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PAPER

# Spatial consumption-based carbon footprints: two definitions, two different outcomes

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**Keywords:** consumption-based carbon footprint, assessment method, areal carbon footprint, input-output, spatial carbon accounting, personal carbon footprint

## Abstract

The spatial consumption-based assessment tradition is already 30 years old. However, while all the well over 100 studies in this field over the past 30 years have been published under the same consumption-based carbon footprint label, the studies actually fall into two main categories, which have substantial differences between them, by definition in what they include, and how they allocate the emissions. The first utilizes the territory principle and the other the residence principle, meaning that it is partly different consumption activities that are included in the two. The territory principle means that consumption activities are included based on where consumption takes place regardless of who the consumers are, whereas the residence principle means that all consumption of the residents is included regardless of where they consume. Overall, the two lead to potentially very different estimates, and fit to different study situations. So far, this important issue has gone without much attention. In this paper we provide in-depth discussion, through a theoretic example, on how the scopes and the allocation principles vary between the two approaches, and on how the approach choice affects the outcome of an assessment. The provided discussion shows how profoundly different the two approaches can be, and emphasizes the importance of being clear in communicating the allocation principle in every spatial consumption-based study. One approach is not superior to another, but instead they show different perspectives, and the practitioner should carefully select the approach with a better fit with the aim of the study in question.

## 1. Introduction

Consumption-based carbon footprint assessments have become a popular complementary approach in spatial carbon accounting (Afionis *et al* 2017, Ottelin *et al* 2019a, Heinonen *et al* 2020). They allocate the global production and delivery chain emissions to the consumers, and therefore inherently include the transboundary carbon flows (Minx *et al* 2009, Baynes and Wiedmann 2012, Afionis *et al* 2017). This makes them efficient complements to territorial assessments, which suffer from carbon leakage (i.e., outsourcing of emissions to other countries via relocation of industrial production) showing as positive development (Rosen 2015). Already one third of the global greenhouse gas (GHG) emissions is embodied in international trade (Kanemoto *et al* 2014, Wood *et al* 2018), and the leakage happens from high growth and developed countries to lower income countries (de Vries and Ferrarini 2017). Focusing solely on the territorial emissions would therefore potentially lead to biased incentives from a global perspective.

The spatial consumption-based assessment tradition is already 30 years old (Common and Salma 1992), and well over 100 studies have been published in the field with rapid growth towards the most recent years (Heinonen *et al* 2020). However, while all these studies have been published under the same consumption-based carbon footprint label, they do not all follow the same methodological approach (Heinonen *et al* 2020). The studies actually fall into two main categories, which have substantial differences between them, by definition in what they include, and to whom they allocate the emissions. Both approaches are also commonly employed (Heinonen et al 2020). The other one utilizes the so-called territory principle and the other the so-called residence principle (Usubiaga and Acosta-Fernández 2015, Owen *et al* 2016), meaning that it is partly different consumption activities that are included in the two. The territory principle means that consumption activities are included based on where consumption takes place regardless of who the consumers are, whereas the residence principle means that all consumption of the residents is included regardless of where they consume. The two allocation principles lead to different treatment of governmental consumption and capital goods as well as explained in detail in section 2. Overall, they lead to potentially very different estimates, and provide a better fit in different situations, and therefore the practitioner should carefully choose the right approach based on the research setting. The situation is similar to gross domestic product (GDP) and gross national product (GNP) in economic bookkeeping, although with them it is well understood that they cannot be held as the same.

This important issue has gone without much attention until now. Heinonen *et al* (2020) bring it up and recommend clearly categorizing the spatial consumption-based assessments as 'Areal carbon footprints (ACF)' or 'Personal carbon footprints (PCF)', but so far no studies exist providing deeper discussion on the differences and their suitability in different situations, or trying to quantify them in the context of spatial carbon footprints. With this study we aim at filling the first of these gaps by investigating the following research questions:

1. How do the scopes and the allocation principles vary between areal and personal approaches to consumption-based carbon footprints?
2. How does selection of the approach (ACF versus PCF) affect the outcome of a consumption-based carbon footprints evaluation?

To answer the questions, we provide a detailed theoretic analysis of the differences of the two approaches related to different types of consumption activities and to the different components of spatial consumption-based carbon footprints. We also provide an analysis of the inherent scope differences of the two approaches, both in terms of included private consumption, and in terms of the allocation of capital goods and governmental consumption. The provided theoretic discussion shows how profoundly different the two approaches can be and emphasizes the importance of being clear in communicating the allocation principle in every spatial consumption-based study. One approach is not superior to another, but instead they show different perspectives, and the practitioner should carefully select the approach with a better fit with the aim of the study in question.

