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Published in:
Ecological Economics

DOI (link to publication from Publisher):
10.1016/j.ecolecon.2020.106778

Publication date:
2020

Document Version
Publisher's PDF, also known as Version of record

Ecological Economics 177 (2020) 106778

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

Tracking the carbon emissions of Denmark's five regions from a producer and consumer perspective

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ARTICLE INFO

Keywords:
LINE
Multi-Regional Input-Output Model
Production-Based Emissions
Consumption-Based Emissions
Local Climate Policy

ABSTRACT

This paper presents a calculation of Denmark's production and consumption-based accounting CO_2e emissions for five regions in 2011. We apply an environmentally extended economic model for Danish municipalities known as the Local "INterregional" Economic (LINE) model, together with a multi-regional input-output model for the world economy (EXIOBASE v3.4). We find that Denmark's Capital region accounts for 41% (28 MtCO_2e) and 31% (27 MtCO_2e) of Denmark's production and consumption-based emissions respectively. By disaggregating regional emissions into industry and product categories, we provide relevant information to producers and consumers in each region concerning areas where the most significant differences towards reducing their carbon footprint can be realised. Mobility, services, food and shelter were the main drivers of emissions in all Danish regions. The Central, North and South Denmark accounted for more than half (9.56 MtCO_2e) of Denmark's food production emissions. The Capital region was the largest source of emissions (3.79 MtCO_2e) related to food consumption. We suggest that dietary changes towards less red meat and dairy products can potentially reduce regional food-related emissions of Danish households. Our results indicate that modest changes in consumer lifestyles are pivotal for local climate mitigation policies, especially in Denmark's biggest cities, Copenhagen, Århus, Aalborg and Odense.

1. Introduction

Today many subnational regions worldwide, particularly cities are at the centre of the damning global consequences of climate change (Chavez and Sperling, 2017; UN, 2014). And, local authorities have been encouraged to participate in the transition towards accelerating climate mitigation and adaptation (European Commission, 2011; IPCC, 2019). Subnational regions are crucial in the fight against climate change; the top 100 highest-footprint cities drive around 20% of global greenhouse gases (GHG) and pressures on existing infrastructure (Lin et al., 2015; Moran et al., 2018). Therefore it is appropriate that local governments and institutions monitor and quantify emissions to inform local climate policy measures and actions rightly (Lombardi et al., 2017; Rauland and Newman, 2015).

A host of studies have revealed that regional differences within a country influence the distribution of environmental impacts and its burdens (Faturay et al., 2020; Ivanova et al., 2017). For instance, regions in countries noted for intensive primary production activities such as agriculture and mining are often not the primary consumers of the corresponding final products (Lenzen and Peters, 2010). Denmark's economic structure varies from one Danish region to another (Danish Regions, 2012; Henriksen et al., 2015). About 88% of Danes live in urban areas, and rural-urban migration is on the rise in Denmark (Andersen, 2011; Denmark Statistics, 2020a). Urban areas in Denmark account for 70% of the national energy demand and 40% of its energy-related carbon dioxide (CO_2) emissions (Danish Energy Agency, 2018; The City of Copenhagen, 2015).

Production-based accounting (PBA) allows countries to take responsibility for carbon emissions within their territorial boundaries; it includes the territorial emissions associated with production for local consumption and exports. A growing number of studies have argued that the PBA incentivises carbon leakage through the import of cheaper pollution-intensive goods from abroad (Jakob et al., 2013; Kanemoto et al., 2012). Consumption-based carbon accounting, also known as

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https://doi.org/10.1016/j.ecolecon.2020.106778
Received 19 November 2019; Received in revised form 28 June 2020; Accepted 29 June 2020
Available online 15 July 2020

carbon footprinting, is considered as a fitting complement to production-based measures for climate policy (Peters et al., 2012; Peters and Hertwich, 2008). It allows for tracking of the global environmental impacts related to local consumption irrespective of where production occurred (Jakob et al., 2014; Wood et al., 2018). CBA assigns the responsibility for emissions to the region where final consumption occurred. It accounts for the territorial emissions associated with the consumption of locally produced and imported goods and services. Therefore, the difference between PBA and CBA emissions is the emissions embodied in trade.

Many authors have systematically quantified and compared the production- and consumption-based accounting environmental impacts at sub-national levels using environmentally extended input-output (EE-IO) models, life cycle assessment (LCA) or hybrid methods (Crawford et al., 2018; Dias et al., 2018; Wakiyama et al., 2020). Some authors have addressed the relevance of monitoring and managing the carbon footprint (CF) and fluxes of emissions embodied in trade for cities or country-regions (Chen et al., 2016; Wiedmann et al., 2010). Using an EE-IO modelling and consumption-based accounting, Larsen and Hertwich (2010) quantified the CF of 429 Norwegian municipalities, including the CF of the services rendered by Trondheim municipality (Larsen and Hertwich, 2009). Lenzen and Peters (2010) and Chen et al. (2017) used a detailed spatial multi-regional input-output (MRIO) models to calculate the CF of two of Australia's biggest cities, Sydney and Melbourne, as well as the fluxes of emissions to and from other cities. Several Industrial Ecology Lab (IElab) studies have assessed the environmental footprints of household consumption of US, Australian and Asian cities or counties using MRIO models (Chen et al., 2016; Wakiyama et al., 2020; Yu et al., 2017). A variety of authors have applied the community-wide infrastructure footprint (CIF) to assess the CF of cities and counties all over the world (Chavez and Ramaswami, 2013; Lin et al., 2015).

Previous regional climate studies of Denmark show that efforts to reduce territorial emissions are challenged by outsourcing emissions from abroad to Danish regions (Boyd et al., 2018; Ghosh et al., 2009). While the IO literature is replete with studies of Denmark's national carbon footprint (CF), there are a few CF studies for Danish cities or municipalities and regions. This is explained by the lack of consistent and harmonised methods and the availability of limited regional data for monitoring the emissions of Danish regions (Schmidt and Muños, 2014; Weidema et al., 2006). In the absence of reliable information on subnational GHG emissions and emissions embodied in trade, the implementation of effective climate policies by local authorities is constrained. For instance, Realdania (2018) assessed more than 100 Danish municipal climate initiatives. They concluded that the majority of the policies were biased towards city administration and waste management, energy efficiency and cleaner transport with little or no attention to local food systems. However, local food systems merit further investigation and policy attention given that (1) agricultural emissions make up a quarter of Denmark's national GHG emissions (Nielsen et al., 2019), (2) Denmark uses 62% of its land area for intensive feed crop production and livestock breeding (Danish Agriculture and Food Council, 2014), and (3) Denmark's per capita meat consumption is twice the size of the global average and exceeds the Food and Agriculture Organization's (FAO) global dietary intake recommendations (FAO, 2020a).

The aim of this paper is twofold. Firstly, it calculates and compares the production-based accounting (PBA) and consumption-based accounting (CBA) emissions of Denmark's five regions. Secondly, it quantifies the production- and consumption-based emissions of different food products for all Danish regions and discusses opportunities for emission reductions. To the best of our knowledge, this study attempts to advance earlier CF studies on Danish regions by Boyd et al. (2018) and Ivanova et al. (2017) by estimating the household CF of Danish municipalities (and regions) based on reliable household consumption expenditure and municipality-specific direct household

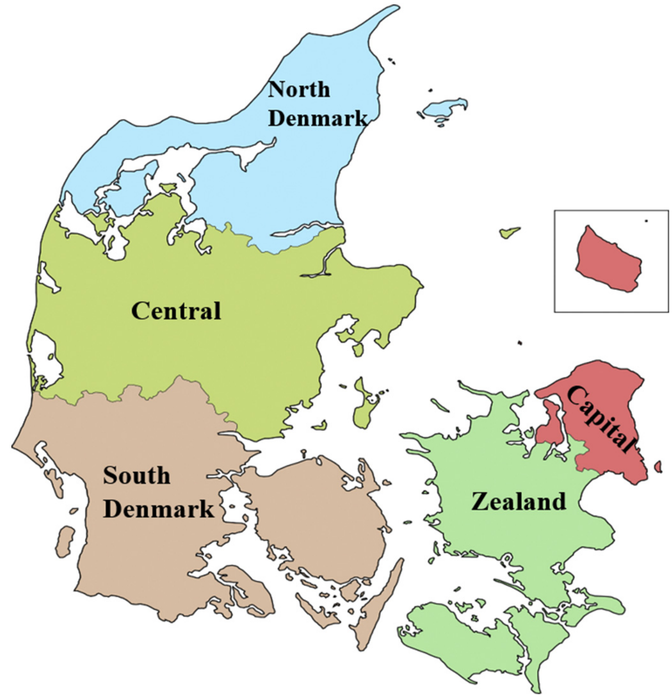

Fig. 1. The five regions of Denmark under the NUTS-2 level.

emissions data (Denmark Statistics, 2017; Olsen and Rærmose, 2010). Also, we perform the analysis of the study for a more recent reference year (2011) than earlier studies.

To achieve the objectives of the study, we combine the municipal IO tables (IOT) from the LINE model (Local "INterregional Economic" (LINE) model by Madsen (2005), (see description in section 2.1) and air emissions extensions from EXIOBASE database for the year 2011 (Stadler et al., 2018). EXIOBASE database allows us to perform CBA/CF emissions calculations for 200 products while accounting for the differences in global production technologies and emission intensities related to Danish imports.

2. Method and materials

Denmark is divided into five administrative regions made up of 98 municipalities; the Capital, Zealand, Central, North Denmark and South Denmark (see Fig. 1 & SI, Table S1 p.2). Two distinct models are applied in this study to calculate the production-based and consumption-based accounting emissions (CF) of the five regions. The first is an interregional economic input-output database for Danish municipalities known as the Local 'INterregional' Economic (LINE) model to calculate the regional production-based accounting emissions. Also, we deploy the EXIOBASE database to estimate the consumption-based emissions for all Danish municipalities (regions). Although we calculate the PBA emissions for all municipalities, the results are reported at only regional level under the Nomenclature of territorial units for statistics (NUTS) classification level 2. It is because highly sensitive municipal economic data can be deduced from the production-based emissions results by a backward calculation.

