement effective mitigation strategies, it is important to have accurate, comparable, and comprehensive GHG accounting (Wiedmann 2016, Fry *et al* 2018, see also the review by Lombardi *et al* 2017). Several authors state clearly that CBA should be adopted routinely in cities (Paloheimo and Salmi 2013, Feng *et al* 2014, Chen *et al* 2016a, 2016b, 2017). Wiedmann (2016) propose the concept of a 'city carbon map,' which is a coherent, matrix-like, simultaneous representation of CBCFs and production-based GHG emissions. In addition, several authors discuss more generally the importance of including the indirect global environmental pressure of cities in policy discussions (Schulz 2010, Athanassiadis *et al* 2016, Millward-Hopkins *et al* 2017).

As in the national-scale studies, carbon pricing is a popular topic in the more detailed scale studies as well (table S3 in the SI). Particularly interesting for cities is the promotion of trans-local carbon trading schemes, meaning carbon trading among cities (Chen *et al* 2016a, 2016b, Mi *et al* 2016). Net importer cities could require importing companies to purchase carbon credits from net exporter cities that would use the funds to decarbonize the production. This would lower the CBCF of the net importer cities. From the perspective of the net importer cities, carbon offsets invested in cities and countries where the imported emissions originate can, in many cases, be more efficient and economical than focusing on the territorial emissions alone (Chen *et al* 2016a).

The policy recommendations of the CBCF literature related to urban planning and urbanization are missing a consensus. Several authors discuss urban density policies or the possible environmental benefits of urban density. Some of these authors support urban density policies (e.g. Nässén *et al* 2015, Isman *et al* 2018, Fremstadt et al 2018; see also a policy paper by Lee and Erickson 2017) and some of them question the effectiveness of urban density policies (e.g. Heinonen *et al* 2013a, 2013b, Ottelin *et al* 2018a, Chen *et al* 2018). In addition, some authors discuss more generally about sustainable urban planning (Shafie *et al* 2013, Li *et al* 2015), sustainable transport planning (Minx *et al* 2013, Zhang *et al* 2016), or high consumption in urban areas (Shigeto *et al* 2012, Chik *et al* 2013, Millward-Hopkins *et al* 2017). Several authors highlight that urbanization is an important driver of CBCFs, particularly in developing economies (Feng *et al* 2014, Zhang *et al* 2014, Li *et al* 2015, Liu *et al* 2017, Seriño 2017). However, whether a specific paper supports or questions urban density policies is not explained by the geographic location or spatial scale of the study alone (figure 2 in subsection 3.1). Perhaps because of the missing consensus on urban density policies, several authors suggest tailored policies for urban, suburban, and rural areas (Baiocchi *et al* 2010, Liu *et al* 2011, Ala-Mantila *et al* 2013, Jones and Kammen 2014, Ottelin *et al* 2015).

In order to clarify the reasons for the conflicting policy recommendations, we review the actual results on the relationship between urban development and CBCFs in the following section. We find that the results vary as well. In addition, the impact of urban variables on CBCFs is often low or statistically insignificant (see subsection 4.4 and table S2 in the SI). Thus, the given policy recommendations appear to reflect the empirical findings. The existing literature allows the justification of various policy recommendations.

While carbon pricing and urban density policies are often discussed separately, Gill and Moeller (2018) and Ottelin *et al* (2017, 2018a) point out that these policies are interrelated. If the emissions of car ownership and use are targeted with other policies, such as motor fuel taxes, it diminishes the potential impact of urban density policies due to the increasing rebound effects (Ottelin *et al* 2018a). High motor fuel taxes bring the GHG intensity of car ownership and use close to the GHG intensity of other forms of consumption per monetary unit—and thus it makes no difference whether consumers spend their money on car ownership and use or something else. The conclusion is that with adequate carbon pricing policies, separate urban density policies are ineffective but the demand of transit-oriented and car-free residential areas may increase, due to the increasing expenses related to car ownership and use.