The paper continues next, in section 2, with a presentation of the theoretic context and the theoretic differences between the two approaches related to different components of consumption-based carbon footprints. In section 3, a two regions theoretic example is presented to illustrate the main scope and allocation principle differences. Finally, section 4 draws together the main observations, provides guidance on choosing between the two methods, and discusses further implications for future research.

## 2. Theoretic context

### 2.1. Consumption-based carbon footprints

Both consumption-based methods follow the same basic principle in allocating to the end-user all the production and delivery chain emissions regardless of the geographic locations, with the inclusion of emissions crossing borders (e.g. Baynes and Wiedmann 2012). Consumption-based approaches fit to different geographic scales (national, state, city, neighborhood, etc.) (Ottelin *et al* 2019a), establishing a link between consumption of goods and services and the associated embodied emissions (Baynes and Wiedmann 2012). The footprints are typically assessed using input-output analysis (Heinonen *et al* 2020), which utilizes environmentally extended input-output tables to track the environmental impacts through the production and supply chains (Minx *et al* 2009, Hendrickson *et al* 2006). There are several openly available input-output models that can be used (Heinonen *et al* 2020).

### 2.2. The different allocation principles

The definitions for ACF and PCF are clearly different, although thus far both have been categorized under the same consumption-based footprint calculations. The definitions of Wiedmann (2016, p.163) *'impacts of local production minus impacts embodied in exports plus impacts embodied in imports'* and Steininger *et al* (2018) *'impacts of production for domestic consumption + impacts embodied in imports'* clearly include an areal perspective, allocating to the area in question all global emissions from all activities within the area. Therefore, we call it 'areal carbon footprint' or ACF, following Heinonen *et al* (2020).

On the other side, Heinonen (2012, p. 12) writes that the consumption-based 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 definition excludes the consumption of visitors, but includes the consumption activities of the residents regardless of the geographic location of consumption. The focus is also entirely on the consumer, therefore making it 'personal carbon footprint' or PCF according to Heinonen *et al* (2020).In previous literature these two different principles have been referred to as 'territory and residence principles' (Usubiaga and Acosta-Fernández 2015, Owen *et al* 2016), and as 'residence-based accounting (RBA)' and 'destination-based accounting (DBA)' (Lenzen *et al* 2018) in the context of input-output analysis, but the distinction has not been made clear with spatial consumption-based carbon footprint assessments, where both approaches are used as the same (Heinonen *et al* 2020).

## 2.3. The three main pillars of consumption-based carbon footprints and their differences under the two allocation principles

Consumption-based carbon footprints may, in addition to the consumer direct spending, also include the components of governmental consumption, capital formation and non-profit institutions serving households. The last item is typically small, but the other two can be highly important (see e.g. the review by Heinonen *et al* 2020). Therefore, it can be said that the three main pillars are private consumption, governmental consumption, and capital formation. The above-discussed allocation principles affect these pillars differently, further aggravating comparisons between assessments of different types. In fact, the first component includes different flows in ACF and in PCF, and the latter two can only be consistently reported in ACF approaches with the currently existing assessment models, as explained below (in theory the two different allocation principles can be applied to governmental consumption and capital formation similarly as with private consumption, but thus far not in practice).

### *2.3.1. Private consumption*

The difference between ACF and PCF is clear in the case of private consumption. ACF includes all the purchases within the area in question, regardless of if those making the purchases reside in the area or not. PCF includes the purchases of those residing in the area in question regardless of if the purchase was made within the area or elsewhere. Both include the global production and delivery chain emissions of all the purchased goods and services according to the footprint ideology. These allocation differences are illustrated in figure 1. The studies using household budget survey (HBS) data inherently fall into the PCF category, whereas those using IO model data are either ACFs or PCFs depending on the perspective of the IO model. We return to this issue in the discussion section (see also Heinonen *et al* 2020 for an overview of data utilized in existing consumption-based CF assessments).

### *2.3.2. Governmental consumption*

Many public or semi-public goods and services are not produced only for the residents of the area under question, but also serve the visitors (such as safety and healthcare, public transport etc.). Therefore, if they are included to the scope of an assessment, they cannot be allocated to the residents according to the PCF principle without information about their usage and calculative values domestically and abroad in places visited, but with ACF the allocation remains uniform with the private consumption component. Ottelin *et al* (2018) present a study using Finnish national statistics about the use of public goods and services to allocate these to the users with the PCF principle, and discuss the problems, but this to date is the only known example to the authors about assessing the governmental component using the PCF approach. There seldom is personal-level data available about the use of public and semi-public goods and services even domestically, and not at all of their use on trips away, making it difficult to robustly use the PCF principle. ACF also by definition includes all public and semi-public goods and services produced within the area in question, but with PCF, by definition, the assessment should include the share of public and semi-public goods used by the residents of the area in question, plus those the residents use elsewhere. Particularly the last issue makes it difficult to robustly estimate the use using the PCF principle.