2.1. The Local INterregional economic (LINE) model

The Local Interregional Economic (LINE) model (Madsen, 2005) is an interregional input-output model for Danish municipalities constructed from trade-, use-, and make matrices based on the industry technology assumption. LINE is a spatially extended version of the conventional input-output model based on a two-by-two-by-two principle in a Social Accounting Matrix (SAM) framework (Fig. 2). Unlike

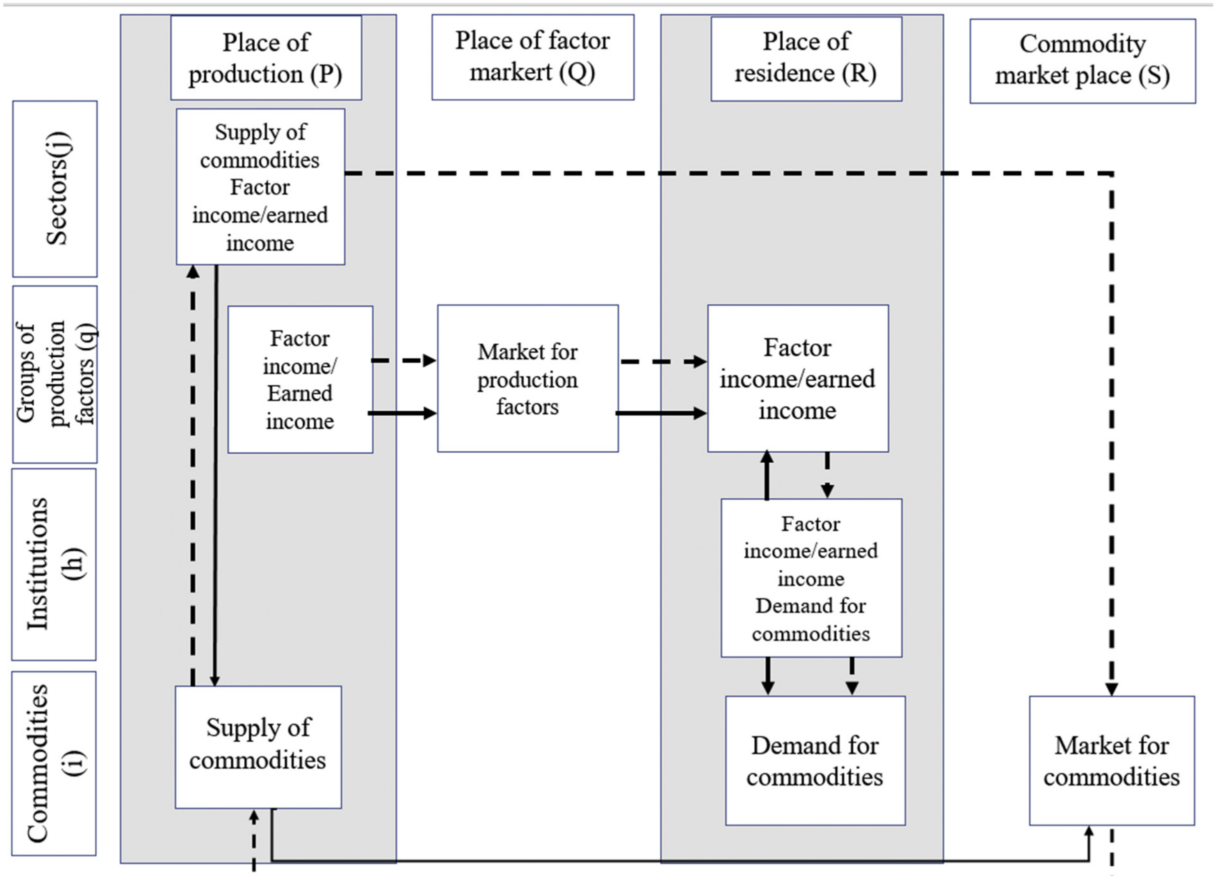

Fig. 2. The real circle of the Local INterregional Economic (LINE) model for Danish municipalities. LINE incorporates a highly disaggregated Social Accounting Matrix (SAM) and the traditional IO Leontief approach. The dashed arrows represent monetary flows in current prices while the thick arrows represent those in constant prices. The vertical axis shows the place of production (P), place of factor market (Q), place of residence (R) and place of commodity market (S). Starting in the upper left-hand corner (Pj), production generates intermediate consumption and employment by industries (j) at the place of production (P). From the place of production (P) to place of residence (R) through a commuting model, employment by industries (j) is differentiated by age, gender and education level groups (g). Labour force at the place of residence (R) depends on population and labour force participation rates by age, gender and education. Labour force and employment determine unemployment by age, gender and education at the place of residence (R).

many sub-regional local economic models, LINE provides detailed spatial interactions between Danish industries, markets and households such as commuting, shopping and tourism (Madsen and Jensen-Butler, 2007). The two-by-two-by-two principle describes two economic agents (producers or industries and consumers or households), two markets (factor market and commodity market) and two interactions between economic agents and markets (trade and commuting) in a local economy. Four geographic concepts are covered by the LINE model, namely the place of production (P), place of residence (R), place of factor market (Q) and place of the commodity market (S) (Fig. 2). The links between the markets and economic agents capture the flow of commodities from an origin to a destination (from sector (Pj) to the commodity market (Si) and from residence to sector or commodity market (Ri or Rj). As a Leontief quantity model based on the Keynesian-income multiplier theory, LINE imitates a cyclical clockwise pattern in the real world (Fig. 2). The model asserts that both production and intermediate consumption of goods and services in the commodity market by households and industries is induced by demand for commodities (Fig.S3). LINE does not differentiate the production technologies of internationally traded intermediate and final products by producing industries and countries, unlike other MRIOs (Wiedmann, 2009).

The single region input-output tables (SRIOT) of the LINE, like the Danish national input-output table, have 117 sectors with all agricultural activities aggregated into one single industry. In this study, we disaggregate the agriculture industry into sub-sectors of the agri-food industry that represent specific crop and livestock industries in each municipality. We apply a non-survey economic allocation method (Madsen and Jensen-Butler, 2007; Saltzman et al., 2018) to disaggregate the agriculture industry by using the employment shares for each agri-food subsector in each Danish municipality from Denmark Statistics (Denmark Statistics, 2020b). Consequently, we obtain a 40 sector interregional input-output table due to computing power and storage limitations (see SI, section 3, and p.10–11). Following studies by Madsen and Jensen-Butler (Madsen and Jensen-Butler, 2004) and Madsen (Madsen, 2005), we establish an interregional quantity model of industry-by-industry IOT as follows;

$$X_j^r = DTS_{IC}Bb\bullet X_j^r + DTf \quad (1)$$

where X_j^r is the gross output by sector (j) and place of production/region (r); D is the make matrix of a particular Danish region, T is the intra-and inter-regional trade matrix representing sales of commodities from the place of production at the place of commodity market; S_{IC} is the shopping matrix for intermediate consumption as share of total intermediate consumption by commodity and by place of production; B is the use matrix that shows the intermediate consumption by commodity as a share of total intermediate consumption by commodity and place of production (region/municipality); b is the intermediate consumption as share of gross output by sector and place of production; f is the final demand by commodity and the place of commodity market.

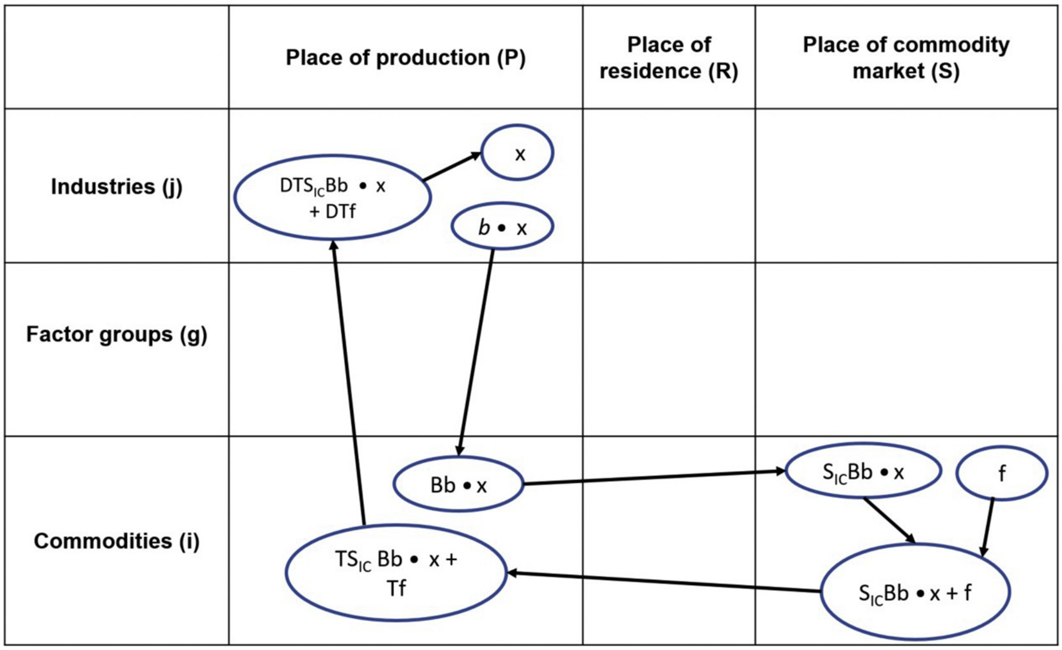

Fig. 3. The conceptualisation of the LINE model in an input-output framework. Further explanation of the LINE model is provided in the SI, sections 2.0–2.1 & 2.3.