Sustainable urban planning covers other aspects aside from urban density and transport planning. Several recent papers highlight the potential of cities to facilitate the sharing economy (Underwood and Zahran 2015, Ala-Mantila *et al* 2016, Fremstad *et al* 2018, Jones *et al* 2018). Decreasing household size in cities is a global trend. This increases the CBCF per capita due to decreasing the sharing of spaces, goods, and services between household members (Ala-Mantila *et al* 2016). However, cities and densely populated areas in general can facilitate sharing between households. Public spaces and public transport are traditional infrastructures for sharing, while online platforms have created new forms of peer-to-peer sharing, such as car pooling and hospitality services. Fremstad and colleagues suggest that cities could increase the reliability and credibility—and thus the volume of peer-to-peer sharing—by regulation, licensing, and insurance policies for example. Ala-Mantila and co-authors remind us that sharing should focus on GHG-intensive goods and services in order to avoid the high rebound effects caused by economic savings.

Carbon sinks and carbon stocks are discussed in the CBCF literature as well (Shigeto *et al* 2012, Paloheimo and Salmi 2013, Ottelin *et al* 2018a, see also Lazarus *et al* 2013). Shigeto *et al* (2012) suggest increasing carbon stocks and forest carbon uptake by increasing the use of wood in buildings. Paloheimo and Salmi (2013) suggest investing in large-scale carbon sinks, such as forests, inside or outside city boundaries. Ottelin *et al* (2018a) remind us that it is important to start thinking beyond 'low carbon' and promote negative emission technologies (NETs), such as carbon capture and storage. Minx *et al* (2017) provide a comprehensive review of NETs. In addition, Ottelin *et al* (2017) highlight that design and planning in general have a low GHG intensity per monetary unit and suggest that planning should aim at creating value for the immaterial characteristics of the built environment rather than heavy construction.

In addition to carbon pricing and urban planning, there are behavioral and technological policy suggestions for cities in the literature. In particular local renewable energy production is promoted (Kyrö *et al* 2012, Li *et al* 2015, Maraseni *et al* 2016a, Chen *et al* 2018). Several authors highlight that cleaner energy production not only reduces the CBCF of the city residents, but that the benefits spread outside the city region as well when the goods and services produced within the city are consumed by the residents of other areas (Hu *et al* 2016, Laine *et al* 2017, Lin *et al* 2017). Chen *et al* (2018) stress the importance of making the leap into renewable energy production, since smaller steps, such as investments into new energy-efficient coal power, cause infrastructure lock-ins for decades. Information campaigns, policy guidelines, and carbon footprint calculators for citizens are promoted as tools to change consumption behavior towards more sustainable lifestyles (Jones and Kammen 2011, Chik *et al* 2013, Wiedenhofer *et al* 2017).

4. Relationship between urban structure and CBCFs

4.1. Scope of the review

During the policy analysis, we found that the policy recommendations on urban density and urban development more generally are both missing a consensus. To clarify this important topic, we review here the actual results regarding the relationship between urban development and CBCFs. Out of the 103 reviewed studies, 35 include a clearly defined variable to describe urban structure and a sub-national comparative analysis. The following review of the results focuses on these studies. The main findings of the 35 studies with some key information are presented in table S2 (in the SI).

Most of the 35 studies compare absolute emissions between units with different degrees of urbanization, usually ranging from urban to rural with a differing amount of categories between these extremes. A smaller share (13 of the remaining 35) focus on the effect of sub-urbanization or urban sprawl. Most of the papers (27), use some kind of a classification of municipalities or other administrative units that divide up the areas based on their degree of urbanization, but a dichotomous urban–rural variable, without finer-grained resolution of different types of areas, is used rather often as well (9/35).