### *2.3.3. Capital formation*

With capital formation the situation is the same. Similar to public goods, capital is formed not only for the residents, but for visitors as well, and (actually largely) to support industrial production and trade. In ACF the allocation principle is again clear, all capital formation within the area in question belonging to the ACF of the area. With PCF, there is an obvious problem. In theory, all capital formation could be allocated to the final goods and services enabling these emissions to show as embodied emissions of the final products (Södersten *et al* 2018a). This allocation would allow for them to show in the PCFs similarly as the embodied emissions show

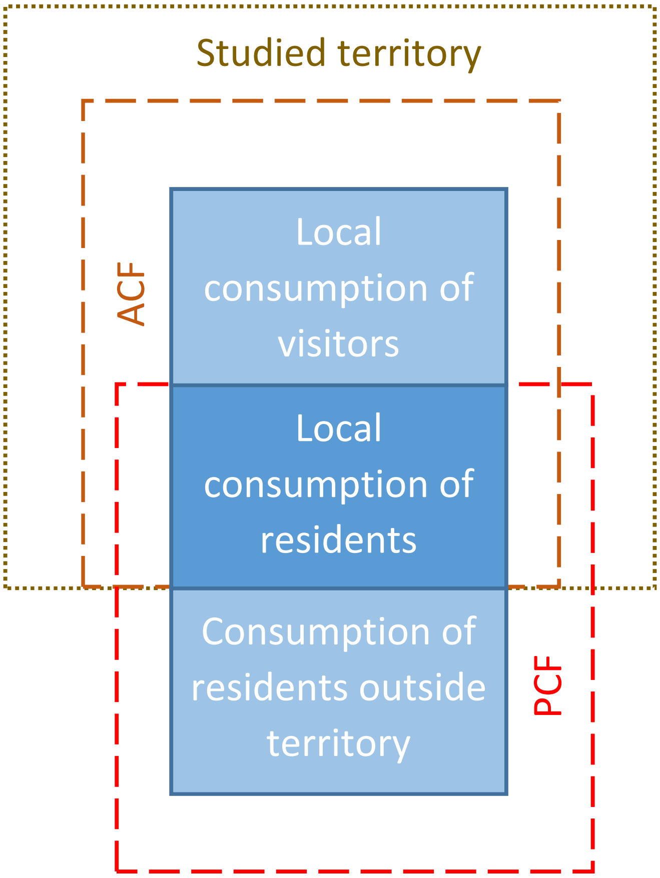


**Figure 1.** An illustration of the scope and allocation differences between ACF and PCF.

currently. However, this would mean that it would no longer be the capital formation in the area in question, and the global production and delivery chain emissions of that, but rather a highly scattered entity of emissions from capital formation around the globe related to the production and delivery of the goods and services purchased by an individual. The existing assessment models do not allow this allocation. Therefore, capital formation is only reported in ACF approaches if at all, or in studies combining the two approaches for a hybrid model as is commonly done (Heinonen *et al* 2020). Figure 2, retrieved from Heinonen *et al* (2020), illustrates the above discussed differences.

## 3. A theoretic two regions example

The above described makes it clear that ACF and PCF can potentially lead to very different outcomes. The difference is the most obvious with governmental consumption and capital formation, ACF accommodating them without methodological deviations, and PCF not being able to accommodate them without giving up on methodological coherence (before the emergence of models including the use of public goods and allowing the allocation of capital to the final goods and services). The private consumption component is also clearly different in the two, but different in different ways when looking further into the sectors of it. We next discuss these differences through a theoretic example, giving also numeric examples from previous studies.

### 3.1. The two hypothetical regions

Let's consider two hypothetical geographic areas, A1 and A2, for which we want to calculate the consumption-based carbon footprints. A1 is a center of work, education, and tourism, and a center of a commuter belt, drawing in visitors throughout the year. A2 is the area next to A1, from where many students and workers commute to A1, and at the same time an area not drawing in visitors to a significant extent. Both areas are equally affluent in terms of income levels and purchasing power, and their economies are based on similar technologies (e.g. they have the same stationary energy production GHG intensity per unit of output).

