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Combining material flow analysis with life cycle assessment to identify environmental hotspots of urban consumption

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A B S T R A C T

Understanding the global environmental impacts of local consumption is an area of growing interest among policymakers and consumers. By knowing what products comprise urban consumption "hotspots," municipalities and consumers alike could take deliberate actions to target and discourage consumption of high-impact products. In this paper, a new method for identifying environmental hotspots of consumption is presented. The main methodological advances are the following: i) material flow analysis of urban areas and life cycle assessment are combined; ii) a 16-year time-series of urban consumption data is used for selection of the most suitable representative products and for trend analysis; iii) representative products are selected systematically from consumption data of 1000 product types; iv) representative products are scaled up to represent consumption of the product groups; v) hotspots are identified by simultaneously evaluating six environmental impacts - acidification, climate change, eutrophication (marine and freshwater), photochemical ozone formation, and resource use; vi) for the case study, hotspots are connected to the city's profiles. The method was applied to the Swedish cities Stockholm, Gothenburg and Malmo and to Sweden in total. Electronics is a hotspot for all the studied areas and all the studied impacts and should be a prioritized product group for action. Fuel is a hotspot shared by all the areas while vehicles is a hotspot in Gothenburg. Meat is a nationwide hotspot, but not for the cities investigated. Gothenburg and Stockholm could collaborate to find effective measures for their common hotspot machinery. Thus, the method can be used to identify hotspots and find which product types could be part of national versus local programs.

1. Introduction

Cities are responsible for approximately 80% of global resource use and energy consumption and 75% of global greenhouse gas (GHG) emissions (Intergovernmental Panel on Climate Change, 2014; UNEP, 2012). The continuing global shift of populations from rural to urban areas is likely to increase this environmental impact, as 68% of the world's population is expected to be urban by 2050, compared to 30% in 1950 (International Resource Panel, 2018; United Nations, 2018). Urbanization is strongly connected with higher incomes (GDP) (The International Bank for Reconstruction and Development/The World Bank, 2009), which can lead to lifestyle changes that include greater consumption of goods (Satterthwaite, 2009; World Health Organization, 2003). It is essential to understand the environmental impact of urban consumption to effectively address the problem.

Many cities have strategies and tools supporting a reduction of direct environmental impacts like emissions to the atmosphere and the subsequent impact (e.g., the Swedish Environmental Objectives (Naturvårdsverket, 2017)), but lack guidance on reducing indirect impacts. The indirect environmental impacts of consumption are complex and may occur elsewhere (before or after the use phase),

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not visible to the consumer (European Commission, 2012). For example, an automobile not only has a direct impact on the environment while it is running; the processes of collecting the materials for and producing the vehicle have impacts as do other parts of the life cycle. These impacts must be understood and considered when evaluating the environmental impact of consumption in cities.

Several methods have been used to estimate the environmental impact of consumption including environmentally extended input-output tables (EE-IO) (Tukker et al., 2006), multi-regional input-output tables (MRIO) (Druckman and Jackson, 2009; Hertwich and Peters, 2009), and ecological footprint (Wackernagel and Rees, 1996) or carbon footprint (Larsen and Hertwich, 2010a). However, the above approaches are all based on aggregated data and are usually used for sector analysis at the national or global level, unless detailed economic data is available at the local level (as in Norway, e.g., Larsen and Hertwich (2010b)). Greenhouse gas emissions can be calculated per sector (e.g., education, healthcare, agriculture, etc.), but product-level data that may be relevant for smaller scale analysis are often lacking (e.g., Larsson and Bolin (2014)). Municipalities and regions can benefit from having area-specific and product-level information to customize their targets and make more informed decisions regarding, for example, public procurement. Regions may have varying consumption profiles due to various factors including household composition, economic structures, the degree of urbanization, and even climate (Gerstberger and Yaneva, 2013). It is therefore relevant to know what specific product categories drive environmental impact in the region to design strategies that will most effectively reduce impacts.

At the urban scale, a combination of material flow analysis (MFA) or IO and life cycle assessment (LCA) has been used (Finnveden et al., 2009; Goldstein et al., 2013). Applying LCA for analysis of urban material flows' environmental implications is also useful in designing sustainable urban metabolism (Kalmykova and Rosado, 2015). The LCA method is used to estimate the potential environmental impacts throughout a product's lifespan. The assessment quantifies inputs and outputs of materials, energy, water, and emissions during the various phases of the product's life, from raw material extraction through production, manufacture, use, and end-of-life treatment (recycling and/or final disposal) (Baumann and Tillman, 2004). However, in previous approaches (García-Guaita et al., 2018; Goldstein et al., 2013; Lopes Silva et al., 2015), specific product categories are not analyzed. Rather, these studies look at selected flows (e.g., energy, food, or buildings) (Goldstein et al., 2013) or general consumption categories like electricity or food (García-Guaita et al., 2018; Lopes Silva et al., 2015). Using general categories like food, buildings, etc. Precludes design of effective policies that would address the most impactful product types. It is for example known that different food categories may vary by orders of magnitude for different impacts, and buildings exhibit a range of impacts depending on the materials used. In another approach, urban wastewater pipeline networks were analyzed using hybrid MFA-LCA, but the purpose of this analysis was for future management of pipelines (Venkatesh et al., 2009). The combined MFA-LCA approach has also been used to evaluate the environmental impact of solid waste management, quantifying how impacts may be reduced under various waste stream scenarios at an urban scale (Turner et al., 2016), or assessing opportunities for circular economy (Iacovidou et al., 2017), both with the intention of aiding decision makers. In other approaches, the "basket-of-products" method, where selected products represent entire product categories, has been applied. This method has been used at the national or EU level (European Commission, 2012; Notarnicola et al., 2017; Rydberg et al., 2014). Selection criteria and final product choices vary between studies, however, and previous studies either have few representative products (European Commission, 2012) or are limited to food products (Castellani et al., 2017; Notarnicola et al., 2017). In this study, we analyze a robust set of product categories with a higher resolution than has previously been available.

Huysman et al. (2016) quantified consumption impacts of a European Union (EU) citizen for the year 2007 using EE-IO and compared them to the results of an LCA quantification of the same environmental impact (Huysman et al., 2016). The results obtained with the LCA were much lower than those obtained with EE-IO and the resulting ranking of the consumption activities differed considerably. This difference was explained by two main factors: the EE-IO method covered the entire material-product chains in an economy while LCA covers a part of the materials-product chain, and impacts in the LCA study were underestimated because no upscaling of representative products to product groups was applied, meaning that the impacts reflect the representative products only. In the method described in this paper, representative products' masses are scaled up to equal the mass of the entire product category.

With rare exceptions (e.g., Huppes (2006)) most consumption impact studies have focused on the climate change indicator global warming potential (GWP), using kilograms of carbon dioxide (CO_2) equivalents or carbon footprints, and overlooked other environmental impacts like acidification, eutrophication, photochemical ozone formation, and resource use (e.g., Department for Environment Food and Rural Affairs (2011), Hertwich and Peters (2009), Minx et al. (2013), Yetano Roche et al. (2013)). The nitrogen calculator is another tool that analyzes the nitrogen footprint (similar to the carbon or ecological footprint) but focuses on one indicator (Leach et al., 2012). By looking only at a single indicator, high impact products could be overlooked and thus not targeted by policy-makers. Recommendations could be made to substitute a product (for example, electric vehicles for fuel vehicles) that could have high impacts in a different impact category (like acidification), a concept called "burden shifting," where an intended reduction in one aspect of the life cycle unintentionally increases the environmental impact of another (Bjorn et al., 2018; Hellweg and Milà i Canals, 2014). In this method it will be possible to see the impact of consumption in several categories which allows for a more comprehensive analysis of high impact products, thereby reducing the risk of burden shifting.

Furthermore, most studies use only one year of data (e.g., household consumption in 2007 (Ivanova et al., 2014), average Gothenburg resident consumption in 2010 (Larsson and Bolin, 2014), carbon footprint of UK settlements in 2004 (Minx et al., 2013), impact per inhabitant in Santiago de Compostela in 2015 (García-Guaita et al., 2018)) and are thus unable to identify consumption trends. There are exceptions to this where multiple years are evaluated (e.g., Nilsson and Brandt (2013)), but trends are not analyzed. Consumption in cities changes over time, which can affect hotspots. Moreover, some years may have data that represent particular or unusual events that could lead to misleading results, and it is therefore beneficial to use a longer time span of data. In this study, more than ten years of consumption data have been used.