By applying the Leontief approach (Leontief, 1970), the output for each industry in each region is:

$$X_j^r = (I - DTS_{IC}Bb)^{-1}DTf = (I - A)^{-1}DTf = LDTf \quad (2)$$

where "I" is an identity matrix; $DTS_{IC}Bb = A$ is the direct input requirement coefficient matrix that represents intermediate consumption by sector; L is the Leontief inverse of the industry-by-industry type, $L = (I - A)^{-1}$. The final demand by commodity and by the place of the commodity market, f, is expressed by the place of production (Tf) when multiplied by intra-and interregional trade data (T). By multiplying the make matrix (D) with the production by commodity, we obtain the production by sector (DTf). LINE is run for a number of iterations to derive the equilibrium output for all municipalities by industries (see Fig. 3 & SI, section 2.4 p.8–9).

2.1.1. Production-based accounting emissions

The LINE model has no environmental extensions. Therefore to calculate the production-based GHG emissions for each Danish region, we extend the LINE with the industry-by-industry EXIOBASE database's air emissions accounts for Denmark. EXIOBASE is an EE-MRIO describing inter-industry and product monetary transactions of 44 countries and five rest-of-the-world regions for 200-products and 163-industries (Stadler et al., 2018). EXIOBASE consists of over 700 environmental stressors assigned to industries and products for all 49 regions (see SI, section 4.2 p.12–13 for further details for EXIOBASE). We extract Denmark's environmental satellite account for three greenhouse gases; carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_20), and CO_2e for 163 industries for the latest year available, 2011. We apply a concordance matrix to consistently aggregate the emissions for 163 industries in EXIOBASE to match the 40 sectors of LINE's SRIOT (see SI, section 5 p.13). We obtain (F_i^{DK}), a 4-by-40 matrix with each row sum representing the total amount of each pollutant 'i' generated by all industries in Denmark. Each column of F_i^{DK} represents the amounts of each pollutant generated by each industry in Denmark. The PBA CO_2e emissions for region r, F_r^{pba} is calculated as follows:

$$F_r^{pba} = \sum_{j=1}^{40} s_j^{DK} X_j^r \quad (3)$$

where s_j^{DK} is a 1-by-40 vector of the carbon intensity of industry 'j' in Denmark, calculated as the ratio of total direct CO_2e emissions of industry 'j' to the total economic output of industry 'j' in Denmark; X_j^r is the output of industry 'j' required to satisfy a given final demand of industry 'j' in the Danish region 'r' as calculated in Eq. (2).

2.1.2. Consumption-based accounting emissions

We calculate the CBA emissions (CF) for each Danish municipality using the product-by-product EXIOBASE database. Applying EXIOBASE for CBA of regional emissions allows us to account for region-specific production technologies and emission intensities of all Danish imports. Unlike the LINE model, EXIOBASE database does not provide subnational IOT but trade-linked national IOT. Therefore, we assume that all Danish regions have a production technology similar to Denmark's.

The CBA method allows us to distinguish between emissions associated with the consumption of locally produced and imported products for each Danish region. We calculate the CF for all Danish municipalities using the global production technology matrix, region-specific emissions and Denmark's final demand vector in EXIOBASE. The only change we make to EXIOBASE is to disaggregate Denmark's household final demand into 98 distinct final demand vectors representing all Danish municipalities. We do this by building and constructing a consumption expenditure concordance matrix for Danish municipalities (see SI, section 6 p.13–14 for detail description of the method). Consumption expenditure shares represent consumer lifestyle for 46 consumption categories accessed from Denmark's Household Budget Survey database. Due to the unavailability of official emissions data for all products for each Danish municipalities, we assume that Denmark's national carbon intensities for all products in EXIOBASE is the same for each Danish municipality. We calculate the household CBA emissions (or CF) for each Danish region as follows:

$$F_r^{cba} = \sum_{i=1}^{n} (s(I - A)^{-1}y_m + f_m^{hh}) \quad (4)$$

where F_r^{cba} is a 1-by-5 vector of the CF of region r; n represents the number of municipalities in region r; s is a 1-by-9800 vector contains the direct carbon intensities for 200 products for 49 regions, including Denmark in EXIOBASE. Each element of s represents the total CO_2e emissions generated per unit of output for each product for all regions. A is the global direct input coefficient matrix (9800-by-9800); A and s are obtained as $s = f\hat{x}^{-1}$ and $A = Z\hat{x}^{-1}$, where, f, x, and Z are the matrix of the vector of direct carbon emissions for products, the vector of the total output of products, and the inter-product transactions matrix respectively; '^' represents the diagonal matrix of the vector; y_m is the household product final demand vector (9800-by-1) for Danish municipality 'm'. The final demand vector of each Danish municipality is a combination of consumption expenditures for locally produced products and imported products; f_m^{hh} is the direct household emissions of Danish municipality 'm' obtained from Region Syddanmark (http://www.data2go.dk/tal-data/) – see SI. Table S13 p.19.

We calculate the consumption-based emissions by products for each Danish region, F'^{cba}_r as follows:

$$F'^{cba}_r = \sum_{r=1}^{5} s(I - A)^{-1}\widehat{y_m} \tag{5}$$

The results obtained from Eq. (5) represents the life-cycle or indirect (upstream) carbon emissions associated with household consumption in each Danish municipality (and region) by origin (region in question, other Danish regions and the rest of the world). It also allows us to distinguish between the indirect carbon emissions associated with the consumption of locally produced products in each municipality (and region) in Denmark (the so-called indirect domestic carbon emissions) and indirect carbon emissions embodied in imported products (the so-called indirect foreign carbon emissions). For a detailed description of all variables used in the CF calculations, the reader is referred to SI, Table S6.

3. Results

3.1. The regional distribution of Denmark's PBA and CBA GHG emissions

Table 1 shows the total and per capita production-based emissions and CF for all Danish regions. Denmark's production-based emissions amounted to 69.52 Mt. CO_2e while its consumption-based emissions amounted to 87.67 Mt. CO_2e in 2011. On average, every Dane accounted for 12.48 tCO_2ecap^{-1} of emissions from production and 15.71 tCO_2ecap^{-1} emissions related to consumption. The Capital region accounted for 31% and 41% of Denmark's production-and consumption-based carbon emissions, respectively. Together, Central, South Denmark and North Denmark accounted for 52% (36.39 Mt. CO_2e) of Danish emissions from production. Zealand and North Denmark were the lowest contributors to Denmark's PBA emissions and CF, respectively. The per capita PBA emissions and CF was highest for North Denmark, 19.53 tCO_2ecap^{-1} and 17.21 tCO_2ecap^{-1} respectively. The Central region had the lowest per-capita CF of 15.20 tCO_2ecap^{-1}.

The consumption-based emissions exceeded the PBA emissions for all regions except for the Capital region and North Denmark. In other words, the Capital and North Denmark were net-exporters of emissions embodied in trade while the other three regions were net-importers of emissions embodied in trade (see SI, Table S14 & Fig.S5 p.19–20). The emissions embodied in exports to the rest of the world accounted for about 55% (18 Mt. CO_2e) and 16% (5.38 Mt. CO_2e) of the total PBA emissions of the Capital and North Denmark respectively. South Denmark was responsible for the highest amount of emissions embodied in exports to rest of the country (5.85 Mt. CO_2e or 25%) while Zealand recorded the least of 2.37 Mt. CO_2e (10%). About 21–23% of the total consumption-based emissions were embodied in imports across all Danish regions. The Capital and Central region accounted for about 31% (13.46 Mt. CO_2e) and 23% (9.69 Mt. CO_2e) respectively of Denmark's emissions embodied in imports from the rest of the world. On the other hand, the emissions embodied in imports from the rest of the country were highest in South Denmark (5.26 Mt. CO_2e) and lowest in North Denmark (2.30 Mt. CO_2e). We provide further details on the emissions embodied in trade for all regions in the supplementary information (see Table S9-S10 p.16–17).

The CF of all Danish municipalities ranged from 35 kt - 7.44 Mt. CO_2e (see Fig. 4). The top-10 highest CF municipalities accounted for 32% (27.88 Mt. CO_2e) of Denmark's CF while municipalities in the bottom-10 lowest CFs accounted for 3% (2.92 Mt. CO_2e) of Denmark's CF (see SI, Table S13 p.19–20). The four biggest municipalities in Denmark (Copenhagen, Århus, Aalborg and Odense) that formed 25% of Denmark's population accounted for 21% (18.21 Mt. CO_2e) of Denmark's CF. Copenhagen (København) municipality accounted for the highest share (8% or 7.44 Mt. CO_2e) of Denmark's CF. Læsø municipality had the lowest CF of 35.11 kt CO_2e in Denmark, followed by Fanø (54.65 kt CO_2e) and Samsø (59.65 kt CO_2e).

In contrast, the per capita CF of municipalities in Denmark ranged from 13 to 24 tCO_2ecap^{-1} (see Fig. 4B). The largest spread of per capita CF was between municipalities in the Capital region (see SI, Table S18 p.24). Albertslund municipality had the lowest per capita CF of 13.08 tCO_2ecap^{-1} while Gentofte recorded the highest of 24.06 tCO_2ecap^{-1}. Although the Copenhagen municipality had the highest CF in absolute terms, we find that some sub-urban municipalities slightly outside Copenhagen municipality like Aalborg, Gentofte, and Hørsholm had relatively higher per capita CFs than Copenhagen municipality. This finding could be explained by the high population density of Copenhagen municipality relative to other top-10 highest CF municipalities in the Capital region (see SI, Fig. S7 p.22 & Fig.S10B p.29).

Fig. 4B Per capita consumption-based emissions/CF (tCO2ecap − 1) of Danish households all Danish municipalities, 2011.