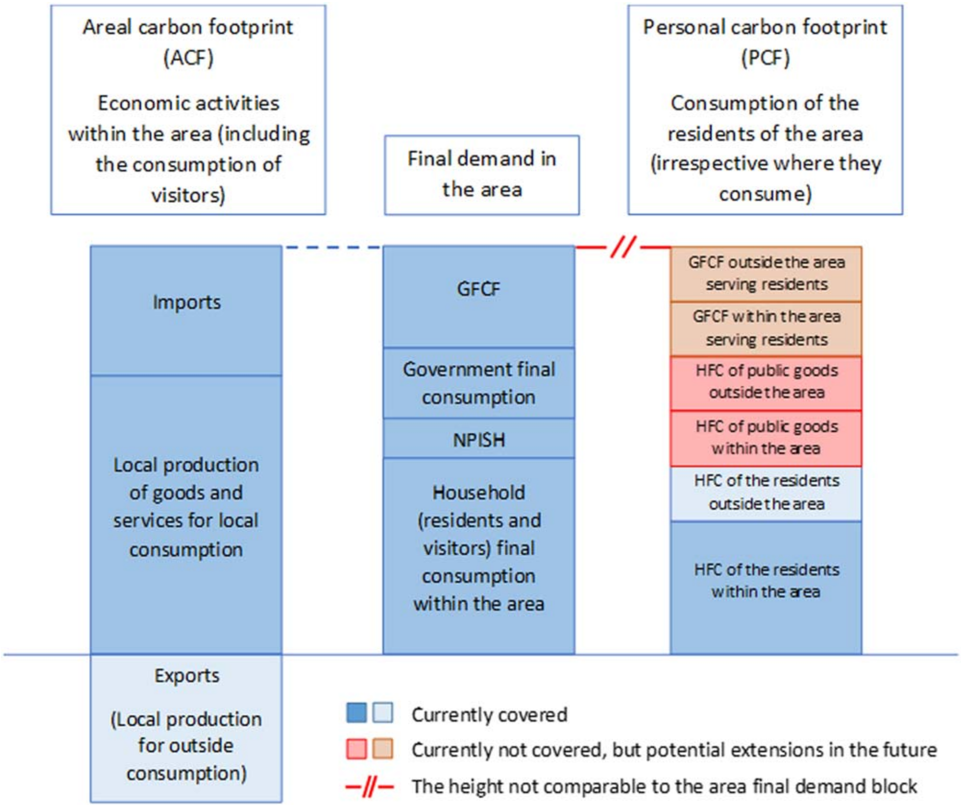


**Figure 2.** Illustration of the differences between the two types of allocation principles, areal and personal. Reproduced from Heinonen *et al.*, CopyRights (2020) with permission from Elsevier. In the figure GFCF means Gross Fixed Capital Formation, NPISH Non-Profit Institutions Serving Households, HFC Household Final Consumption.

### 3.2. Capital formation and governmental consumption

It is likely that with the assumptions made for A1 and A2, capital formation focuses on A1. Infrastructure and service facilities are produced to accommodate visits, whereas in A2 needs are significantly lower. Also, due to A1 being a center of work places, there likely is production for export, and therefore industrial capital formation. With an ACF approach, the capital formation component becomes high in A1, but low in A2. While capital formation is largely driven by visitors to and production in A1 in this example, allocation to the visitors according to the PCF principle would require detailed information about the use. For the overall footprints this issue can be very significant. Capital formation has been reported to cause potentially over 50% of the overall footprints in rapidly developing locations (e.g. Mi *et al* 2016, Li *et al* 2018). Ivanova *et al* (2016) report capital formation to cause 24 $\pm$ 7% in their selection of 43 countries included in the Exiobase MRIO model (Wood *et al* 2015).

With governmental consumption the situation is similar. The needs for many governmental services in A2 are much lower than in A1, and it is to a significant extent the A2 residents who benefit from many governmental services available in A1. Having similar income and purchasing power levels, the utilization of different public services is likely similar, but in ACF the governmental consumption component becomes high in A1, whereas in A2 it remains low. Overall, governmental services don't have as important a role as capital formation, but still 7 $\pm$ 3% in the above-mentioned Ivanova *et al* (2016) comparison of 43 countries. In our example we could imagine A1 to place to the high end with ~10% share due to the needs of serving the visitors in addition to the own residents, whereas A2 would place to the low end at ~4, for not needing to serve visitors, and even the residents spending a major part of their time away.

### 3.3. Personal consumption

Under these conditions the personal consumption components of the carbon footprints for the two areas become highly different depending on the selected allocation method. PCFs are presumably relatively equal due to the equal disposable incomes, since it makes little difference whether the consumption happens within A1 or A2 (or elsewhere), and any differences are therefore mainly driven by different lifestyles. ACFs, however, are presumably highly different, and not comparable to PCFs. For A1, ACF becomes high because of the spending of visitors, be they workers or tourists, and yet higher or lower depending on if the local residents spend their