Many of the studies listed here focus on individual cities or countries, without drawing connections between cities within a country (with again, rare exceptions (Larsen and Hertwich, 2010a)). This limits decision makers' ability to see what level of strategy (i.e., local, regional or national) may be most effective. Given that consumption profiles can vary among urban areas (Rosado et al., 2016), consumption-related policies could potentially be more successful if they are region-specific. In this method, it will be possible to see if there is a need for region-specific policies and, if so, for what product categories.

A “hotspot” as defined in this study is a product category with high environmental impact in multiple impact categories. By targeting the hotspots of urban consumption, both policy-makers and consumers can act to reduce high-impact consumption while minimizing the risk of burden shifting. In the literature, high impact products or consumption categories are not always called hotspots but are still identified in several of the studies. A hotspot threshold of 10% of the total impact has been seen in the literature (Pelton and Smith, 2015), but there is no precise agreed upon level. A hotspot can also be selected visually, by, for example, selecting the highest peaks on a graph.

This study aims to illustrate a consumption-driven environmental impact hotspot identification method, using Swedish consumption data to show how target (i.e., high-impact) product types can be found using hybrid MFA-LCA for national and sub-national (urban in this case) geographical areas. Using proportionally scaled-up masses of representative products systematically selected from a comprehensive set of product categories, we analyze the impact of consumption on multiple impact types across several regions. The method is shown using data from the three largest Swedish municipalities: Stockholm, Gothenburg, and Malmo, and also at the national level for Sweden. Sweden has a population of approximately 9.900.000 and Stockholm, Gothenburg, and Malmo municipalities have populations of approximately 1.540.000, 580.000, and 308.000, respectively. All three cities have shown growing trends in both population and GDP over the past three decades (Statistics Sweden, 2018.). The method, however, is intended to be useful for any region at any scale (national, regional, urban) with relevant data. The method allows for the analysis of multiple impact categories, and by using several years of data, this approach enables comprehensive analysis of consumption trends and their effect on hotspots. This also makes it possible to determine the geographical resolution necessary for consumption reduction measures, either at the regional or national level.

2. Method

The combined MFA-LCA hotspot identification method used to quantify the environmental impact of consumption in urban areas is outlined in Fig. 1 and explained in detail in Sections 2.1 through 2.4.

2.1. Total consumption

The annual masses of product types consumed in the metropolitan areas of Stockholm, Gothenburg and Malmo during 1996–2011 and for Sweden during 2000–2011 were found (Kalmykova et al., 2015b), and the average mass over the years evaluated was calculated. The consumption data was quantified using the UMAn model, an MFA model that uses trade, transport, production, and employment data to estimate the total consumption within a specific region. The model quantifies the urban Domestic Material Consumption (DMC) by calculating domestic extraction plus imports, minus exports, which are quantified using statistical transport and trade data. Raw goods or intermediate products are transformed into final goods based on the economic activities found in the area of study. Consumption data therefore include both materials produced locally and imported materials, and are presented as final goods. Detailed descriptions of the MFA method used, the data sources, and the data quality have been reported previously (Kalmykova et al., 2015b, 2015c; Patrício et al., 2015; Rosado et al., 2014).

The consumption data are categorized into product types using the combined nomenclature (CN), a classification system used in the EU for trade, similar to the Harmonized System used outside of the EU (Eurostat, 2017, 2018). The CN codes are numbered, where numbers signify product types. A two-digit CN code is the most aggregated (e.g., CN16 is preparations of meat or fish), whereas a four-digit CN code is more specific (CN1601 is “sausages and similar products”). This study refers to the four-digit and the two-digit CN codes as “product type” and “product category,” respectively. The complete list of all the levels CN-codes and their description can be found in EEC Council Regulation 2658/87 (European Union, 2017).

2.2. Representative products

For this study, representative products at the CN-4 (product type) level were chosen based on three criteria: high consumption by mass of products within a product category, consistent consumption of products with respect to time and geography, and common product types with known high environmental impact reported in the literature. In a step-by-step process, the MFA data were first analyzed to identify the top product types consumed by mass in each product category. These were then evaluated for consistency over time (products that were highly consumed in fewer than three years of the sixteen evaluated were not considered to be representative). The top consumed product types that were consistently consumed were supplemented by-products that may have low mass but could have high impacts, based on the literature (e.g., Tukker (2006)). Two product categories (machinery and electronics) were significantly larger and more heterogeneous than the remaining categories and additional representative products were selected. The representative products were then connected to LCA profiles. For more details on the representative product selection, see Lavers et al. (2017).

The final list (or “basket”) for the Swedish cities Stockholm, Gothenburg, and Malmo includes 71 product types (CN-4), like “apple” and “banana” from 43 product categories (CN-2) like “fruit.” One or several products have been designated to represent each product category, as presented in Table A1 in Appendix A. The final number of representative products depended on a sensitivity analysis within each product category, and ranged from one to six products.

The mass of each representative product in a product category was scaled up by the factor of M/M_r, where M is the total mass of all products in the category and M_r is the total mass of representative products in this category. This effectively redistributes the mass of non-representative products among the representative products in the category. The mass redistribution is done in proportion to the share of each representative product in the total mass of representative products, as shown here in Equation (1):

$$m_i^{'} = m_i + m_0\frac{m_i}{M_r} = m_i = \frac{M_r + m_0}{M_r} = m_i\frac{M}{M_r} \quad (1)$$

where m_i is the mass of ith representative product in the given category; $m_i^{'}$ is the upscaled mass of ith representative product in the given category; and m_0 is the total mass of non-representative products in the given category. $M_r = \sum_{i=1}^{N} m_i$ gives the total mass of representative products in the given category, where the variables $m_1 \ldots m_N$ are the respective masses of the representative products and $M = \sum_{i=0}^{N} m_i$ gives the total mass of the category. M is also the sum of M_r and m_0. This applies to every product category with more than one representative product. For product categories with only one representative product, the consumption of the total category was used.

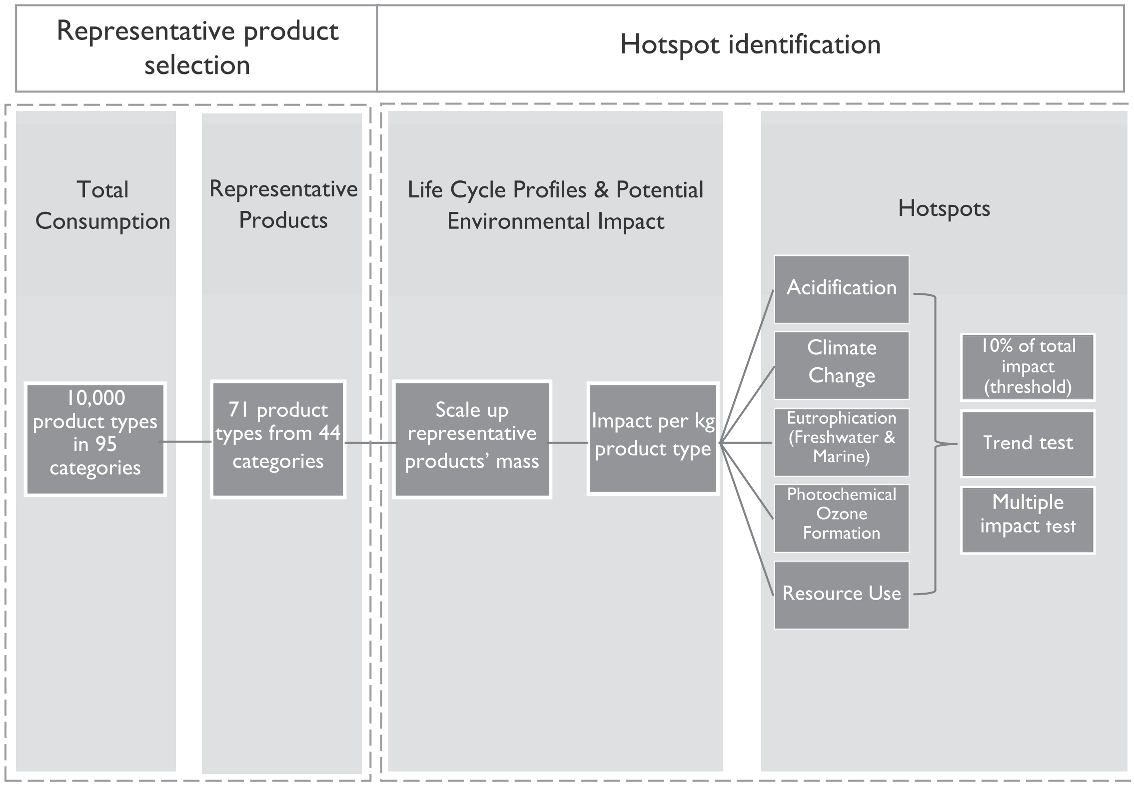

Fig. 1. Flow chart of method to find target product groups with high environmental impact. The first two steps ("representative product selection") are described in depth in Lavers et al. (2017), and the final two ("hotspot identification") are developed in this paper.