3.2. Denmark's regional PBA and CBA GHG emissions by industry and consumption clusters

Fig. 5 shows a comparison of the production-based emissions and CF for eight industry and product groups across all Danish regions. From a production perspective, mobility and shelter accounted for more than half of Denmark's emissions from production, 33% (23.02 Mt. CO_2e) and 30% (20.87 Mt. CO_2e) respectively. Next to these two industries was the food industry contributing to 16% and 83% (11.17 Mt. CO_2e) of Denmark's total PBA and agricultural emissions respectively (see Table S13 & S14, p.20–21). Clothing, services and trade industries were the least contributors to Denmark's emissions from production. Together, these industries accounted for only 4% (2.68 Mt. CO_2e) of Denmark's PBA emissions. The Capital region accounted for the highest shares of

Table 1
Production and consumption-based accounting emissions for Denmark's five regions, 2011.

Region	PBA (Mt CO_2e)	PBA per capita[a] (tCO_2ecap^{-1})	CBA (Mt CO_2e)	CBA/CF per capita[b] (tCO_2ecap^{-1})	Population in 2011
Capital	28.26	16.45	27.19	16.11	1,713,624
Central	11.48	9.07	19.67	15.20	1,265,601
North Denmark	11.34	19.53	9.38	17.21	580,293
South Denmark	13.57	11.29	17.85	14.99	1,201,365
Zealand	4.98	6.08	13.59	16.70	818,321
Denmark	69.62	12.48	87.66	15.71	5,579,204

[a] PBA refers to the production-based accounting emissions.
[b] CBA refers to the consumption-based accounting emissions; "CF" refers to carbon footprint.

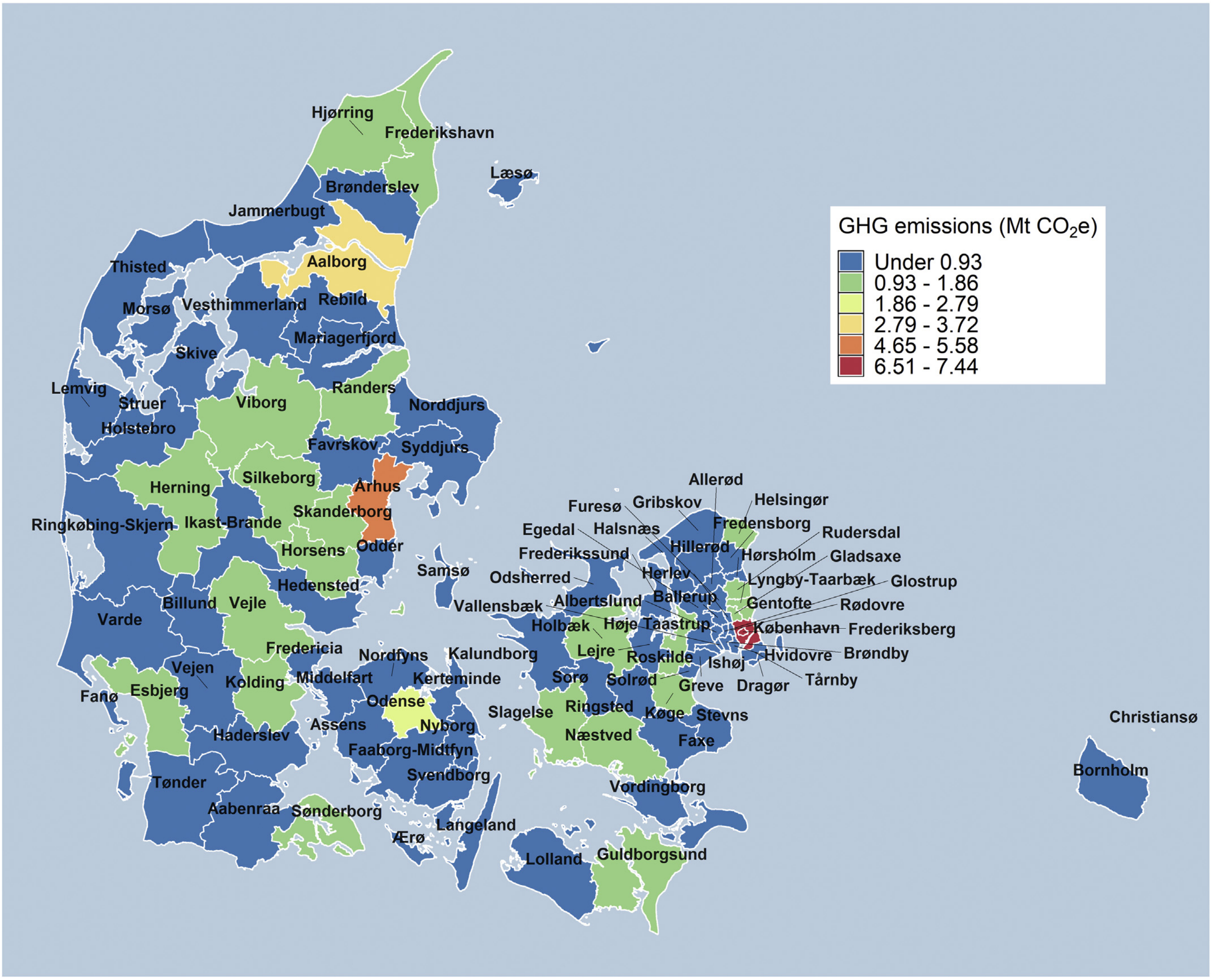

Fig. 4. A Total consumption-based emissions/CF (Mt CO_2e) of Danish households all Danish municipalities, 2011.

Denmark PBA emissions from mobility and shelter, 83% (19 Mt. CO_2e) and 25% (5.30 Mt. CO_2e), respectively. Together, North and South Denmark account for 67% (7.52 Mt. CO_2e) of Denmark's food production emissions. The Capital region was the least contributor to Denmark's emissions from production (3% or 337 kt CO_2e). PBA emissions related to manufacturing industries was highest in the Capital region (816 kt CO_2e) and lowest in North Denmark (241 kt CO_2e). Denmark's production-based emissions from construction were most significant in North Denmark (4.88 Mt. CO_2e or 68%) and the Capital region (1.01 Mt. CO_2e or 14%).

From a consumption perspective, services accounted for the largest share (37% or 29 Mt. CO_2e) of Denmark's CBA emissions/CF, followed by food (15% or 11.61 Mt. CO_2e) and manufactured products (14% or 11.28 Mt. CO_2e). The CF of clothing and trade together accounted for the lowest share (5% or 3.21 Mt. CO_2e) of Denmark's CF across regions. Together the Capital and Central region accounted for 55% of Denmark's CF associated with services. The Capital region accounted for 33% (3.79 Mt. CO_2e) and 30% (2.76 Mt. CO_2e) of Denmark's CF related to food and shelter, respectively. Besides the Capital region, the Central region and South Denmark together accounted for a significant share of Denmark CF with regards to shelter (43% or 3.91 Mt. CO_2e). North Denmark accounted for the lowest share (12% or 1.16 Mt. CO_2e) of Denmark's CF related to construction while the Capital region accounted for the highest (26% or 2.50 Mt. CO_2e). The CF related to mobility in Denmark amounted to 4.19 Mt. CO_2e - the Capital region accounted for the largest share of the total (47% or 1.98 Mt. CO_2e), followed by the Central region (20% or 841 kt CO_2e). The CF of manufactured products was highest in the Capital region (2.93 Mt. CO_2e or 26%), followed by the Central region (24% or 2.73 Mt. CO_2e) and South Denmark (21% or 2.35 Mt. CO_2e). North Denmark was responsible for the lowest share of Denmark's CF related to mobility and manufactured products (7% or 283 kt CO_2e and 12% or 1.32 Mt. CO_2e respectively).

3.3. *Food-related production and consumption-based carbon accounts*

Fig. 6 shows the results for the PBA and CBA emissions of food products for each Danish region; the PBA minus CBA emissions is the net exported emissions embodied in trade. Overall, Denmark was a net exporter of emissions embodied in food trade; its emissions embodied in food exports amounted to 5.74 Mt. CO_2e compared to 3.57 Mt. CO_2e for the emissions embodied in food imports (see SI, Fig. S8 p.27). Except for the Capital region, all other Danish regions were net-exporters of emissions embodied in food trade (see SI, Fig. S8 p.25).

Livestock breeding and cereals production contributed to 78% (8.75 Mt. CO_2e) and 15% (1.72 Mt. CO_2e) respectively of Denmark's food production emissions. In parallel, the Central, North and South