4.2. Absolute CBCF comparisons

When comparing the averages of the absolute CBCF without controlling for any background variables, the more urban areas tend to have higher footprints (Zhang *et al* 2016, Seriño 2017, Fremstad *et al* 2018, see table S2 in the SI). The majority of the reviewed papers for this section (19 papers) conclude that, generally, the higher the level of urbanization, the higher the consumption-based emissions. This result seems to hold regardless of the level of development of the country as it is replicated in countries like China (Liu *et al* 2011, Maraseni *et al* 2016a, Wiedenhofer *et al* 2017) and India (Murthy *et al* 1997), as well as in Finland (Heinonen *et al* 2013a, Ala-Mantila *et al* 2014) and the US (Heinonen 2016, Fremstad *et al* 2018). Also, the typical emission profiles tend to be similar regardless of the level of development: more rural dwellers have an emission profile that is more weighted towards direct emissions, and vice versa, the profile of more urban dwellers is weighted towards indirect emissions (Ala-Mantila *et al* 2014, Gill and Moeller 2018).

However, a couple of contradicting results have been reported that state that the CBCF decreases with the increasing level of urbanization. For the US, Jones and Kammen (2014) reported that the rural dwellers footprint was 0.7 tons higher than that of a resident of the urban core. For the UK, Minx *et al* (2013) concluded that, in their assessment, three urban settlement types had slightly lower carbon footprints than the two rural settlement types, but also highlighted the large variation within each of these groups. Also, for Finland Heinonen *et al* (2013b) found that the average emissions of a middle-income rural dweller are a bit higher than those of a middle-income dweller residing in the country's capital.

The conclusions about urban sprawl—meaning comparisons of absolute average emissions between urban and suburban areas—are somewhat more controversial. In Finland, several studies have found inner urban residents to have the highest CBCF (Heinonen *et al* 2011, Ottelin *et al* 2015, 2018a, Ala-Mantila *et al* 2016). Fremstad *et al* (2018) and Heinonen (2016) presented similar findings to those from the US. In contrast, for the US Jones and Kammen (2014) reported the average CBCF to be higher in suburban cities and towns compared to urban core cities. Also, the results of Nässén *et al* (2015) (in Sweden), and Ala-Mantila *et al* (2013) and Ottelin *et al* (2017) (in Finland) indicated that inner urban living has slightly lower, or almost similar, GHG consequences to living in the suburbs.

4.3. Areal or personal carbon footprint

In our separate review on the comparability of CBCF studies, which focuses on conceptual and technical issues (Heinonen *et al* 2019), we discussed that there are actually two types of CBCF that differ significantly in their scope, but are reported as the same. We named these the *areal carbon footprint* (ACF) and the *personal carbon footprint* (PCF). The ACF covers all consumption-based emissions caused by economic activities within the borders of the studied area, irrespective of who causes them, whereas the PCF covers all consumption-based emissions caused by the residents of the studied area, irrespective of where the emissions are caused. There are also hybrids of the ACF and PCF in the literature, and the scope is generally not stated clearly. From the perspective of the impact of urban development on CBCFs, the most important difference between the two CBCF types is that the ACF typically includes the governmental consumption and gross fixed capital formation (GFCF) that hybrids may or may not include, and the pure PCF, by definition, does not (see Heinonen *et al* 2019, for details). In particular, the investments in new construction and infrastructure that are included in the GFCF are important when studying the impacts of urbanization on the CBCF. Thus, this may explain the difference in the absolute results described above since all the studies that find a lower CBCF in urban areas than in suburban or rural areas study the PCF.

Another important issue is that when the level of detail of the spatial scale is increased, it becomes impossible to assess the ACF, which requires data on economic activities within the area, such as national or regional accounts. Although some studies have added the GFCF to the PCF, this has been done by giving equal shares to all residents of the area, since there is no data available for more personalized allocation (Ottelin *et al* 2018b). Thus, it should be noted that currently practically all CBCF studies having a more detailed spatial scale than the city-use PCF, which is typically based on household expenditure surveys and lacks insights into the consumption of public goods and services, and the GFCF.

4.4. Statistical analyzes explaining CBCF

The usual criticism of CBCF studies that only compare the averages of dwellers living in areas with different degrees of urbanization is that they often remain purely descriptive (Baiocchi *et al* 2010) and do not allow analyzing and separating the relationships between urban development and several other variables connected with the variable of interest: the CBCF. Aiming to correct these shortcomings, 21 out of the 35 studies on urbanization in our sample include some sort of statistical analysis, usually a single or multivariable regression analysis. Of course, the definitions and ranges of control variables, be they spatial or socioeconomic, vary between studies, and thus straightforwardly comparing the results has its caveats.