2.3. Life cycle profiles and calculation of potential environmental impacts

The scaled-up mass of the representative products was multiplied by the impact per kilogram of product, based on the life cycle profiles. The impact of each product type (CN-4 level, e.g., CN0401 milk, CN0403 yogurt, and CN0406 cheese) was aggregated (summed) to the CN-2 product category, e.g., CN04 dairy. The results are presented by CN-2 category as the use of representative products does not indicate that one particular product is the main contributor.

The European Commission Joint Research Centre (JRC) International Reference Life Cycle Data System (ILCD) Handbook (European Commission, 2010) life cycle impact assessment method and cradle-to-gate LCA datasets from LCA databases (ecoinvent v3, thinkstep and IVL internal database) were used to estimate potential environmental impacts. The software GaBi v7 was used to build the models. The cradle-to-gate method converts inputs from and outputs to nature during the various phases of the life cycle into estimated environmental impacts, from extraction of raw materials through the production stage, but before products are distributed to consumers. JRC/ILCD's recommended midpoint indicator categories (i.e., climate change, acidification, eutrophication, photochemical ozone formation, and resource use) were analyzed, as other impact categories and endpoint indicators have higher uncertainty (European Commission, 2010, 2011).

2.4. Hotspot evaluation

The hotspots were identified at the CN-2 product category level following three steps. First, product types were selected for further evaluation as "preliminary hotspots" if the impact (based on their average consumption over the years evaluated) exceeded the threshold of ten percent of the total impact value per impact category (e.g., total sum of kg CO_2-equivalents for climate change of all product types). In the second step, the consumption trends of the identified preliminary hotspots were analyzed. Preliminary hotspots with decreasing trends were re-evaluated using the last year of data (2011) to see if the hotspot status remained, i.e., the impact still surpassed the 10% threshold, a so-called "trend test." Product types with impacts exceeding the 10% threshold and passing the trend test in two or more impact categories ("multiple impact test") were identified as final hotspots.

If the average impact of a product type did not exceed the 10% threshold, but some portion of the box plot exceeded the threshold in multiple impact categories and consumption values showed an overall increasing trend, the product category was included as a potential future hotspot. If the trends were decreasing or constant, they were not included as a potential future hotspot.

2.5. Assumptions and limitations

The main assumptions and limitations of the method are:

- The environmental characteristics of the representative products are assumed to be similar to all products in the category. After scaling up their masses, these representative products are used to describe the total consumption of the product category. The influence of this assumption on the accuracy of results for a specific category will depend on the heterogeneity of the category, and on the representative product's share of the category. For heterogeneous categories, we have therefore selected more than one product. For relatively homogeneous categories, the upscaling will not introduce any significant errors beyond those stemming from the life cycle impact (LCI) profile of one product. The purpose of the method is to identify priority product groups and not individual products, so the differences of the products within the group are inconsequential.

- The analysis was performed using cradle-to-gate, rather than cradle-to-grave LCI-data (i.e. the use and end-of-life phases are not included). This means that:
  a. The analyzed system is the upstream impact of consumption patterns, not the overall impact of consumption;
  b. The impacts of the combustion of fuel and gas products were not included;
  c. Waste treatment activities (e.g., wastewater treatment) occurring upstream from the point of consumption are included in the cradle-to-gate LCI-data.
- Generic, non-region specific and static LCA datasets (i.e., the same LCA dataset for each year of analysis) were used. This does not allow for new, less impactful technologies to be considered and the "unburdening effect" is therefore not taken into consideration (Cucek et al., 2012). There may be large differences in environmental performance for specific products depending on the region of production. By using generic data, however, the results will be somewhere between extremes, which is a reasonable basis for hotspot identification. No conversion factors were applied to the retrospective LCIs.
- The 10% hotspot threshold is arbitrary, but serves the purpose of shortlisting product categories of interest. An alternative approach could be to include as hotspots those products that contribute to the total environmental category impact up to some percentage of the accumulated impact. We tested the number of hotspots found using $\pm$20% as a margin of error of the 10% threshold to analyze the sensitivity of the results to the threshold, see Section 3.2.

Some of these assumptions and limitations may result in over- or underestimation of values in the calculation of hotspots. However, they can be considered as random in nature and unlikely to displace the calculated environmental impacts in the same direction. The uncertainties of the results are therefore not likely to impact the recommendations for policy makers and individuals' lifestyle choices drawn from the hotspot analysis.

3. Results and discussion

3.1. Case study results

First, we present the consumption impact results, which are based on scaled up masses of representative products multiplied by impacts per kilogram. Here, we show how consumption impacts can vary between regions and examine potential reasons for the variation. Representative product selection was previously reported (Lavers et al., 2017) and can be found in Appendix A. Then, we present the preliminary hotspots, and the results of the trend and multiple impact tests which identify the final hotspots. Finally, we describe the implications of the results and provide examples of how this information can be used.

3.1.1. Consumption impacts

The environmental impacts of consumption in the different regions analyzed varied in magnitude (see Table 1 for results based on average consumption over the time period studied and Appendix B for the time-series results). This suggests that specific regional policies could be considered for certain product categories, as discussed in Section 3.1.4.

In Table 1, we present the top five product categories per region and impact category and their corresponding percentages of the total impact. These environmental impacts include impacts that occur up until the use phase, and are either indirect or direct, depending on the product type. For example, if a specific industry is located within the municipality, the production impacts are directly present in the municipality, but if a good is imported, the impacts occur at the origin and are indirect impacts in the municipality. The impacts that occur while the product is being used (e.g., people driving cars) and those that occur at the end of life phase (e.g., recycling or landfilling of car parts) are not included in these results. These results are a precursor to hotspot identification and are discussed to identify regional differences. Only product categories that exceeded the 10% threshold became preliminary hotspots.

As seen in Table 1, although the top five products are fairly consistent among the cities, they do not follow an identical ranking. The top five products consistently contribute, with one exception (climate change, Malmo), to greater than 50% of the total impact. The difference in rankings can be explained by the cities' different profiles, as described below, and is also in line with both the urban typology classification and the regional differences in carbon footprints found in other studies (Jones and Kammen, 2011; Kalmykova et al., 2015c; Rosado et al., 2016).

Stockholm has a service economy with the highest number of workers in knowledge-intensive services of all OECD metropolitan regions, with 85% of employment in service sectors compared to only 9% and 6% in the industrial and construction sectors, respectively (OECD, 2013). The service economy is also reflected in the traffic at the port of Stockholm: it is the busiest passenger port in Sweden, with over 9 million passengers annually (compared to Gothenburg's 1.7 million) but it handles only 5 million metric tons of freight and oil annually, significantly lower than Gothenburg (Kalmykova et al., 2015c). This could indicate that local vehicle use is primarily for personal or professional use, less so for freight and transport of goods. For Stockholm, the top product type for climate impact is fuel (17%). Most of the goods used by Stockholm are imported, which indicates that the consumption impacts are primarily indirect. Of the goods that are manufactured, 80% are for local consumption. The total results for climate change can be compared to Nilsson and Brandt (2013), whose measurement of 8.2 tons CO2-eq per capita for Stockholm, year 2004, exceeds this study's results of 7.4 for the same year. Nilsson and Brandt use IO-LCA, where the monetary value of each consumption category is combined with an emission intensity for that same category (Wadeskog and Larsson, 2003). IO-LCA includes emissions associated with services, so it is not surprising that the impact value is slightly higher.