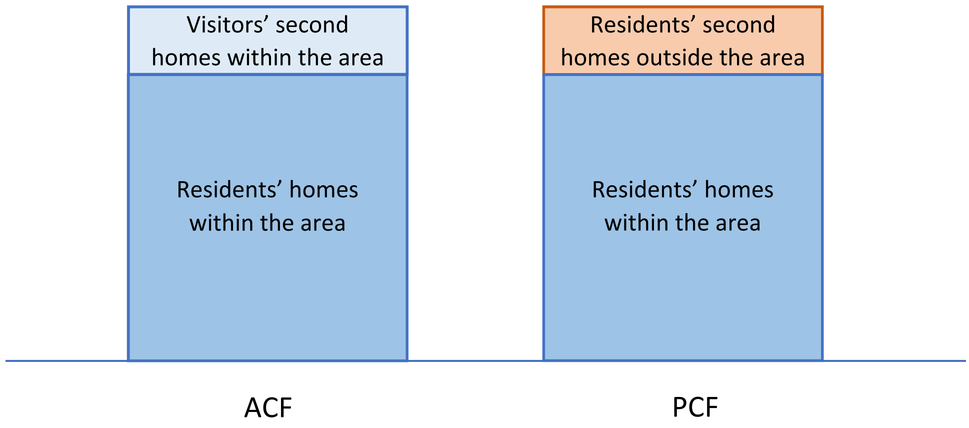


**Figure 3.** Shelter emission scopes in ACF and PCF.

money within the area or elsewhere. PCF for A1 is typically smaller than ACF, but could in theory be as high or even higher, if the spending of the local residents took place mainly outside A1, and therefore counted to PCF but not to ACF of A1. For A2, ACF becomes low as there are few incoming visitors and the local residents commute to A1 to work and spend money. This follows the schematic illustration shown in figure 1 in section 2.

When looking further into the different consumption categories, the two consumption-based assessment methods show higher uniformity in some categories than in some others. We use the following division of private consumption into six main categories to discuss the similarities and differences of the accounting methods:

1. Shelter
2. Ground transport
3. Air travel
4. Food
5. Tangible goods
6. Services

With **shelter**, ACF and PCF should in most cases in theory be close to one another. However, if incoming visitors, for example workers visiting A1 in our example, possess second homes in A1 to a high-enough extent, their visits might show in elevated shelter ACF in A1, and potentially also as reduced shelter ACF in A2. The same could happen with touristic visitors possessing summer houses in A1. Second homes on average only cause a couple of percentages of the overall carbon footprint according to Ottelin *et al* (2015), but for those who possess and actively use for example summer cottages, they can form a share of 10% of the footprint, around one ton per household in Finland (ibid.). Figure 3 illustrates the scope differences between ACF and PCF.

Hotels and office spaces do not appear in the shelter category in either one of the consumption-based methods, but belong to services. In shelter, however, the construction part itself can be considered either as capital formation (e.g. Mach *et al* 2018), or as a good purchased by the resident moving in to the new building (e.g. Ottelin *et al* 2015).

With **ground transport** the difference is potentially high. There might be a significant amount of added transport in a certain area due to incoming visitors, but also the local residents might travel outside to a significant extent. Assuming that A2 residents frequently visiting A1 for work, education, and leisure, also make fuel purchases in A1 on their visit, the ground transport ACF in A1 goes up, and that in A2 is reduced. However, these purchases show in the ground transport PCF of A2, and PCF only varies along with the actual driving of the residents of A1 and A2, regardless of where they drive and purchase fuel. Figure 4 illustrates the scope differences in the fuel combustion emissions from ground transport in ACF and PCF.

Comparable to our two-region example, Heinonen and Junnila (2011) in their PCF assessment report 30%–40% of the private car trip generation in a small city outside the capital area to consist of commuting to the capital area, causing 0.5 tons of GHGs per capita. This is similar to the amount of GHGs the residents of Reykjavik cause driving outside the city according to Czepkiewicz *et al* (2019). Sharp *et al* estimate that an average tourist in Iceland causes around 350 kgs of GHG by their ground transport in Iceland (Sharp *et al* 2016).