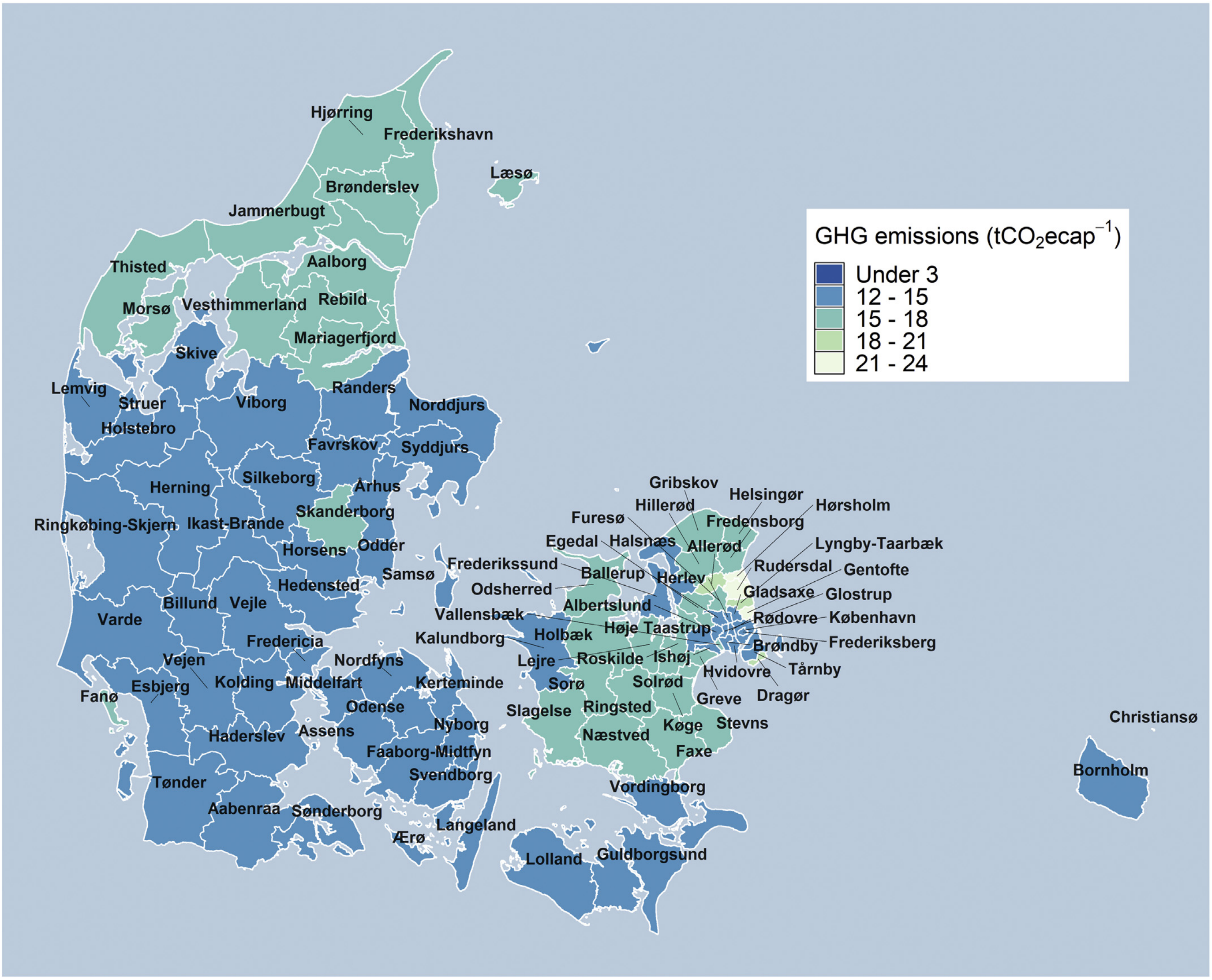

Fig. 4. (*continued*)

Denmark regions contributed 86% (9.56 Mt. CO_2e) of Denmark's food production emissions, mainly due to intensive livestock production (see Figs. S11–14, p.26–27). The Capital region and Zealand accounted for the lowest share of Denmark's food production emissions across all food products. Dairy products and pork accounted for more than half of food production emissions in all regions. Meat and dairy products accounted around 34% of total emissions from food production in both the Central region (3 Mt. CO_2e) and South Denmark (2.98 Mt. CO_2e) while the Capital region had the lowest share of 2% (192 kt CO_2e). Dairy products accounted for 53% (1.98 Mt. CO_2e) of food production emissions in the Central region compared to 40% (136 kt CO_2e) in the Capital region. Pork production accounted for 14–19% of the total emissions from food production. Poultry had the lowest-impact among all animal product. The emissions from cereal production made up 12–16% of food-related emissions. South Denmark was responsible for the highest emissions from cereal production in Denmark (591 kt CO_2e); the Capital region accounted for the lowest emissions from (40 kt CO_2e). The Central region and South Denmark accounted for 66% of Denmark's total production-based emissions related to processed food products, 393 kt CO_2e and 355 kt CO_2e respectively (see SI, Table S16 p.22–23). The total production-based emissions of rest of food, drinks and beverages were highest in South Denmark (229 kt CO_2e) and least in the Capital region (92 kt CO_2e).

From a consumption perspective, Copenhagen, Århus, Aalborg and Odense municipalities accounted for 22% (2.51 Mt. CO_2e) of Denmark's food-related emissions (see Fig. 7). Copenhagen municipality alone accounted for 9% (1.10 Mt. CO_2e) of Denmark's food-related CF. The bottom-10 lowest food-related CF municipalities accounted for only 3% (383 kt CO_2e) of Denmark's food-related CF. Læsø municipality recorded the lowest food-related CF in Denmark (4 kt CO_2e) while Vallensbæk municipality had the lowest food-related CF in the Capital region (235 kt CO_2e).

Generally, per capita, food-related CF was highest in the Capital region (2.20 tCO_2ecap^{-1}) and lowest in North Denmark (1.79 tCO_2ecap^{-1}) - see Fig. 7. Although the per capita food-related CF between municipalities in the Central region, North and South Denmark was quite uniform, the Capital region had a large spread of per capita food-related CF among its municipalities ranging from 1.83–3.36 tCO_2ecap^{-1}. Many of the high-ranking municipalities with regards to per capita food-related were in the Capital region. These municipalities included Gentofte (3.36 tCO_2ecap^{-1}), Hørsholm (3.19 tCO_2ecap^{-1}) and Lyngby-Taarbæk (2.67 tCO_2ecap^{-1}). Århus, Skanderbørg and Odder municipalities in Central region had a relatively higher per capita food-related CF of 2.12, 2.15 and 2.22 tCO_2ecap^{-1} respectively compared to Copenhagen municipality's 1.96 tCO_2ecap^{-1}. Albertslund and Ishøj (Capital region), Morsø and Vesthimmerland (North

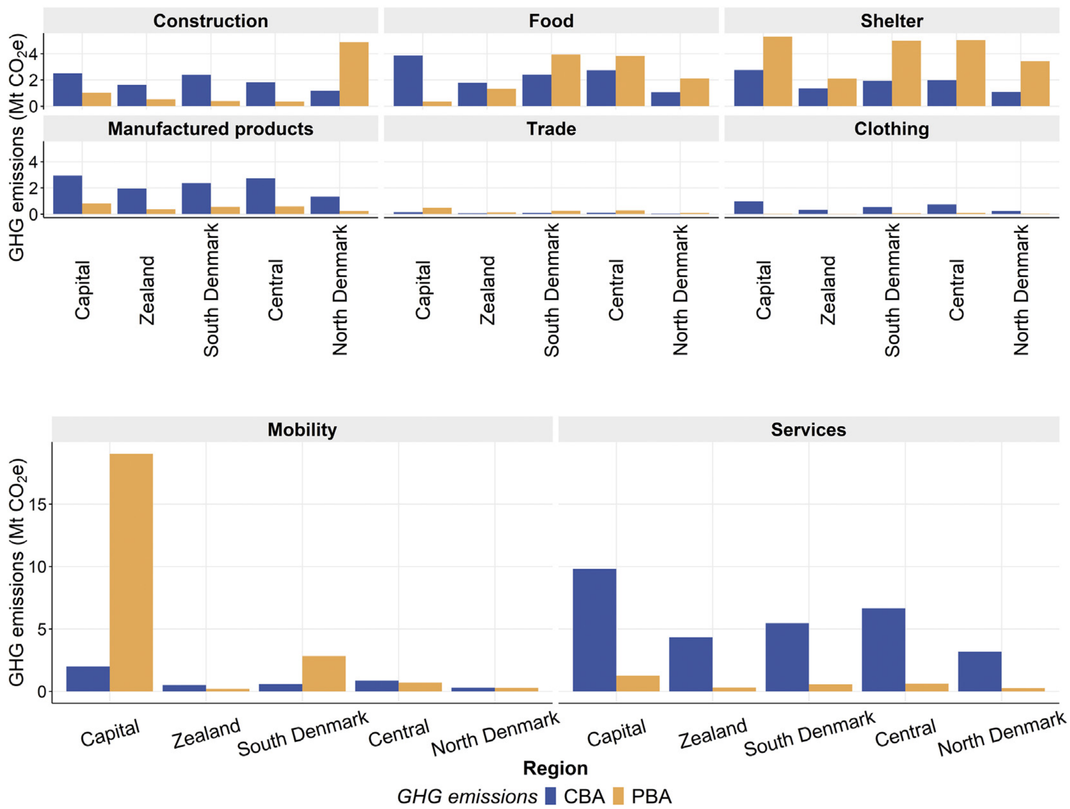

Fig. 5. The production-based and consumption-based accounting emissions (Mt CO_2e) aggregated into eight industry and product clusters respectively for the five Danish regions, 2011. CBA emissions exclude direct household emissions.

Denmark), and Tønder and Vejen (South Denmark) were among the bottom-10 lowest per capita food-related CF municipalities.

The share of CF for specific products in total CF of food is the same across regions because we assumed the same production technologies for all Danish regions. However, the absolute CF values vary between regions (see Fig. 6). Animal-based, plant-based and non-classified (highly processed) food products accounted for 45%, 17% and 38% respectively of the CF of food in all regions.