Gothenburg's high impact product categories include vehicles prominently and across various impacts. This is mainly due to the characteristics of the city, home to the busiest port in Scandinavia and a large proportion of heavy industry, including the vehicle industry. This suggests that more of the impacts are direct. However, it should be noted that these impact levels are based on final good consumption, not on consumption required for production. The industrial and construction sectors employ 16% and 7% of the workforce, respectively. More than 30% of Sweden's foreign trade passes through Gothenburg (over 62 million metric tons of freight and oil annually). This likely influences the number of vehicles needed to transport goods to and from the port (Rosado et al., 2016) as almost 90% of domestic transport of goods is via truck (Trafikanalys, 2016). A study by Larsson and Bolin found 7.4 tons CO_2-equivalents per capita, compared to this study's results of 7.0 tons CO_2-equivalents per capita for the same year (2010). The Larsson and Bolin results include air travel, electricity and heating, which are not included in this study, suggesting that our results would have been higher if we took these aspects into account.

Table 1
Top five product categories per region and impact category, based on average impact over the time span.

Environmental Impact Category	Stockholm		Gothenburg		Malmo		Sweden	
Climate change	fuel	17%	electronics	19%	fuel	9%	electronics	22%
	electronics	11%	machinery	17%	articles of iron/steel	9%	fuel	12%
	machinery	11%	fuel	15%	vehicles	8%	machinery	12%
	vehicles	9%	vehicles	14%	Machinery	8%	meat	6%
	meat	5%	meat	4%	meat	8%	vehicles	6%
Sum % of total		**53%**		**69%**		**42%**		**58%**
Acidification	fuel	21%	electronics	35%	electronics	19%	electronics	32%
	electronics	21%	fuel	16%	meat	14%	fuel	14%
	meat	9%	machinery	12%	dairy	12%	meat	12%
	machinery	9%	vehicles	9%	fuel	10%	machinery	9%
	vehicles	7%	meat	7%	vehicles	6%	vehicles	4%
Sum % of total		**67%**		**79%**		**61%**		**71%**
Eutrophication – Freshwater	electronics	52%	electronics	64%	electronics	54%	electronics	58%
	machinery	20%	machinery	20%	machinery	15%	machinery	20%
	technical instruments	8%	vehicles	7%	vehicles	6%	technical instruments	4%
	vehicles	6%	technical instruments	2%	articles of iron/steel	6%	vehicles	4%
	articles of iron/steel	2%	printed books & newspapers	1%	technical instruments	5%	articles of iron/steel	2%
Sum % of total		**88%**		**94%**		**86%**		**88%**
Eutrophication – Marine	meat	19%	electronics	26%	meat	26%	meat	26%
	electronics	14%	meat	18%	dairy	17%	electronics	14%
	processed meat	12%	fuel	9%	processed meat	11%	furniture	13%
	furniture	10%	furniture	9%	electronics	9%	processed meat	7%
	fuel	10%	machinery	6%	furniture	7%	dairy	7%
Sum % of total		**65%**		**68%**		**70%**		**67%**
Photochemical Ozone Formation	fuel	29%	fuel	24%	fuel	17%	electronics	25%
	electronics	14%	electronics	24%	electronics	13%	fuel	21%
	machinery	10%	machinery	15%	vehicles	9%	machinery	11%
	vehicles	9%	vehicles	13%	articles of iron/steel	9%	vehicles	6%
	printed books & newspapers	4%	printed books & newspapers	2%	machinery	8%	printed books & newspapers	4%
Sum % of total		**66%**		**78%**		**56%**		**67%**
Resource Use	electronics	29%	electronics	40%	vehicles	27%	electronics	46%
	technical instruments	24%	vehicles	30%	electronics	26%	vehicles	15%
	vehicles	23%	machinery	15%	technical instruments	18%	machinery	14%
	machinery	12%	technical instruments	7%	machinery	9%	technical instruments	13%
	furniture	3%	aluminum	2%	aluminum	5%	furniture	4%
Sum % of total		**91%**		**94%**		**85%**		**92%**

Seventy-eight percent of the workforce in Malmo is employed by the service sector, 16% by industry, and 6% by construction. The distribution of climate impact over more products in Malmo than the other two cities may be due to a major transformation experienced by the city since the beginning of the twenty-first century. Rosado et al. (2016) show that the consumption trends in Malmo are variable mainly due to two peaks in non-metallic minerals consumption coinciding with the construction of large infrastructures (one of them the Oresund bridge between Sweden and Denmark). Malmo, although developing towards a service city, still has characteristics of a more agricultural or industrial city and impacts related to food production are still prominent. Malmo's impacts for climate change are distributed among seven products, with iron/steel and dairy being exclusive to this city's high-impact products. The transitional nature of Malmo underscores the benefit of a trend test when trying to identify hotspots.

Given that many studies focus primarily on carbon footprint or CO_2-equivalents per capita, the results for Sweden can be compared to EE-IO or MRIO results from e.g. Exiobase (Wood et al., 2014). We found that, on average, this study's results for Sweden are approximately 16% lower than studies using IO methods, which is in line with previous comparisons of LCA-based models and EE-IO/MRIO (e.g., Huysman et al. (2016), Yetano Roche et al. (2013)). Input-output based models are expected to be more "complete" as they include services, and do not have system boundary cut-offs as required in LCA.

3.1.2. Hotspots identification

Table 2 shows the results of the three-step process for selection of hotspots described in Section 2.4 above, where any product category whose average impact value exceeded the 10% threshold in any impact category was selected as a preliminary hotspot. We present a selection of figures for the three cities in the text, and the results for all impact categories and regions can be found in Appendix B.

Figs. 2 to 7 present climate change and acidification results for Stockholm, Gothenburg, and Malmo, where average values are marked with a dot and the box plots represent the impact results over the sixteen-year time span. As seen here, the highest impact products range in variability both within the time span and the order of ranking.

These results can be used to identify local priorities but also to identify areas for joint efforts. For instance, for climate change, Stockholm and Gothenburg have distinctive hotspots and share three of them; however, their importance for the respective city is different. This suggests that cities can cooperate in finding effective solutions for these hotspots, but these solutions will be prioritized differently depending on the area. Malmo's impacts for climate

Table 2
Preliminary hotspots based on average impact values.

	Preliminary hotspots CN-2 code & name	Impact category exceeded	Consumption trend	Trend test[a]	Multiple impact categories	Final hotspot
Stockholm	02 Meat	Eutrophication marine	Constant	N/A	✗	✗
	16 Processed meat	Eutrophication marine	Constant	N/A	✗	✗
	27 Mineral fuels and oils	All	Increasing	N/A	✓	✓
	84 Machinery/mechanical equipment	All but acidification	Constant	N/A	✓	✓
	85 Electrical machinery and equipment	All	Decreasing	✓	✓	✓
	87 Vehicles	Resource use	Increasing	N/A	✗	✗
	90 Technical instruments	Resource use	Constant	N/A	✗	✗
	94 Furniture	Eutrophication marine	Slightly increasing	✓	✗	✗
Gothenburg	02 Meat	Eutrophication marine	Constant	N/A	✗	✗
	27 Mineral fuels and oils	Climate change, acidification, photochemical ozone formation	Increasing	N/A	✓	✓
	84 Machinery/mechanical equipment	All	Slightly decreasing	✓	✓	✓
	85 Electrical machinery and equipment	All	Slightly decreasing	✓	✓	✓
	87 Vehicles	Climate change, photochemical ozone formation, resource use	Increasing	N/A	✓	✓
Malmo	02 Meat	Acidification, eutrophication marine	Decreasing	✗	✓	✗
	04 Dairy	Acidification, eutrophication marine	Decreasing	✗	✓	✗
	16 Processed meat	Eutrophication marine	Decreasing	✗	✗	✗
	27 Mineral fuels and oils	Acidification, photochemical ozone formation	Increasing	N/A	✓	✓
	84 Machinery/mechanical equipment	Eutrophication freshwater	Constant	N/A	✗	✗
	85 Electrical machinery and equipment	Acidification, eutrophication freshwater, photochemical ozone formation, resource use	Slightly decreasing	✓	✓	✓
	87 Vehicles	Resource use	Increasing	N/A	✗	✗
	90 Technical instruments	Resource use	Slightly decreasing	✓	✗	✗
Sweden	02 Meat	Acidification, eutrophication marine	Constant	N/A	✓	✓
	27 Mineral fuels and oils	Climate change, acidification, photochemical ozone formation	Constant	N/A	✓	✓
	84 Machinery/mechanical equipment	Climate change, eutrophication freshwater	Constant	N/A	✓	✓
	85 Electrical machinery and equipment	All	Slightly decreasing	✓	✓	✓
	87 Vehicles	Resource use	Slightly increasing	N/A	✗	✗
	90 Technical instruments	Resource use	Slightly decreasing	✓	✗	✗
	94 Furniture and bedding	Eutrophication marine	Constant	N/A	✗	✗