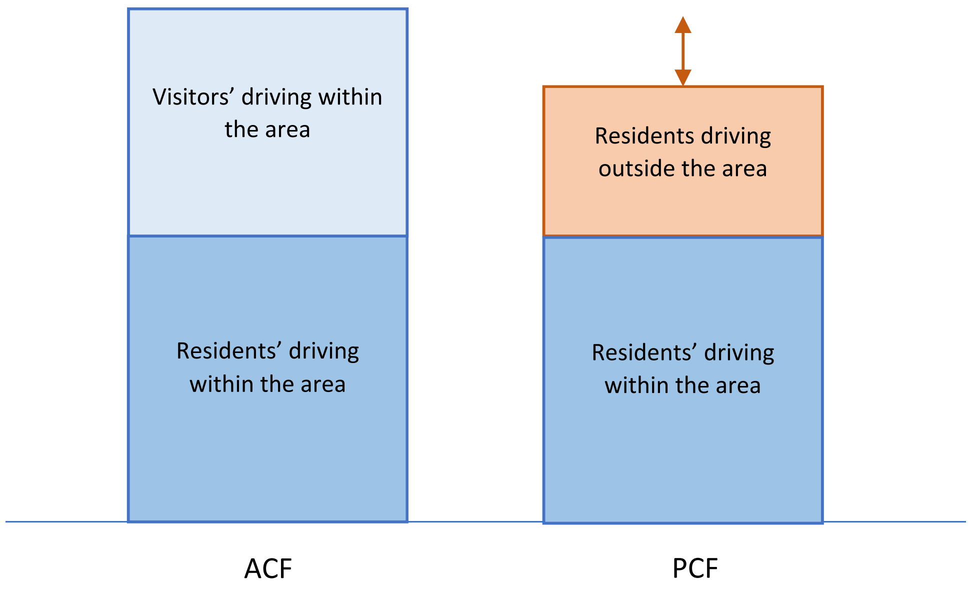


**Figure 4.** Private driving fuel combustion scopes in ACF and PCF.

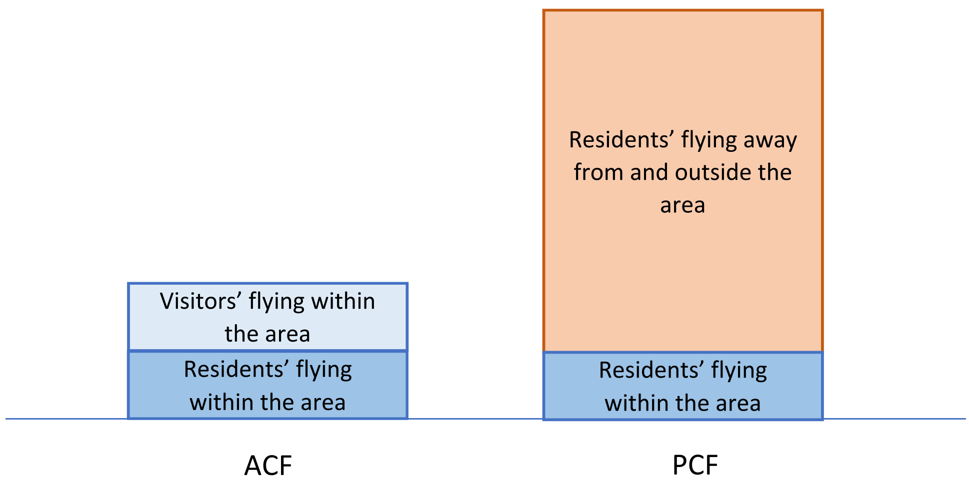


**Figure 5.** Scope differences between ACF and PCF with air travel.

This is 15%–20% of the per capita average of the local residents (Czepkiewicz *et al* 2019, Clarke *et al* 2017). Prior to Covid-19 there were more than 2 million annual visitors coming in (Icelandic Tourist Board 2021), compared to 350.000 residents, meaning that ACF and PCF would show dramatically different outcomes. This supposedly is the case in many touristic locations.

**Air travel** is an interesting and partially troublesome category. In PCF the allocation principle is clear: all flights are allocated to those taking them regardless of the geographic location. In our example, assuming that the residents of A2 would visit A1 by air, all emissions from all flights would be allocated to them in PCF, and the same would be the case even if there would be an airport only in A1 and the residents from A2 would travel there to fly elsewhere. In ACF, however, the allocation principle with these types of transboundary emissions is unclear. Should all the emissions related to all flights from a certain airport belong to the ACF of the area, or fully or partially to the destination location's ACF ? Typically, airports also serve a larger geographic area, and connection flights make an important share, aggravating the allocation issue further in ACF. Due to this, ACF assessments typically omit flights. In country-level assessments domestic flights can be included, but transboundary flights seldom appear in ACF assessments. In practice, there can be significant underreporting of flights also in HBSs, thus leading to underestimation of their role in PCF assessments too (Ottelin *et al* 2019b). Figure 5 illustrates the scope differences between ACF and PCF.

Overall, the air travel issue can be highly significant. Czepkiewicz *et al* (2019) report higher emissions from flights than from ground transport in Reykjavik Iceland, ~2.5 tons of GHGs per capita per year. Of this only a negligible fraction comes from domestic flights, meaning that almost zero emissions would be reported in an ACF assessment (if any), whereas PCF would show extremely high emissions in Reykjavik. This alone is also almost 75% of the global average carbon footprints reported by Ivanova *et al* (2016).