By relatively common consent, the aforementioned 22 articles highlight the role of wealth as the main explanatory variable behind the CBCF, with the role of urban structure playing a smaller role in determining emissions. However, as follows from the methodology (environmentally extended input–output analysis), the role of expenditures or income in determining emissions is rather as expected, and thus, even though the impact of urban variables is often quantitatively small, it is still interesting.

In most papers, when controlling for relevant socioeconomic background variables, such as income and household size, the relationship between urban development and CBCFs is negative: the more urban the area is, the smaller the per capita emissions are (Nässén 2014, Ala-Mantila *et al* 2014, Fremstadt et al 2018, see table S2 in SI). However, some exceptions can be found: for example, in China Liu *et al* (2017) concluded that urbanization and population density increase per capita household CO2 emissions and Li *et al* (2015) concluded that the direct and indirect CO2 emissions of households increase by 2.9% and 1.1% respectively for every increase of one percent in urbanization. However, Li *et al* (2015) did not control for household size, which can have partly affected the result. Also, Seriño and Klasen (2015) and Seriño (2017) found similar relationships for the Philippines. Thus, many have concluded that the process of urbanization, when happening on the side of overall rising affluence levels and changing lifestyles in the less developed world, poses a problem for climate change mitigation (Heinonen *et al* 2013a, 2013b, Zhang *et al* 2016).

Of course, the magnitude of the reported urbanization relationships differs. The highest reported difference between the most urban and most rural area type, other factors controlled for, is around 20% (Fremstad *et al* 2018). Quantitatively smaller differences are also found, for example, in Finland Ala-Mantila *et al* (2014) reported the difference between urban and rural areas to be approximately 15%, and in Sweden Nässén *et al* (2015) found that longer geographical distances increased emissions by about 9% relative to average emissions. Some authors have also concluded that the effect of urbanization (or a variable describing it) might not be universal. For example, Minx *et al* (2013) found that the CBCF decreases with population density, and decreases in the CBCF are larger at lower densities, meaning that increasing the density of denser places is not as GHG effective as is increasing the density of less dense places. Also, Jones and Kammen (2014) argued about nonlinearity, even though their conclusion is different: in their analysis, only the highest densities (3000 people per sqm and above) have a decreasing effect on emissions. Some studies have found the impact of urban variables to be statistically insignificant (Ottelin *et al* 2015, 2018a).

When different emissions categories are explained separately, the negative relationship seems to hold especially strongly for direct emissions (Ala-Mantila *et al* 2014, Gill and Moeller 2018) and for mobility in particular (Zhang *et al* 2016).

Also, multivariable regression analysis—the most commonly used statistical technique in the CBCF literature—is unable to identify causal relationships, and for example, Zhang *et al* (2016) have brought out that the science of CBCF assessments has yet to unpack various effects that occur during the process of urbanization. To combat the problem, they innovatively utilize propensity-score matching in order to be able to identify the different effects of rural-to-urban migration. They demonstrate how their technique prevents the overestimation of the effect of human settlements, apart from the socio-economic factors. Also, other kinds of more developed methods that are more common in the economics and econometrics literature—such as discontinuity regression and experimental designs—are still waiting to be used in order to truly find an answer about the effect of urbanization on consumption-based emissions.

Perhaps some of the aforementioned differences in the reported impacts of the urban variables on the CBCF can be traced down to the sometimes very different contexts of studies. There are cultural differences (perhaps partly traceable to historical reasons) in how a city population is typically distributed to different parts of the city structure. Inner city living provides a good example: in the US, it is often associated with lower incomes (Jones and Kammen 2014), whereas in Finland those living in the urban cores tend to be wealthier than the average person (Heinonen *et al* 2013a).