[a] The trend test was only performed for product types with a decreasing trend; N/A = not applicable.

change are evenly distributed among seven products, with iron/steel and dairy being exclusive to this city's high-impact products (Fig. 4). From the table and the figures, one can also see where further analysis may be necessary. For example, the maximum values for technical instruments and aluminum exceed the threshold for climate change in Stockholm (Fig. 2), but the average values do not; see the trend analysis discussion in Section 3.1.2.2. We can also see variability over the time span studied – the larger the span of the boxplot, the larger the variation over the sixteen years of data. Several of the product types appeared as preliminary hotspots in all the studied cities such as: CN85 electronics, CN84 appliances/machinery and CN02 meat. Because the thresholds are relative to the actual local consumption and the cities' distinctive consumption patterns, diverse preliminary hotspots may be obtained, e.g., CN94 furniture and bedding, visible in the figures in Appendix B. Not all preliminary hotspots meet all three criteria (i.e., exceed the threshold, pass the trend test, present in two or more impact categories) and become final hotspots.

3.1.2.1. Hotspots from multiple impact categories. Municipalities need to reduce multiple environmental impact types to meet targets and could leverage their efforts by addressing multiple impact types simultaneously by focusing on hotspots that exceed the threshold in two or more impact types. The Swedish government has aggressive targets to reduce consumption-based environmental impacts both with respect to climate change and water quality (e.g., eutrophication) among other aspects (Miljömålsrådet, 2010). Most municipalities have environmental quality objectives relating to direct impacts (acidification, eutrophication, climate change, photochemical ozone formation, etc.), and some, like Gothenburg, even have goals related to consumption-based (indirect) impacts per citizen (Göteborgs Stad, 2014). It may therefore be beneficial to any of these objectives to focus efforts on multi-impact product categories.

Evaluating several impacts simultaneously enables the identification of high-impact products that may have otherwise been missed. There are several examples of high-impact products, such

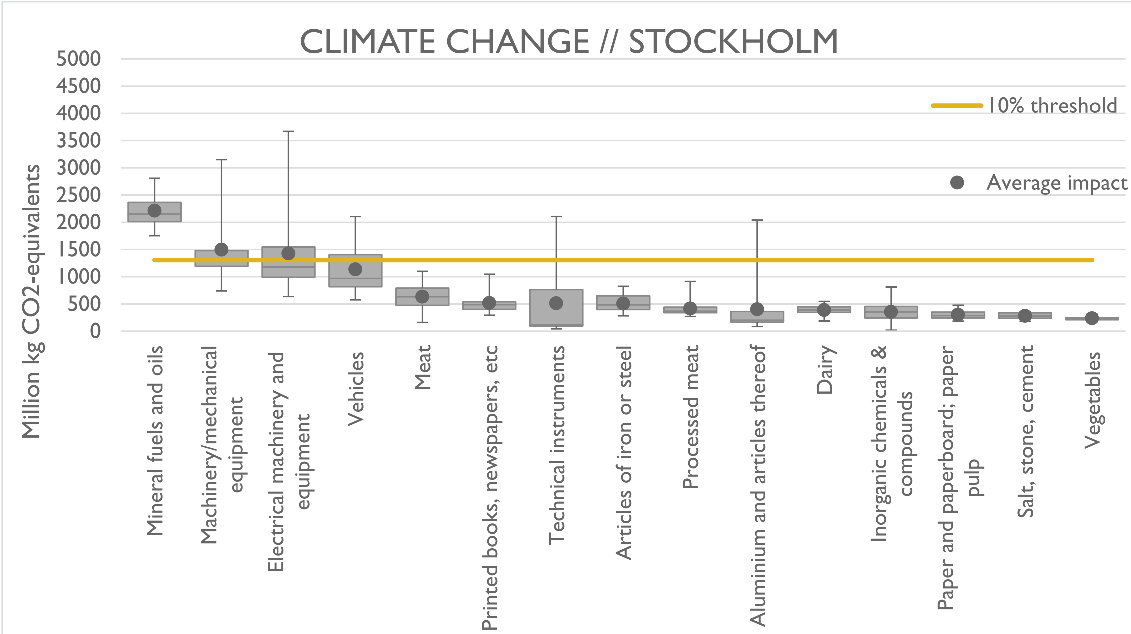

Fig. 2. Climate change results for the top 15 product types in Stockholm, 1996–2011.

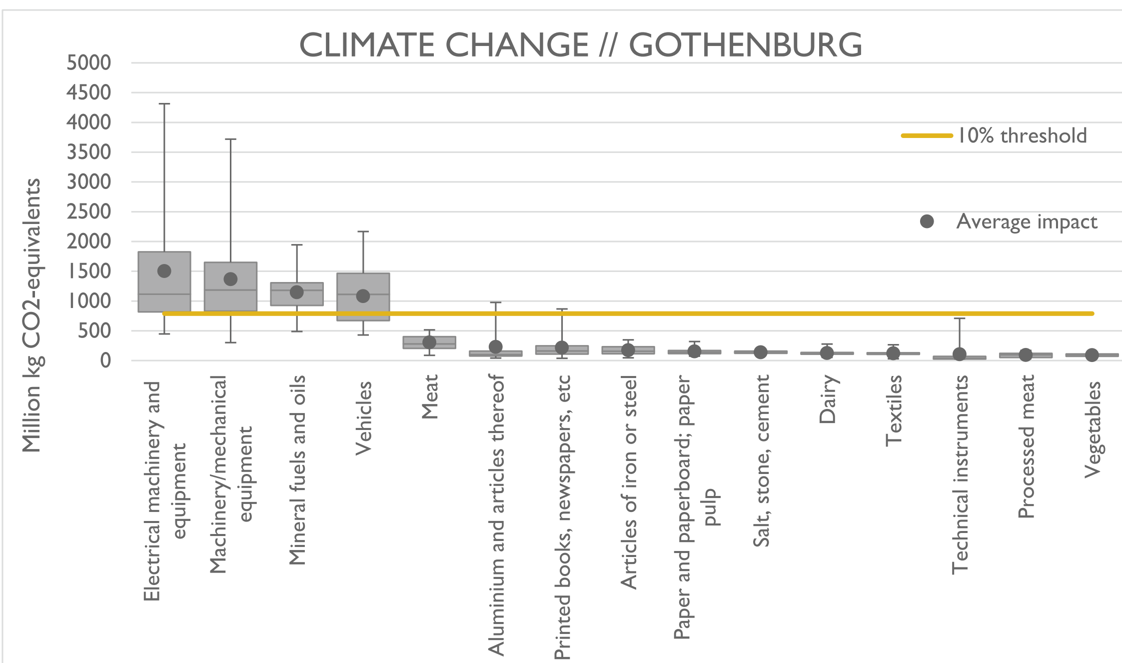

Fig. 3. Climate change results for the top 15 product types, Gothenburg, 1996–2011.

as food products (CN02, 04 and 16), and technical instruments (CN90) which do not exceed the threshold value for climate change and would thus be overlooked by methods where climate change is the sole indicator. In Malmo, CN02, 04, 27 and 85 were preliminary hotspots in two or more impact categories, yet none of these product categories exceeded the climate impact threshold.