Fish products accounted for the single largest share (14%) of emissions from food consumption in all regions. However, together beef

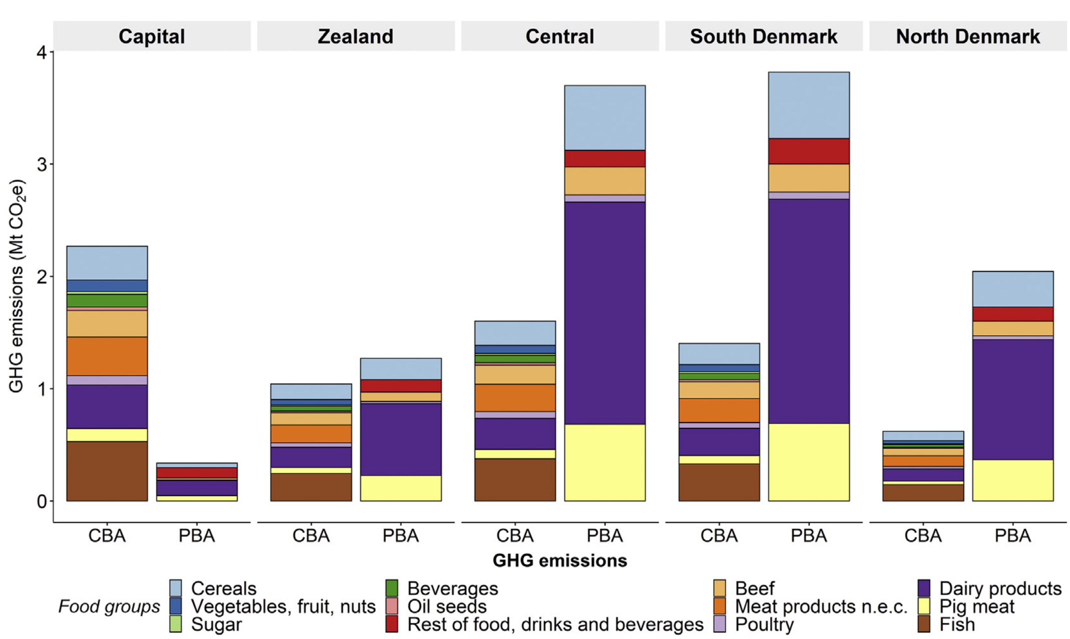

Fig. 6. The production and consumption-based accounting emissions (Mt CO_2e) of food products in all Danish regions, 2011. "PBA" refers to the production-based accounting emissions, while "CBA" refers to the consumption-based accounting emissions/carbon footprint and excludes the direct household emissions associated with food consumption. "n.e.c" refers to not elsewhere classified. The slight difference in products for the two GHG emissions inventories is because of the different classification schemes of the LINE and EXIOBASE models (see SI, Tables S16 & S17 for further details).

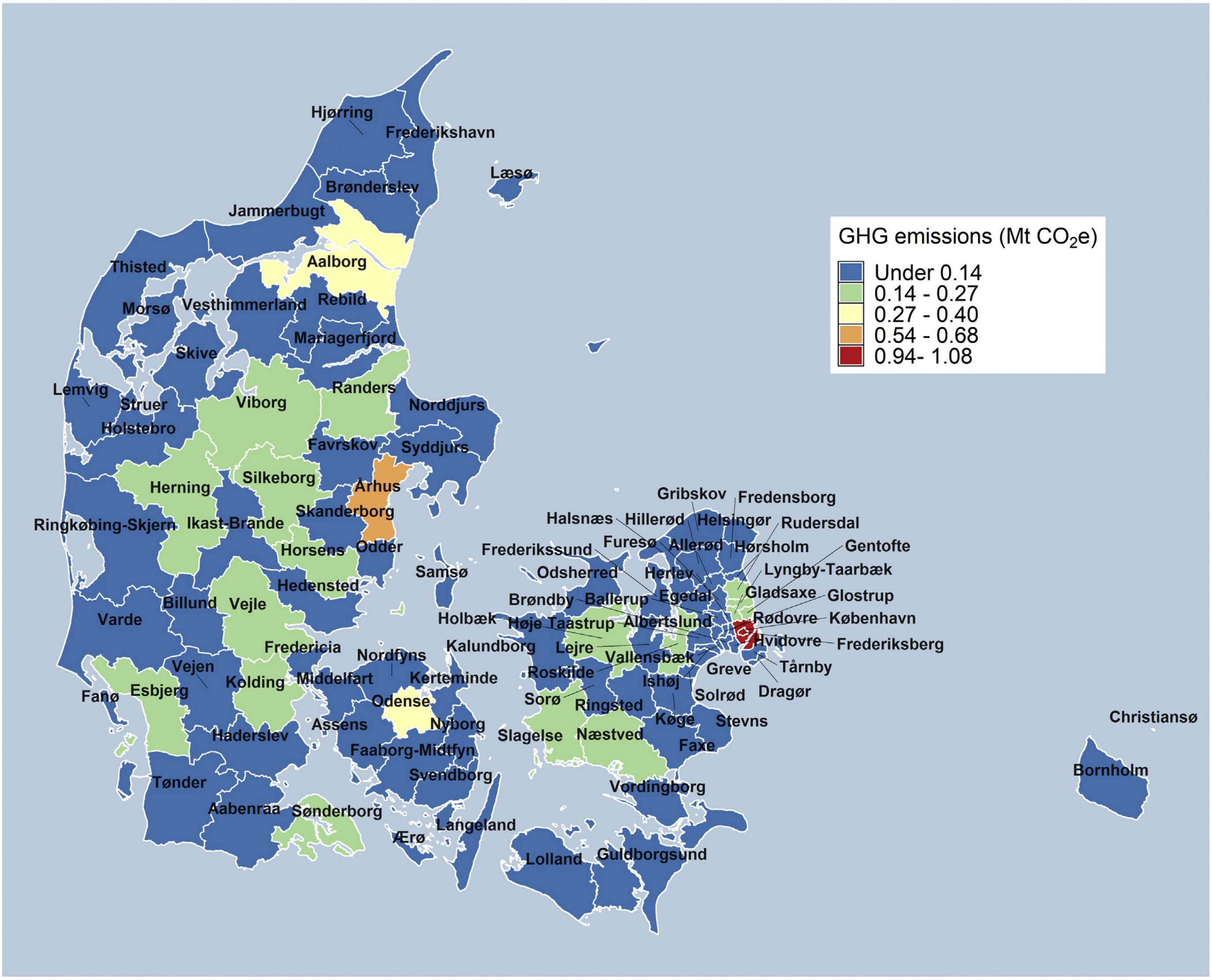

Fig. 7. A The total food-related consumption-based emissions/CF (Mt CO_2e) of Danish households all Danish municipalities, 2011.
Fig. 7B The food-related per capita CF (tCO2ecap − 1) of Danish households all Danish municipalities, 2011.

and dairy products accounted for 16% of the food-related CF in all regions. Also, the CF of all meat products, including non-classified meat products, accounted for 21% of the food-related CF in each region (see Fig. 6). Non-classified meat product refers to processed meat-derived products that are very energy-intensive to produce (e.g. kebab). The Capital and Central region accounted for 32% (529 kt CO_2e) and 23% (378 kt CO_2e) respectively, of the CF of fish products. Dairy products alone accounted for 10% of the total food-related CF for all Danish regions, followed by cereals (8%) and 'vegetables, fruits and nuts' (3%). Danish households consume more dairy products than beef; Denmark's per capita consumption of dairy products was 496 kg compared to 22 kg for beef in 2013 (Osei-Owusu et al., 2019). Moreover, Danish farmers breed cattle mainly for milk than bovine meat (Kristensen et al., 2015). This explains why dairy products form a larger share of Denmark's cattle-related CF with regards to cattle-derived products. Poultry and pork had relatively lower CF than all other animal-based products in all regions (2% of total food-related CF in all regions).

The CF of cereals was highest in the Central region and South Denmark partly because these two regions are the major hubs of livestock production in Denmark (see SI Fig.S11–14, p.29–31).Danish farmers use about 75% of Denmark's cereal production as fodder for livestock production (Danish Agriculture and Food Council, 2014). Among plant-based products, beverages were the third-highest source of Denmark's total food-related CF. Oilseeds and sugar were the lowest sources of Denmark's food-related CF in all regions, representing a share of 2% of the total. The CF of beef and dairy products was largest in the Capital region (626 kt CO_2e) and lowest in North Denmark's (173 kt CO_2e). The CF of 'vegetables, fruits and nuts' was lower compared to all animal products except for poultry in all regions. For example, in Central Denmark, the CF of 'vegetables, fruits and nuts' amounted to 73 kt CO_2e compared to 215 kt CO_2e for cereals and 447 kt CO_2e for beef and dairy products. Non-classified food products (or highly processed foods) constituted a significant share of each region's food-related CF with the Capital region and Central region contributing the highest amounts of 1.44 Mt. CO_2e and 1.02 Mt. CO_2e, respectively.

4. Discussion

4.1. Are big cities decisive for meeting national GHG emissions targets?

The results of this paper show that Denmark's national GHG emissions are allocated differently between and within Danish regions due to the differences in the demo-geographic characteristics and economic structures of each region (see Fig. 5). In this study, we find that the top