Overall, the studies on the relationship between urban development and the CBCF are not unanimous in their conclusions, nor are they coherent in the approaches used to examine the relationship. Also, the footprinting methodologies vary, for example, the way of calculating infrastructure investments is likely to affect how the urbanization relationship appears. Moreover, the used urban measures are often very aggregated and based on administrative boundaries rather than on more useful structural definitions of different area types. Thus, the comparability and practical usability of many of the results is not very strong, which reduces the suitability of the results for policy-making as well. In addition, there is a shortage of the time-series and longitudinal studies that are needed to make causal claims about the relationship.

5. Conclusions

5.1. Main findings and suggestions for improvements

In this systematic review, we reflected on the policy implications of the CBCF literature, meaning studies that use a consumption-based GHG assessment. We analyzed and summarized the policy implications for different spatial scales. In addition, we reviewed the results regarding the relationship between urban development and CBCFs in order to clarify why the policy implications are sometimes conflicting, particularly in the case of urban density policies and urban development more generally. For policymakers, we have summarized the current policy recommendations of the CBCF literature at international level (table 1), national level (table 2), and city level (table 3) above. Official CBA, as a complement to PBA, and carbon pricing policies are the most highlighted policy instrument in the recent literature.

The review of the policy recommendations revealed that their emphasis is on policy outcomes rather than on the policy instruments that are needed to achieve the wanted outcomes. A shift towards policy instruments would be helpful from the decision-makers' and policymakers' perspectives. In addition, the policy implications should be better grounded on the results of the study and previous literature. Then again, it is sometimes valuable to provide more visionary and creative policy suggestions as well, but it should be clarified when the policy implications are not directly derived from the results of the study.

Comparing the policy recommendations of the CBCF literature to the recommendations of climate change literature in general reveals similarities as well as some significant differences. For example, carbon pricing policies, technological solutions and changing travel behavior are promoted outside the CBCF literature as well. Based on our review, we conclude that the unique features which consumption-based perspective can bring to policy discussions include (1) responsibility of emissions (2) awareness of rebound effects (3) sustainable consumption and lifestyles, and (4) tailored policies for different population segments.

Adopting CBA enables wealthy cities and nations to see and take responsibility of emissions that are driven by their demand but take place outside their territorial boundaries (Wiedmann *et al* 2015, Afionis *et al* 2017). At the same time, it reveals the possible rebound effects and trade-offs related to climate actions (Ottelin *et al* 2018b). If we take for example the above mentioned carbon pricing policies and technological solutions, the CBCF literature reveals limitations and challenges that cannot be captured by PBA alone. National carbon pricing policies may lead to increased consumption of imported goods, which may have high embodied emissions (Peters and Hertwich 2008). Similarly, technological investments (e.g. new infrastructure) may require imported products, whose embodied emissions are not included in the territorial accounting (Ramaswami *et al* 2012). However, such rebounds and trade-offs are case specific and depend on time and place and existing regulation (Chitnis *et al* 2014, Ottelin *et al* 2017, Gill and Moeller 2018). Thus, nations and cities should have a continuous CBA reporting of their own to increase their awareness and to revise policy interventions accordingly.

Perhaps the most obvious unique policy feature of the CBCF literature is the direct advices for consumers and households regarding sustainable consumption and lifestyles. The reviewed literature highlights that there isn't one solution, but various paths to sustainable lifestyles (Ivanova *et al* 2015, Ala-Mantila *et al* 2016, Wiedenhofer *et al* 2018). However, some studies are skeptical about the possibilities of consumers, particularly because of the rebound effects related to shifts in consumption (Nässén *et al* 2015, Ottelin *et al* 2017). Several studies suggest tailored top-down policies as well, to allow differentiation between population segments (Baiocchi *et al* 2010, Heinonen *et al* 2013a, Jones and Kammen 2014, Ottelin *et al* 2015). For example, public transportation in dense urban cores and electric vehicles and solar panels in suburban areas.