3.1.2.2. The effect of consumption trends. Using temporal data allows for a more nuanced view of consumption patterns to better predict the need for reduction measures. A temporal analysis of the hotspots was performed; Table 3 and figures in Appendix C show the consumption trends of the preliminary hotspot product categories for each investigated region. CN87 vehicles and CN27 fuel show an increasing trend in all regions, despite efforts to change mobility modes (Friman et al., 2013). This agrees with the findings of Gothenburg municipality, who measured a steady increase in vehicle traffic that parallels the population increase despite reduction efforts including a congestion tax (Trafikkontoret, 2016). Although vehicles did not become a final hotspot in Stockholm or Malmo, trends in both cities suggest that they could be potential future hotspots. CN85

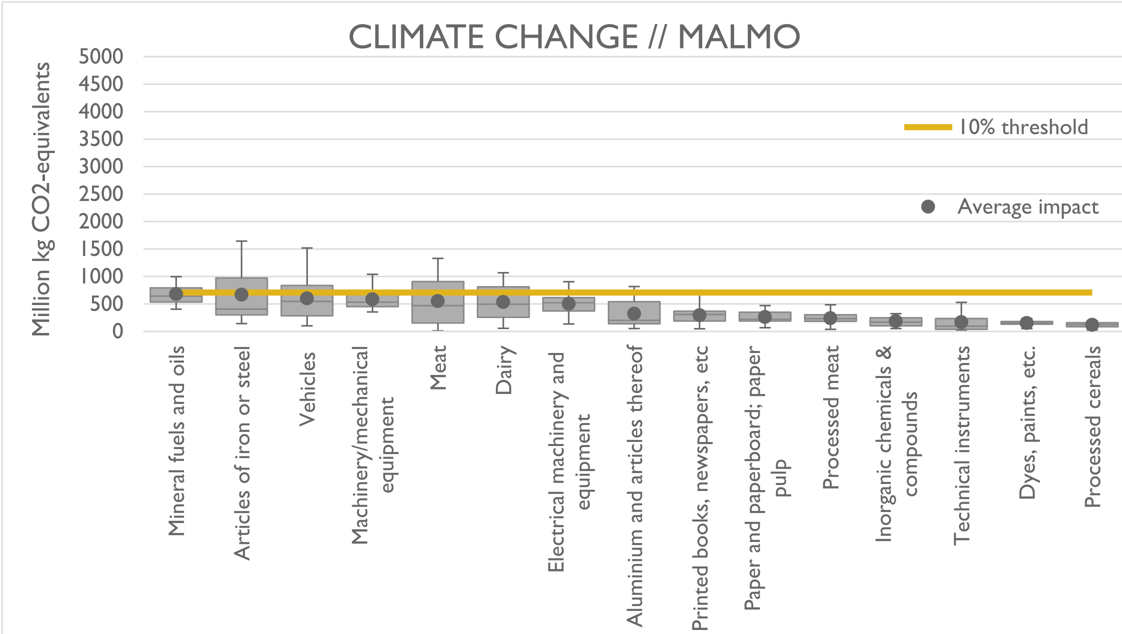

Fig. 4. Climate change results for the top 15 product types, Malmo, years 1996–2011.

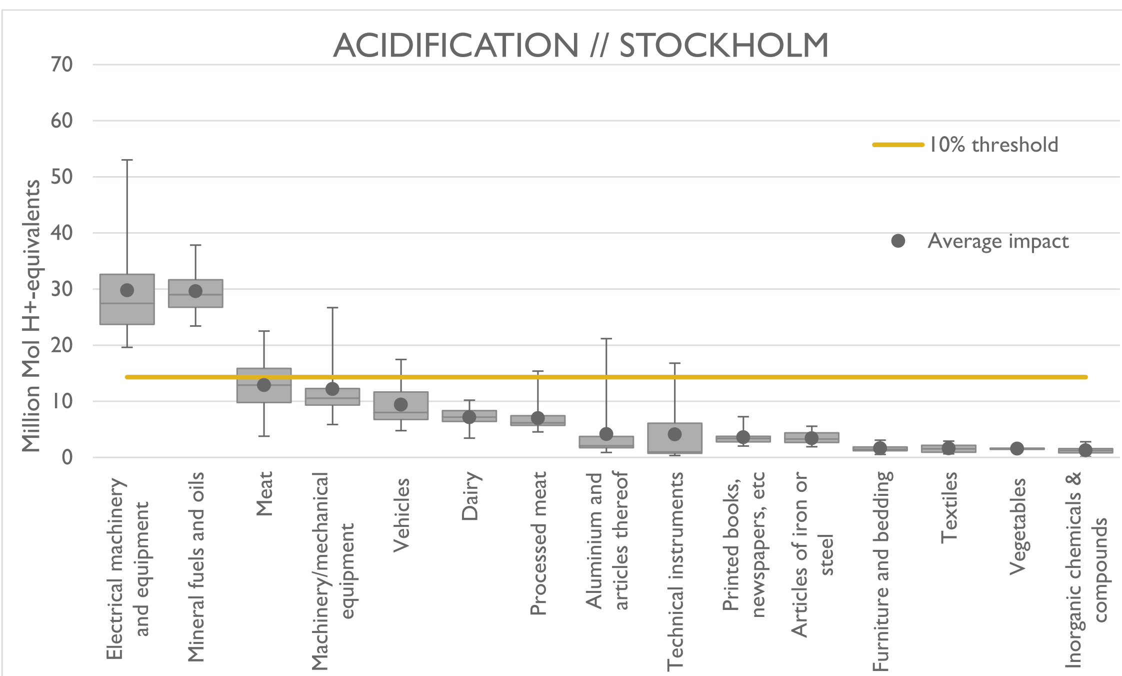

Fig. 5. Acidification results for the top 15 product types, Stockholm, years 1996–2011.

electronics shows a decreasing trend in all regions, but still has a high impact in the final year of analysis. Some product categories showed decreasing trends and did not exceed the 10% threshold in the latest evaluated year (2011) so were removed from the list (see products with an "X" under Trend test, Table 3).

In some cases (like climate change in Malmo) the average impact value did not exceed the hotspot threshold, but the maximum impact value of certain product categories did, underscoring the benefit of a trend test. Table A3 in Appendix A presents these potential future hotspots based on maximum values. The following categories were added as potential future hotspots as they exceeded the 10% threshold in 2011 and showed increasing trends: aluminum in Stockholm and Gothenburg, and vehicles in Stockholm and Malmo. All final and potential future hotspots are presented in Appendix C.

3.1.3. Final hotspots

The final hotspots in Stockholm are fuel, machinery, and electronics; in Gothenburg, fuel, machinery, electronics, and vehicles; in Malmo, fuel and electronics; in Sweden meat, fuel, machinery, and electronics. Many relevant studies (e.g., Larsson and Bolin (2014); Minx et al. (2008); Nilsson and Brandt (2013)) do not

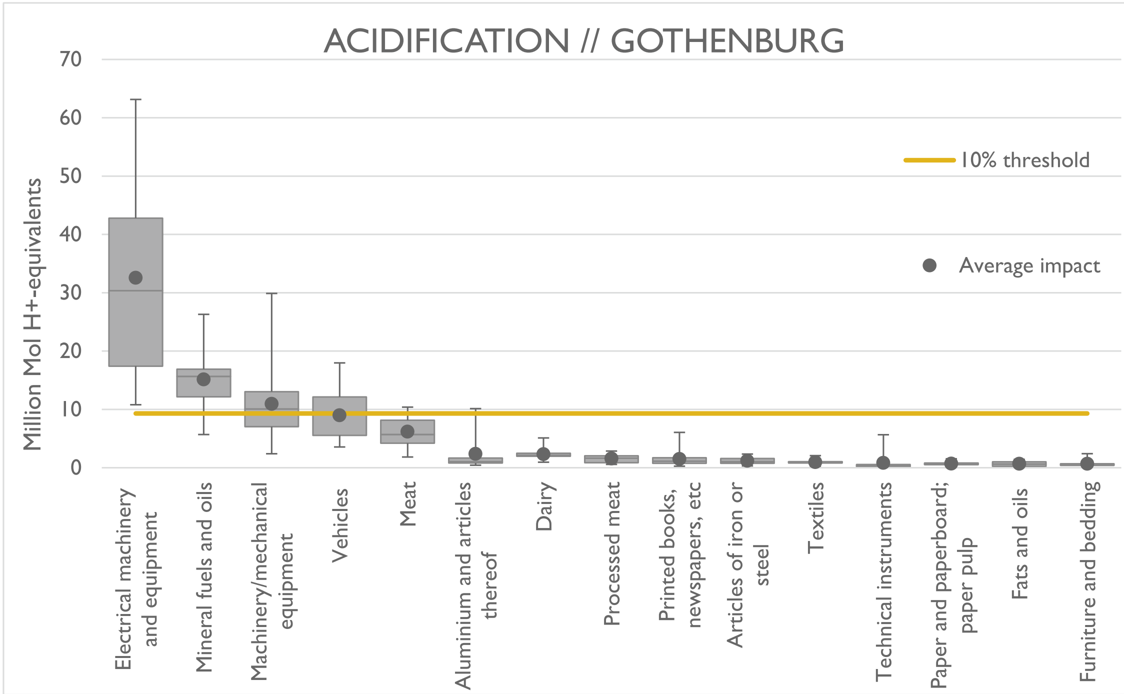

Fig. 6. Acidification results for the top 15 product types, Gothenburg, 1996–2011.