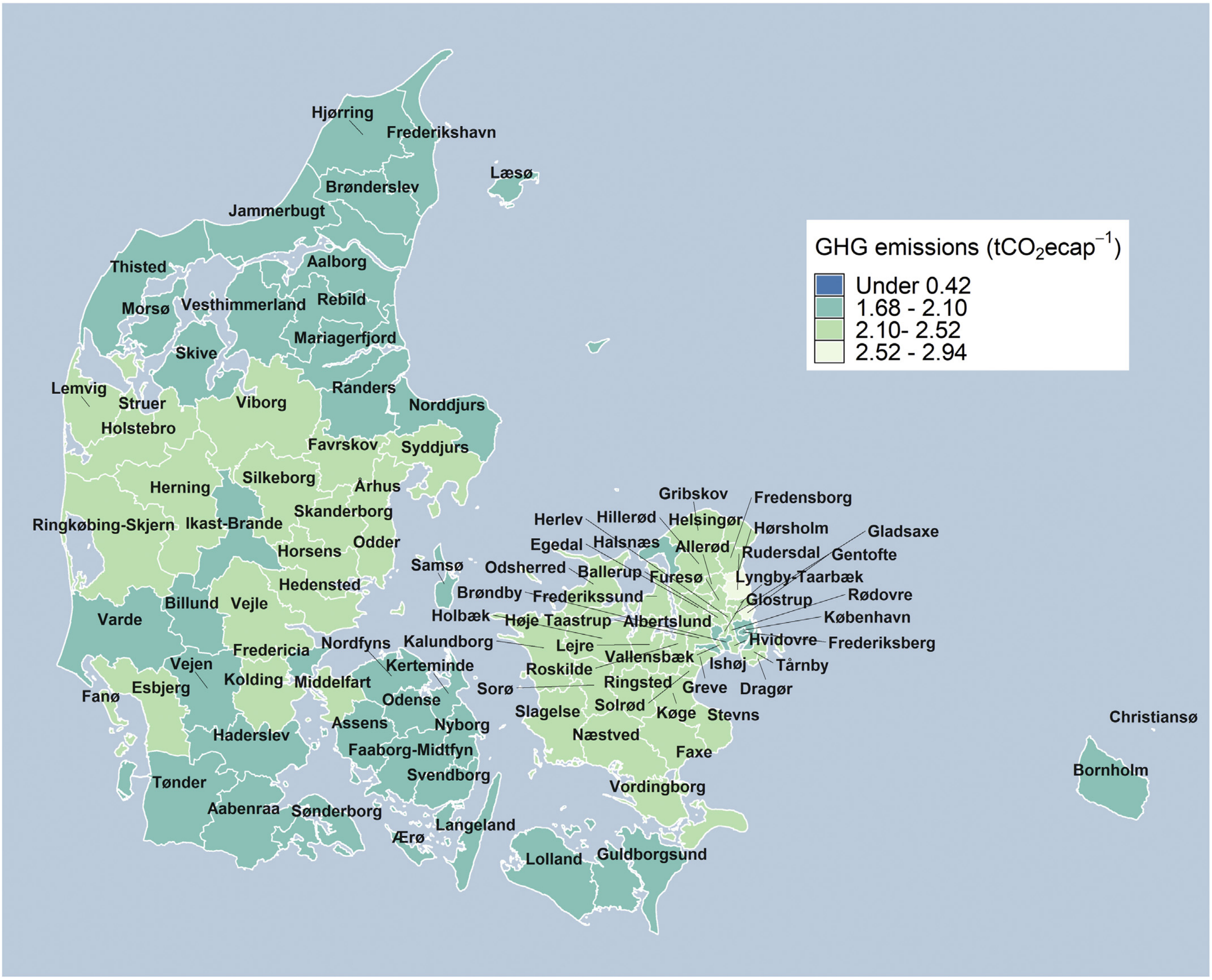

Fig. 7. (*continued*)

10 highest CF municipalities contributed to about 32% of Denmark's CF. The results of this study reveal that most of the densely populated Danish municipalities are among the top-10 highest CF (see SI, Table S13 p.19). Our findings are consistent with earlier studies that have identified big cities as global emission hotspots (Hoornweg et al., 2014; Moran et al., 2018). The population of Copenhagen municipality is growing and has increased by 8% since 2011 (see SI, Table S2). More than half of the Capital region's population live in Copenhagen municipality. Copenhagen municipality was the largest source of Denmark's CF (9% or 7.44 Mt. CO_2e). Besides Copenhagen municipality, we find that other densely populated municipalities such as Aarhus, Aalborg and Odense had significantly high CF (see SI, Fig. S10B p.29). We find that Denmark's urban municipalities have a relatively higher per capita CF than rural municipalities (see Fig. 4B & SI, Fig. S2). The relatively higher incomes in urban municipalities than in rural areas, also explains the differences in per capita CF (see SI, Fig.S7 p.22). Some studies argue that the emissions per unit of output are often higher in rural or suburban areas than urban areas or cities (Jones and Kammen, 2014; Minx et al., 2013). According to the C40 network, more than 40% of the required global GHG emissions reductions of the Paris Agreement can be driven by the world's major cities (C40 et al., 2019). The findings of this paper suggest that reaching Denmark's ambitious target of reducing GHG emissions by 70% by 2035 will require effective local climate change solutions, especially in Denmark's four biggest cities (Copenhagen, Århus, Aalborg and Odense).

4.2. Opportunities for reducing emissions for Danish regions

From a production perspective, the results of the study point to the importance of climate mitigation and adaptation initiatives, especially in the mobility, shelter and construction industries in all Danish regions. Generally, we find that these sectors, in addition to the food industry, comprise the top three sources of emissions from production for all regions.

Reducing emissions from mobility should remain a top priority in all regions, especially in the Capital region. The Capital region was responsible for 83% of Denmark's production-based emissions from mobility, mainly due to its high air travel, road and rail transportation compared to all other regions (The City of Copenhagen, 2015). Although the Copenhagen municipality has reduced CO_2 emissions from transport by 9% compared to 2010 levels, the share of the transport-related emissions in the region's total emissions increased from 24% in 2010 to 34% in 2015 (The City of Copenhagen, 2015). The significant reduction in travel time for cars together with improvements in road and renewable energy infrastructure in the Capital region, especially in the Copenhagen municipality has increased the use of electric public transport (The City of Copenhagen, 2015). The Danish government has recently passed a statute to assist with Denmark's transition to automobiles fuelled by renewable energy, encourage the use of public transportation, promote cycling and make air transport more sustainable by 2035 (Pujari, 2019). Local authorities in the Copenhagen municipality have remarkable progress by increasing the number of commuting cyclists in Copenhagen to 41% of its population (CPH, 2012).

With regards to shelter and construction, the improvement in the efficiency of buildings will be critical towards reducing emissions from district heating of buildings in Denmark especially in densely populated municipalities in the Capital region, Central and South Denmark (Becqué et al., 2015). The application of renewable sources of energy for heating and electrification of buildings can serve as a means of energy-saving and lower GHG emissions from buildings (Kammen and Sunter, 2016). The cement industry is responsible for about 8% of the world's CO_2 emissions (Huang et al., 2018) and about 2% of Denmark's CO_2 emissions. North Denmark's accounted for 68% of Denmark's production-based emissions from construction and is home of Aalborg Portland, Denmark's biggest cement producer and the world's largest exporter of white cement. Despite the even distribution of construction-related consumption-based emissions across regions, the Capital region accounted for the highest share (26%) of the CF of construction products. The Danish concrete industry plans to reduce CO_2 emissions of its supply chain by 2030 (Dansk Beton, 2019). About 60% of Aalborg Portland's CO_2 emissions from cement production is due to the combustion of limestone. The results of this study suggest that the innovation of sustainable alternatives to cement such as recyclable materials for building and construction or carbon capture and storage technologies could serve as a viable emission reduction strategy (Bains et al., 2017; Cui and Kær, 2019).

This study shows that together, services and food consumption accounted for half of the CF of all Danish regions. Similar to previous studies by Larsen and Hertwich (2011, 2009), we find that densely populated regions are associated with high carbon emissions from the delivery and consumption of services from financial, educational, health and hospitality institutions. We recommend concerted efforts by the local governments and private businesses to commit to reasonable emission cuts from energy use, transportation, and food consumption linked to the services industry.

On average more than half (55%) of the CF of all Danish regions was embodied in imports (see SI, Table S9 & S10, p.17–18). The Capital region and North Denmark, the main trading hubs and largest net exporters of emissions embodied in trade need carbon reduction plans centred on sustainable supply chain infrastructure and cleaner production of goods and services for local consumption and exports. As shown in this study, the Capital and Central regions recorded the highest emissions embodied in imports. Therefore, local authorities in these regions should their respective emission reductions strategies at promoting household and industrial consumption of cleaner products produced in Denmark and abroad such as renewable energy, eco-friendly foods and manufactured products and sustainable building and construction materials (see SI, Table S9 & 10 p.17–18).

4.3. *Sustainable farming and climate-friendly dietary changes for local climate mitigation*

The results of this study reveal that the food industry is the third-largest source of Denmark's production-based emissions with a share of 16% (11.17 Mt. CO_2e) (see SI, Table S7 p.16). The Central region, North and South Denmark accounted for about 87% of Denmark's emissions from food production (see Fig. 6). Supply-sided policies towards agricultural GHG emission reduction is appropriate for these regions. The Ellen MacArthur Foundation (2019) recommends local food self-sufficiency, circular and regenerative agricultural practices such as reduced chemical fertilisers and pesticides use on farms and urban farming as viable strategies for sustainable local food systems. Urban agriculture or increased subsistence agriculture in low food-producing regions like the Capital region may help reduce help the environmental load of food production in the rural or remote regions. Urban farming, such as hydroponics and gardens promote sustainable agricultural practices that reduce natural resource use and environmental impacts associated with the import of food products from longer distances abroad (Walters and Midden, 2018).

The findings of our study suggest that reducing emission from the production of livestock products should be a top priority of local authorities in the Central region and South Denmark. Livestock emissions constituted 18–34% of food production emissions of the agriculture-intensive Danish regions. Therefore concerted efforts to reduce emissions from feed production and enteric fermentation by ruminants is suitable for these regions that have a high concentration of crop and livestock farms (see SI, S11-S13 p.29–30).

The results of this study indicate that for Denmark to achieve its emissions reduction targets a reduction in the consumption of dairy and meat products could be a potentially viable policy option. A number of authors propose dietary changes from high impact food products like meat towards low impact plant-based foods like vegetables, fruits and cereals by consumers to lower global GHG emissions (Poore and Nemecek, 2018; Springmann et al., 2018). Such policy prescriptions are in line with our results as the CF of animal-based products was twice the size of plant-based products for all Danish regions (see SI, Table S15 p.21). In this study, we find that meat and dairy products are the largest sources of food-related emissions in all regions, while poultry was the lowest source of emissions from animal-based products. From the results of this study, 'vegetables, fruits and nuts' had a relatively lower CF compared to all animal products except for poultry (see Fig. 6). Modest reductions in the consumption of animal products and increase in the consumption of plant-based foods by Danish households could reduce Denmark's GHG emissions (Bruno et al., 2019). However, dietary change campaigns due to environmental concerns should consider its related health consequences.