With **food**, **tangible goods**, and **services** the allocation principles are clear, and the differences are potentially large between ACF and PCF, particularly in tangible goods and in services. Food includes only groceries, whereas food services are in services, and therefore visitor spending typically is not an important factor in food. In all three, however, any purchases of visitors show in the ACF of the location where the purchase was made, and not in the ACF of the home location of the visitors. Similarly, all purchases elsewhere show in the PCF of the home location, and not in the PCF of the location where the purchase was made. A1 in our example would therefore have higher ACFs in all the three categories due to the purchases of the commuters from A2 and other visitors. With these categories, it is difficult to find directly comparable numbers from previous studies due to too many uncertainties for a direct comparison using and IO model without conducting a long and difficult study. For example, the well-known problem of under reporting in household budget surveys (HBS) would lead to differences unrelated to the methodological aspects. In addition, the fit between the HBS data and the existing IO models is often not very good, and the utilized concordance matrices cannot erase the problem, leading again to differences in the estimates arising from other sources than from the methodological differences. In addition, with many studies the reporting is not transparent enough for the reader to clearly understand which allocation principle the study in question utilizes. Some indication of the importance is given by Sharp *et al* (2016), who estimate that an average incoming tourist to Iceland causes 200–250 kilograms of GHGs on their trip in these consumption categories. This can be quite a significant amount in touristic locations, and in Iceland is actually much lower in emissions compared to the activities than would be in many other locations due to the almost zero carbon stationary energy system in the country.

## 4. Discussion

There are two commonly utilized allocation principles guiding consumption-based carbon footprint assessments, but so far they have been treated as the same (Heinonen *et al* 2020). This study was set to investigate how the allocation principles vary between the two, areal and personal, approaches and how this could potentially affect the outcomes in different consumption sectors. First the methodological differences in the scopes and allocation principles of the two approaches were opened up and then a theoretic example of two regions presented together with numeric examples from previous studies. Previously, Heinonen *et al* (2020) have brought up the existing situation of two different allocation principles being used under the same consumption-based footprint label without the studies recognizing the issue or discussing the findings from the allocation principle perspective. To the knowledge of the authors this is the first-ever in-depth analysis of these differences and their implications, and therefore it sets important guidelines for future studies in the field.

It was shown that the two allocation principles can lead to very different outcomes, meaning that studies using different approaches should not be compared to one another without considerable care. At the same time, however, one or the other is not absolutely superior. They actually depict different issues, and therefore the practitioners should also carefully select the approach providing a better fit with the target of the study. Many consumption-based carbon footprint studies investigate the lifestyles of the people in a certain geographic area, or compare across different areas (e.g. Bin and Dowlatabadi 2005, Heinonen and Junnila 2011, Heinonen *et al* 2013, Ala-Mantila *et al* 2014, Baiocchi *et al* 2015, Ivanova *et al* 2016, Wiedenhofer *et al* 2017, Shigetomi *et al* 2021). In such studies, the authors should use the PCF approach, or they risk that what they observe as lifestyles is actually largely affected by visitor consumption. And if capital goods and governmental consumption components are included, the assessment includes emissions caused to serve visitors as well as the local residents. Then when studying for example the global climate change impact of consumption in a certain geographic location (e.g. Steininger *et al* 2018, Davis and Caldeira 2010, Hertwich and Peters 2009), ACF is clearly superior as it includes all private consumption in the area, but also can accommodate governmental consumption and capital formation without deviations from the allocation principle (with currently available IO models and data). However, since these ACF assessments can be heavily affected by visitor consumption, they should not be called personal footprints even when presented on a per capita basis. It is also somewhat risky to use per capita or per household as the functional unit in these assessments, at least without clearly noticing that it is not just the consumption of the residents of the area which is included in the assessment. Table 1 gathers together the key strengths and weaknesses of the two approaches, and presents some examples of applications.

In the future it would be highly desirable to see such IO models which would allow allocation of these two components to the end users of the goods and services, as it is the consumers who drive these emissions as well. Work in the field of capital goods has taken place (Södersten *et al* 2018a-b, Font Vivanco 2020), but so far the available IO models only allocate these emissions based on the territory principle. The governmental

**Table 1.** The key strengths and weaknesses of ACF and PCF, and examples of research goals with one or the other providing a better fit.

| | ACF | PCF |
|---|---|---|
| Strengths | –All within-territory activities included with their global emissions, giving indication of how the location is like (in comparison to others) | –All consumption of residents included regardless of where they consume |
| | –Governmental consumption and capital goods possible to include without deviation from the allocation principle within existing assessment models | –Allows lifestyle studies, e.g. comparisons between households with different characteristics and locations |
| | | –Fits to different spatial scales without scalability problems (as location of consumption is irrelevant) |
| Weaknesses | –Should not be communicated as the carbon footprint of the residents of the area in question (due to the inclusion of visitor consumption) | –Typically merges two data sets with a concordance matrix: household consumption data with environmental intensity based on MRIO tables |
| | –Visitor consumption included, potentially significantly affecting the outcome | –Significant data problems to overcome to enable inclusion of governmental consumption and capital goods without deviations from the allocation principle |
| | –Locals' consumption outside territory not included, potentially leaving out large parts of consumption activities (particularly with small spatial scales, e.g. with neighborhood assessments) | –Higher data requirements to capture correctly the emissions of private consumption if a large share takes place outside territory (would require a MRIO for consumption allocation) |
| Examples of applications | –The global climate change impact of consumption in a certain geographic location | –Global GHGs analyzed based on (economic) consumption patterns of the residents in specific region |
| | –The roles of capital goods and governmental consumption in different locations on different levels of development | –CF differences due to income and consumption differences within the area in question |
| | –Transboundary flows of emissions / emissions embodied in trade | –Correlation of built environment qualitied with consumption and the resulting GHGs |