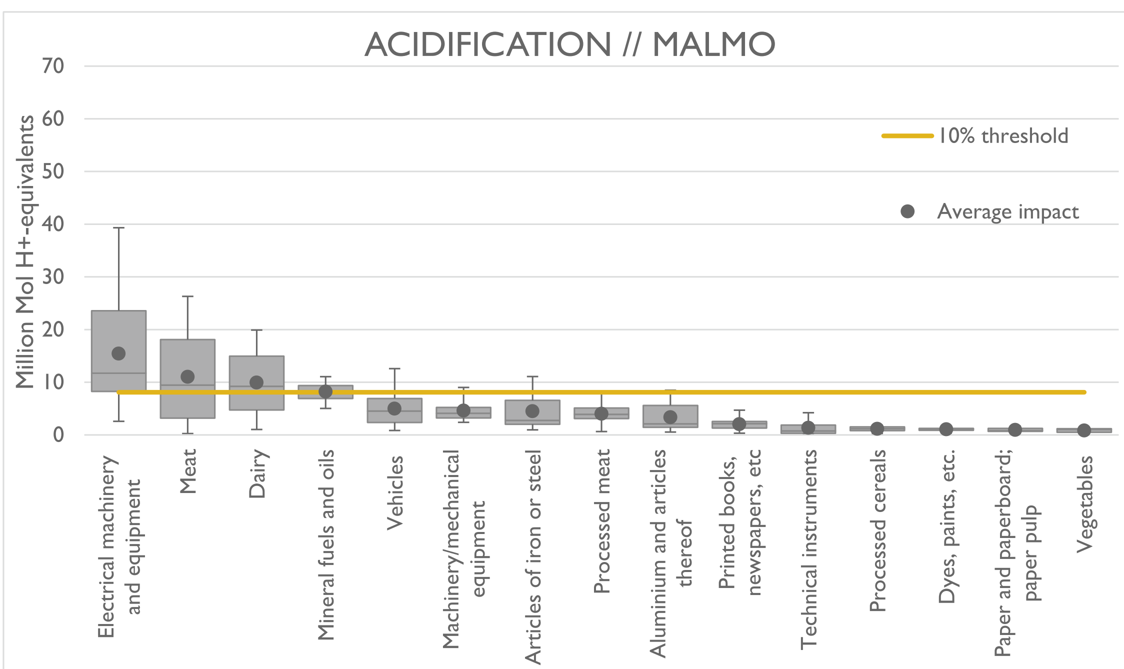

Fig. 7. Acidification results for the top 15 product types, Malmo, 1996–2011.

Table 3
Number of final hotspots based on different hotspot thresholds in the regions investigated.

	Number of hotspots			
Hotspot threshold	Stockholm	Gothenburg	Malmo	Sweden
8%	4	4	5	4
9%	3	4	4	4
10%	3	4	2	4
11%	3	3	1	4
12%	2	3	1	3

specify candidate product categories for reduced consumption and it is therefore not possible to compare this study's recommendations with respect to hotspots. The exceptions to this are Notarnicola et al. (2017) and Huysman et al. (2016). Notarnicola et al. (2017) modeled hotspots of food consumption for European Union residents, designating cheese, beef, pork, and beer as impact hotspots. These are most easily compared to this study's product categories of dairy, meat, pork and beverages, of which only meat was found to be a final hotspot, and solely for Sweden as a whole. Huysman et al. (2016) found food, shelter, mobility, and consumer goods to be hotspots, which could be compared to vehicles/fuel, and some of the consumer good product categories like electronics.

3.1.4. Implications of the results

Given that actual local consumption is used for the environmental hotspots identification, the obtained results enable formulation of custom-made regional policy solutions targeting specific product categories. In Sweden, public procurement is a significant contributor to consumption (e.g., healthcare, education, etc.), and municipalities and other public bodies control their own consumption. It is difficult to identify how much consumption is driven by public procurement, but studies suggest that municipal operations could comprise 18–25% of total consumption, based on waste statistics (Nielsen, 2013) or IO analysis (Sinclair, 2013). This implies that internal local regulations could have a significant impact. Public procurement can be low hanging fruit for impact reduction policy application not only due to the considerable size of the handled material flows but also because top-down implementation is possible. Moreover, municipalities and governments can implement measures and incentives to encourage or discourage certain types of consumption. For example, the Swedish government has recently incentivized refurbishment and repair of certain items of electronics and machinery with a tax reduction, and the city of Gothenburg has opened several facilities where citizens can repair goods (Gabrielson, 2017; Government Offices of Sweden, 2018). Such a mix of national and regional action can help reduce the consumption of high-impact goods.

Differences in results for the studied areas, with regards to both hotspots and consumption trends, indicate that there is an opportunity for region-specific reduction efforts as well. For example, CN02 meat is considered a hotspot for Sweden in general, but not for the studied cities. CN27 fuel and CN85 electronics are common hotspots for the country and the cities and are therefore relevant for nation-wide policies.

There is also a potential for regions to work together to identify symbiotic solutions. By sharing data and ideas, cities can reduce their impact more effectively. For example, Gothenburg and Stockholm share CN84 machinery as a hotspot and could adopt compatible policies. CN87 vehicles is a hotspot in Gothenburg and a potential future hotspot in Stockholm and Malmo.

Those product types that produced hotspots in more than one impact category make prioritization of targets for policies easier. Policies targeting such products could potentially be most effective by creating synergies and solving several problems simultaneously, at reduced cost. For example, CN85 electronics is a hotspot for all evaluated environmental impact categories in Stockholm and Gothenburg and for four out of six impact categories in Malmo. Other product types with wide ranges of impacts are CN87 vehicles, and CN84 appliances/machinery. The impacts reported by this study are attributed to the cradle-to-gate phase of these products, i.e., product life stages before purchase by consumers. Therefore, existing Swedish policies targeting the use phase of electronics (e.g., energy efficient appliances) and disposal phase (separate collection and recycling) do not address the observed impact. Instead, the demand for new electronics, appliances, machinery, and vehicles should be managed in addition to the already existing use and disposal phase policies. Demand for electronics is soaring (Kalmykova et al., 2015b), and at the same time service lifespans (lifespan of the product from purchase to disposal) are plunging, not only for mobile phones but over a wide range of products, see for example a case of TVs and monitors in Sweden (Kalmykova et al., 2015a). Even though the consumption trend between 1996 and 2011 indicates decreasing consumption of electronics, this may be due to electronics weighing less, not reduced quantities. To curb demand for new electronic appliances, implementation of concepts like service economy and circular economy may be necessary. These concepts include strategies that may decrease the pool of products necessary to fulfill population needs, such as: providing Product Service Systems, sharing products, and product reuse and refurbishment (Kalmykova et al., 2018).

3.2. Method discussion

The method presented in this paper allows for identification of hotspots specific to the region's metabolism, resulting from the type of economy and socio-economic characteristics, among other aspects (Rosado et al., 2016). An additional benefit of using region-specific consumption data is that decision makers can observe changes in consumption trends in the future and track progress to see if targets have been met, using results from historical data as benchmarks.