However, there seems to be one profound shortcoming in the CBCF literature from the policy perspective. Few studies make any connection from the reported CBCFs to any suggested sustainable levels—for example, the planetary boundary framework (Steffen *et al* 2015) or the IPCC 1.5 °C degree warming scenario (IPCC 2018)—leaving the findings without any baseline. More discussion on the sufficiency of the suggested policy approaches is called for.

In addition, the review of the results on the relationship between urban development and CBCFs revealed that more caution is needed in the interpretation of the results. Only a small share of the reviewed studies actually operates at a precise enough level to allow for making strong claims about the relationship. However, the most accepted conclusion is that when urbanization is understood as a process influencing not only the spatial location but also lifestyles and consumption choices, the urban dwellers with high levels of wealth and a low number of household members pose a challenge for climate change mitigation. On the other hand, the literature on the impacts of urban structure within cities is relatively thin and inconclusive. More studies focusing on detailed spatial scales are needed, particularly analyzes using more elaborate area descriptions than the ones based on administrative boundaries. To increase comparability, more comparative studies using larger datasets are called for.

5.2. Directions of future research

Below we provide guidelines for future research collected from the most recent reviewed literature, meaning studies published between January 2015 and June 2018. Several recent studies highlight that further research on the underlying factors for consumption and lifestyle choices are important in order to understand how behavior and associated carbon footprints can be influenced. This includes understanding and modeling the choices of where people live in the first place (Gill and Moeller 2018), how they travel and migrate (Zhang *et al* 2016), how they interact within social, cultural and built environment networks (Poom and Ahas 2016), and how a sharing economy with environmentally beneficial outcomes could be supported (Chen *et al* 2018, Fremstad *et al* 2018). Case studies specific to local circumstances and practices are as important as conceptual and generic models (Wiedmann 2016). In addition, the need to account for the rebound effects of behavior changes has been highlighted by many studies (Chen *et al* 2018, Druckman and Jackson 2016) and important results have been presented (Thomas and Azevedo 2013, Chitnis *et al* 2014, Ottelin *et al* 2017).

The global reach of city footprints requires urban planning and policies to go beyond local issues and adopt a global perspective (Chen *et al* 2016b, Athanassiadis *et al* 2016). At the same time, it is equally important to make research and methods applicable at the municipal level in order to enhance their usability (Laine *et al* 2017). This issue has also been highlighted in the broader literature on urban carbon footprints (Lazarus *et al* 2013, Lin *et al* 2015, Ramaswami *et al* 2017). The CBCF is one among many possible options to examine the GHG emissions induced by urban areas. For example, the community-wide infrastructure footprint (CIF) (Ramaswami *et al* 2012)—which focuses on the urban infrastructure that serves households, businesses, and industry—may be more practical sometimes, since it focuses on significant sectors that cities have a direct influence on. Lazarus *et al* (2013) and Erickson and Morgenstern (2016) use similar reasoning to support a focus on energy consumption, transportation, and waste management. However, one of the main concerns arising from the CBCF literature is that focusing on specific sectors may be insufficient for addressing the continuously increasing global emissions. Rebound effects are one particular aspect that most other indicators cannot capture.

However, the importance of infrastructure and other investments has been noted within the reviewed CBCF literature as well. Chen *et al* (2018) call for further studies of how business and government investments influence city carbon footprints (Chen *et al* 2018). At a detailed spatial scale, there are difficulties in including investments and public consumption into the assessments (see subsection 4.3). The situation could be improved by covering the use of public goods and services at household level in household budget surveys in the future (Ottelin *et al* 2018b) and endogenizing capital in the multi-regional input–output (MRIO) models (Södersten *et al* 2018).

Several studies have highlighted the opportunities and additional insights that can be gained from scenario or dynamic analyzes that explore the consequences of certain policy options more explicitly (Chen *et al* 2017, Heinonen 2016, Millward-Hopkins *et al* 2017). In addition, there is a lack of the time-series and particularly longitudinal studies that are needed to make strong causal claims between policy actions and CBCF outcomes. Furthermore, being able to conclusively answer the question about density-CBCF relationship require use of more precise spatial classifications and GIS-based data about the urban structures.

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