consumption component is also interesting as it varies significantly between countries depending on which services are provided as public or semi-public, and which are sold in the private market (e.g. education and health care). Ottelin *et al* (2018) present an early work with PCF allocation of these to the residents of the area in question, but several data problems remain to be solved. Accurate PCF assessments would also actually require information about the use of these services in each location visited outside the home area, which is a requirement not easily fulfilled.

The ACF-PCF issue might become more pronounced when the spatial scale decreases. IO models are seldom available for smaller spatial units (Heinonen *et al* 2020), except for some early examples of city- and regional-level models (e.g. Chen *et al* 2017, Wiedmann *et al* 2015, Hasegawa *et al* 2015). It can be hypothesized that the issue becomes of higher relevance when the spatial unit analyzed gets smaller (and consumption of residents takes place outside the area to a higher extent). In touristic cities and regions private consumption can be dominated by visitors, and similarly a higher share of the governmental and capital components can serve these visitors instead of the permanent residents. In addition, the capital component can be dominated by production of means of production and transport infrastructure (Mi *et al* 2016, Chen *et al* 2018, Li *et al* 2018), of which a large share might not serve neither the residents or the visitors, but rather industries and export business.

Despite this study being the first of its kind in the field of spatial consumption-based carbon footprints, the same allocation principle issue has been discussed before in different contexts. Usubiaga and Acosta-Fernández (2015) and Owen *et al* (2016) have referred to it as 'territory and residence principles' in the context of how MRIO models allocate emission, and Lenzen *et al* (2018) as 'residence-based accounting (RBA)' and 'destination-based accounting (DBA)' in a consumption-based assessment of global tourism, which is another clear example where PCF (or RBA) is superior. With this study we aim at highlighting the importance of first choosing the right method to a study based on the research question(s), and then communicating it clearly to the readers what the chosen method was in the field of spatial consumption-based carbon footprints. Researchers applying IO-models also need to understand the allocation principle used in compiling the chosen IO model. Of the existing most widely utilized models, GTAP and Eora employ the territorial principle, whereas WIOD and EXIOBASE use the residence principle (Owen *et al* 2016). Ignoring the allocation principle difference in selecting the IO model for a study might lead to problems with the validity of the findings. PCF assessments also often employ private consumption data from other sources than the IO model (Heinonen *et al* 2020), and use that to replace the data in the model. This brings about an additional source of uncertainty, particularly when done using a territory-based model, leading to a situation in which the emission intensities don't necessarily reflect well the goods and services bought by the residents. This could well be the case in locations with significant visitor consumption, as the consumption patterns of visitors and locals might be different, affecting the model's intensities. Another problematic case arises if a significant share of the residents' consumption happens elsewhere. The assumption inherently taken is that the associated emissions are the same as with the same products sold locally, but this might not be the case. This problem is actually similar to when using a single-region IO model, and assuming domestic emission intensities for imports. It is therefore a possibility that in some cases a multi-region IO model does not actually solve this problem.

Many existing studies are also actually hybrids between the two allocation principles, for example in using the residence principle in the personal component assessment, but the territory principle in assessing the governmental and capital components (see Heinonen *et al* 2020). Moreover, even the PAS2070 standard's guidelines for a consumption-based assessment of the GHGs caused by a city follow this same hybrid approach as is evident from the definition: '*The [consumption-based] 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 [consumption-based] 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). According to the quote from the standard, governmental consumption and capital formation are allocated to the residents using ACF approach even though these don't solely serve the residents, but for private consumption that of the residents only is included following the PCF approach. It remains unclear though if the consumption of the residents abroad is included or not. This situation of all kinds of hybrid approaches existing further reduces the comparability across studies, and further highlights the responsibility of the one utilizing a certain study to interpret the findings correctly. In the future we hope that this study helps in clarifying the scope and the methodological approach to all readers.

While this study has theoretically shown that the scope and allocation principle differences between the two consumption-based carbon footprint approaches are important and require attention in future studies, it is still to be quantified how significantly different the results are for different countries and sub-national units. Future studies should therefore run comparisons on different spatial levels and across countries in different geographic locations and at different levels of development and get deeper into the reasons causing the detected differences, as well as discuss further when and where one approach is more appropriate than the other. Most importantly, however, all future studies should clearly identify the approach, use it consistently, and interpret the results through the correct lens.

## Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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