The method uses rigorously chosen products to represent product categories. The masses of these representative products are scaled up and then multiplied by impact factors to get a more accurate assessment of the product category's environmental impact than methods that do not use scaling. High impact product categories, or hotspots, are determined based on impact threshold exceedances in multiple impact types and a consumption trend analysis. By evaluating several impact categories, the method helps identify policies and environmental measures that avoid trade-offs, and thus do not result in burden shifting. Moreover, the trends found using multiple years of data validate the selection of hotspots. This multifaceted selection procedure is therefore a robust method to identify hotspots.

We present a summary of the strengths, weaknesses, opportunities, and threats (SWOT analysis) of the approach in Fig. 8.

This method is a useful tool for the identification and prioritization of region-specific hotspots that can be applied at any scale for which MFA data is available. The main difference for national and regional- or urban-level applications of the method is that data availability may be better at the national scale than at the local scale. For example, Eurostat, the statistical organization for the EU, has a database of national annual MFA statistics starting from 2008 for the EU, which are compiled using a standardized method (Eurostat, 2001, 2017, 2018). Although MFA data is currently not commonly collected by city administrations, the analysis is frequently performed by researchers as demonstrated by the online database Metabolism of Cities (Metabolism of Cities, 2018.) and the growing number of studies using MFA.

The criteria for both representative product and hotspot selection can be applied to any MFA data, regardless of categorization, and the method can be adapted to different cases if needed. For example, if multiple years of data are not available, the absence of a trend test may not invalidate the results, especially in the case of stable economies; see discussion below on hotspot thresholds.

The results produced by combined MFA-LCA are similar in value to carbon footprint and IO-studies, as reported in Section 3.1. Moreover, the results provide a level of detail not available in most IO-methods that present results for sectors (“food”, “construction”) rather than specific product groups.

As presented in Section 3.1.4, the method can also help identify products for which governing bodies of different regions may collaborate or where a larger, national level program may be more appropriate. Furthermore, the results of the method can be used by decision makers to evaluate proposed consumption-related measures or policies. For example, the possible effects of measures targeting hotspots can be quantified, estimating how consumption of products and the corresponding environmental impact could change, as described in Lavers Westin et al. (2019). In that study, a selection of municipal measures addressing Gothenburg's hotspots

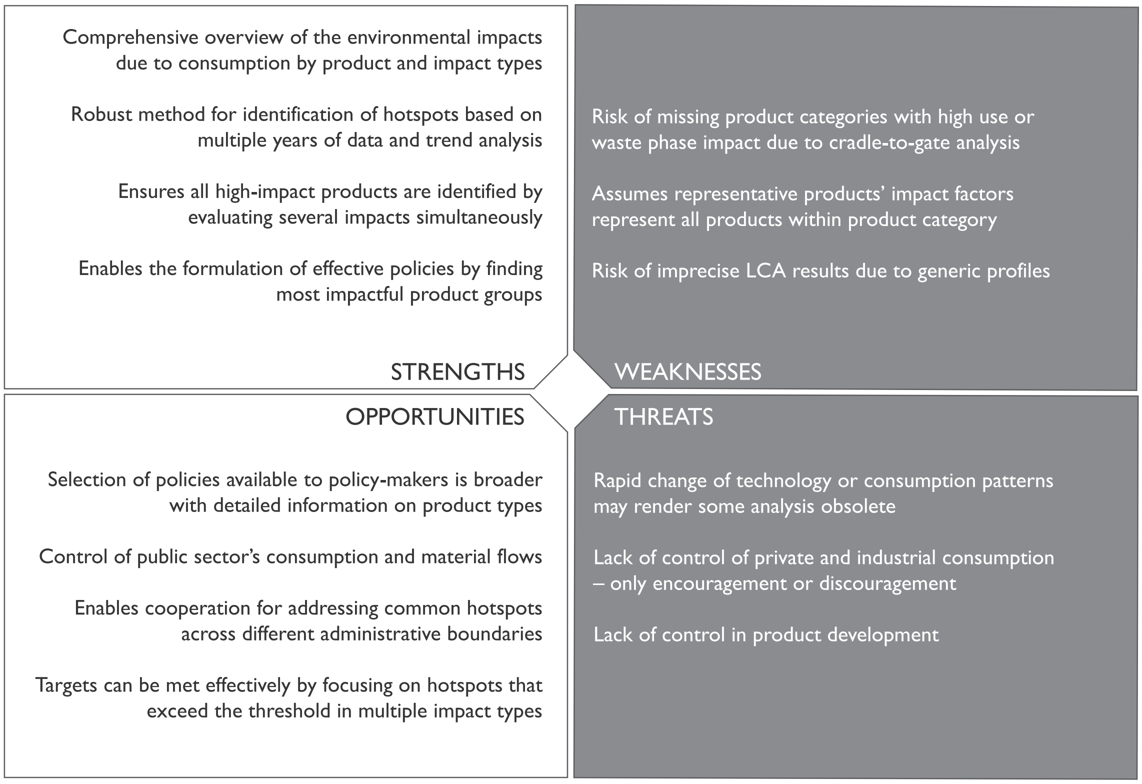

Fig. 8. Summary of the strengths, weaknesses, opportunities and threats of the method.

were quantified and compared to environmental impact goals.

In the case study described in this paper, we present results using a threshold of 10% of the total impact. The purpose of the threshold is to identify several priority product groups for which decision makers may try to influence consumption and to ensure that several impact categories can be addressed simultaneously. However, the use of a certain percentage threshold to identify hotspots may affect results. A more stringent (i.e., higher) percentage will reduce the number of hotspots found, and a lower threshold may identify too many to allow for prioritization. In the case study, adjusting the hotspot threshold affects the number of hotspots as presented in Table 3. Full details on the impact of the hotspot thresholds can be found in Appendix D. Users of the method may need to test several thresholds to find the optimal number of hotspots for the region.

As seen in Table 3, the number of hotspots identified does not change much for the regions with consistent consumption trends (Stockholm, Gothenburg, and Sweden). Of the three criteria, requiring that a product group exceed the threshold in two or more impact groups reduces the number of hotspots more than the trend test does for Stockholm, Gothenburg, and Sweden. For Malmo, however, the trend test significantly alters the number of hotspots. This indicates that for regions in transition (as described in Section 3.1.1), trends may affect hotspots and it may be more important for these types of cities to have several years of consumption data than it is for more established systems where consumption patterns have stabilized.

4. Conclusions

Due to growing populations and increasing consumption of products and thereby resources, there is a rising need for municipalities and countries to address the environmental impact of consumption. However, the tools currently available to practitioners to identify priority product types for reduced consumption are often based on one year of national data and only address one impact category, climate change. The purpose of this study was to develop a method for identifying environmental impact hotspots of urban consumption that uses an extended time span of regional data and assesses multiple impact categories simultaneously. The results could then be used to identify priority product categories and determine whether region-specific or national programs for reduction were more relevant for the product category in question.

By using product-level, region-specific consumption data together with representative products and life cycle profiles, priority product types, or hotspots, were identified. Hotspots, defined here as product types that consistently exceeded 10% of the total impact in two or more impact categories, were identified for Sweden and the three major metropolitan areas in Sweden: Stockholm, Gothenburg, and Malmo. Electronics is a hotspot for all the studied areas and all the studied impacts and should be a prioritized product group for action. Transportation is another important area for action as fuel is a hotspot shared by all the areas while vehicles is a hotspot in Gothenburg and a future hotspot in the other cities. Meat is a nation-wide hotspot, but not for the largest cities. Gothenburg and Stockholm could collaborate to find effective measures for their common hotspots. The results indicate that "one size does not fit all" — but perhaps, fits many — and that there should be both national and regional approaches to reduce consumption and its subsequent impacts.

In summary, the method presented in this paper advances current hotspot identification methods by a multifaceted, step-by-step approach that includes multiple impact types and enables regions to be compared. Policymakers can also benefit from this method, which provides guidance as to where to focus consumption reduction efforts and allows for benchmarking for future measures and policies.

In the future, a sector analysis of high impact products to determine the relative amounts of public versus private consumption will enable improved targeting for consumption reduction. It may also be useful to evaluate at which stage of the life cycle intervention would achieve the highest impact reduction. In addition, consumption data can be reviewed to see if the reduction measure had the intended effect, i.e., lower levels of consumption. For example, one can look at consumption data sometime after a policy or measure has gone into effect and compare it to previous years' data. Combining MFA and LCA can, therefore, aid decision makers in both designing and following up policy choices.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.04.036.

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