Denmark is one of the world's major exporters of fish and fish products in the world (8th in Europe in 2019) but it imports as much fish products as it exports (European Commission, 2019). From the results of this paper, the emissions embodied in imported fish products to Denmark made up 59% of the CF of fish products in all regions (see SI, Table S9 & S10 p.17–18). The high share of fish products in Denmark's food-related CF can not be attributed to high consumption of fish products in Denmark. In contrast to other livestock products, Denmark's fish consumption (22 kg cap^{-1}) was just lower than the European average (23 kg cap^{-1}) and slightly higher than the global average (19 kg cap^{-1}) in 2013 (FAO, 2020b). However, Denmark is still among the top-10 EU nations with the highest per capita household expenditure on fish products (€ 101 in 2018), placing it behind notable countries like Portugal, Luxemburg, Spain and Italy (European Commission, 2019). In this study, the high CF of fish products can be linked to (1) the high energy-related carbon emissions along the supply chain (Thrane, 2006, 2004) – also see SI, Table S19 p.24. (2) High per capita household expenditure on fish products compared to all other food products (Eurostat, 2018). To reduce the CF of fish products, (Weidema et al., 2006) and Thrane (2006) suggest significant reductions in the high fuel consumption per kilo of fish caught in Denmark specifically through the improvement in fuel efficiency for primary fish production and changes in the fishing gears. Poore and Nemecek (2018) reveal that unsustainable fish farming is a high emitter of methane emissions that are discharged by fish excreta and unused feed at the base of ponds (see SI, Table S19 p.24). Our results for the CF of fish products reveal an interesting dimension for climate mitigation related to food products that the most recent study on Denmark's national food-related CF by Bruno et al. (2019) miss because the authors exclude fish products from their analysis.

Copenhagen municipality was accountable for 9% (1.08 Mt. CO_2e) of Denmark's food-related CF; twice the size of the second-highest municipality's food-related CF (Århus). Massive cuts in Denmark's food-related CF by households in the four biggest Danish municipalities are necessary because together these municipalities accounted for 22% (2.51 Mt. CO_2e) of Denmark's food-related CF. Local authorities in Danish municipalities could nudge its inhabitants towards the 'planet healthy diet' recommended by The EAT-Lancet Commission (Willett et al., 2019). Also, local initiatives such as providing a variety of climate-friendly diets in public canteens, restaurants and supermarkets at affordable prices as well as continuous public education on the health benefits of climate-friendly diets can accelerate transitions towards sustainable local food systems (C40, Arup, University of Leeds, 2019; Ranganathan et al., 2016). Lastly, reducing food loss along the food chain and food waste by households, together with the practice of circular economy principles in cities and municipalities will partly reduce emissions from food waste on landfills and treatment (Ellen MacArthur Foundation, 2019).

4.4. Comparison with other studies

The findings of this study affirms the results of similar studies of the U.K. by Baiocchi et al. (2010) and of the U.S. by Jones and Kammen (2014) that cited subnational regions as the new frontlines in the fight against climate change given their significant contribution to both local and global emissions. Similar to the study of Ivanova et al. (2017) on Europe's subnational CF, we find that an average Danish household is among the highest emitters in Europe on a per capita CF basis. The results of our study show that Denmark's five regions have a relatively higher per capita CF (see Table 1) compared to the EU average of 8.58 tCO_2 and 8.87 tCO_2 in 2011 and 2015, respectively (Friedlingstein et al., 2019). Comparing our results to those of Ivanova et al. (2017), we also find that Danish households have high per capita CF (like households in Finland, Ireland, and the U.K.) because they have relatively higher average incomes and consumption levels than most EU subnational regions. While prior studies have found very high absolute or per capita CF for the Capital region relative to other regions (Lin et al., 2015; Moran et al., 2018), it is not the same for Denmark as shown in this study (see Table 1). Using a regression approach, Ivanova et al. (2017) revealed that the low-income inequality between Danish regions in contrast to countries like the U.K and U.S. accounted for the small differences in the per capita CF across Danish regions.

4.5. Uncertainty and limitations of the study

Although we apply EXIOBASE database for the CF analysis, MRIO models have been associated with some data limitations and uncertainties extensively documented in the literature (Moran and Wood, 2014; Rodrigues et al., 2018). The primary sources of uncertainties centre around data collation, integration of data from different sources and assignment of environmental stressors to products or sectors (Peters et al., 2011; Wiebe and Yamano, 2016). Some authors have called attention to the errors with GHG emissions extensions of MRIO databases (Ballantyne et al., 2015; Liu et al., 2015). The differences in the emissions accounts of MRIO databases are partly due to differences in regional electricity use and fossil fuel use coefficients applied in emissions accounting, including the inclusion or exclusion specific emission inventories like soil and deforestation emissions. For instance, we find significant differences between Danish agricultural emissions reported by the Danish Centre For Environment and Energy (DCE) (Nielsen et al., 2019) and that of EXIOBASE. DCE accounts for additional agricultural emissions like soil carbon emissions and those associated with field burning not reported in EXIOBASE's emissions inventories.

Despite the availability of SRIOT for Danish municipalities, the complexities and differences in sector/product aggregation levels of the IOT of LINE and EXIOBASE precluded our adoption of an embedded subnational approach into an MRIO framework for the CF calculations. Therefore, we calculated the CF of Danish regions by assuming that all regions "mimic" the country's production technologies while in reality, the production technologies of each Danish region exhibit spatial heterogeneity. Although the disaggregation of the agri-food industry in LINE increased its resolution, it reduced the number of sectors in LINE from 117 to 40 due to computing power constraints. The level of industry/product details can affect the accuracy of CF calculations to a degree (Steen-Olsen et al., 2014). Lenzen (2011) argues that the disaggregation of IO data is often preferable to the aggregation of environmental extension data given the availability of reliable data. The industry and product resolution of the IOT in this study is apt for our analysis. Su and Ang (2010) argued that a 40-industry IOT was sufficient to evaluate the emissions embodied in Chinese's global trade. Extending LINE with emissions data of EXIOBASE may have been fraught with unavoidable uncertainties or errors due to the differences in the classification of industries for the two MRIO databases. We did not quantify the uncertainties associated with our disaggregation of the agriculture industry and integration of LINE and EXIOBASE data. Therefore, we suggest that future studies explore the influence of such procedures on CF calculation outcomes.

The confidentiality, limited availability and in some cases, the absence of relevant economic and environmental data at the sub-national level for Denmark precluded us from performing our analysis for the current year. Moreover, most MRIO models are not published annually, and the not too recent data used for this study is a present limitation of most IO studies (Rodrigues et al., 2018). Today Danish municipalities continue to make concerted efforts to track their territorial emissions using big data intelligence solutions (CPH, 2012; Realdania, 2018). We hope that future studies on this topic will focus on providing solutions to missing data challenges for Danish cities and municipalities. This will help researchers construct an MRIO database for Danish municipalities/regions that plausibly captures the interactions between subnational regions in Denmark and the global economy.

In the absence of household expenditure data for all products in EXIOBASE and for all Danish municipalities, we approximate the household expenditure data for Danish municipalities using consumption expenditure data from Denmark's Household Budget Survey (Denmark Statistics, 2017). Although we obtain reasonable CF for all Danish municipalities, our estimation of the final demand for all municipalities may have fraught with some uncalculated errors. Building the consumption expenditure concordance matrix, we assumed that all municipalities in the same Danish region have the same ratio of consumption expenditure to disposable income for all product categories due to lack of data at the municipal level (see SI section 6, p.13–15). Therefore we may have concealed within-group differences between municipalities in the same region with regards to their final demand. Also, bridging the gap between the 46 product clusters of Denmark's Household Budget Survey data and EXIOBASE's 200 products using a consumption expenditure concordance matrix could be a potential source of uncertainty (see SI section 6, p.13–15). We suggest that future research examine the uncertainties associated subnational carbon footprinting involving proxy final demand expenditures based on consumption expenditure concordance matrices from household survey data.

5. Conclusion

In this paper, we presented the results of a top-down environmental-economic analysis of the regional emissions of Denmark from a production and consumption perspective using the LINE model and EXIOBASE database. For both GHG emission accounting methods, we find that the Capital region of Denmark was the largest source of Denmark's national GHG emissions. Our study highlights the importance of fulfilling the already existing net-zero emissions climate plans of Denmark's top-4 highly-populated municipalities; Copenhagen, Aalborg, Odense and Århus. Besides these municipalities, the findings of the study indicate that local climate policies are equally important for other suburban municipalities like Gentofte and Hørsholm that have a relatively higher per capita CF than the national average. We also find that domestic and internationally traded GHG emissions constitute significant shares of the CF of all Danish regions, particularly the Capital region and Central region. High emissions from the consumption of services were characteristic of urban municipalities or big cities where the largest share of Denmark's population are employed in the healthcare, recreational, financial and educational sectors. Generally, urban municipalities had higher emissions embodied in food consumption than remote and rural municipalities where food production was often the most dominant economic activity. Moderate reductions in the consumption of animal-based products in all regions, particularly for meat and dairy products are important for local climate mitigation targets.

Given that this study covered Denmark's carbon flows in 2011, a scenario analysis with dynamic IO computable general equilibrium model could provide useful results on the potentials for reducing GHG emissions at present. Future studies should make use of reliable municipal GHG satellite data for industries, together with novel and integrated EE MRIO techniques like carbon maps and econometric models (Fry et al., 2018; Jiang et al., 2019; Lenzen et al., 2017). Lastly, a probe into the socio-economic and geo-demographic determinants of the CF of Danish regions in the future studies will be relevant for local climate policies centred on influencing consumer lifestyles for climate mitigation.

Authors' contribution

A.K.O·O. initiated the study and wrote the paper. A.K.O.O performed most of the analysis with support from J.L. and M.T. N.J.L and J.L carried out the analysis with regards to the LINE model. M.T. and D.C. supervised the study and commented on the drafts and final manuscript. All authors commented on and gave final approval for publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This project has received funding from Arhus University under the Global Analysis of Trade-related Emissions project (AUFF-GATE-24912). We wish to express our gratitude to the Centre for Regional and Tourism (CRT) research, Denmark, for providing rights to use the LINE model and regional data on Danish municipalities. We immensely thank Prof. Richard Wood of Norwegian University of Science and Technology (NTNU) for granting access to the EXIOBASE database developed under the CREEA project and Eivind Lekve Bjelle for all technical assistance with regards to the use of the database. Lastly, we express our appreciation for the useful comments of all anonymous reviewers and Edgar Towa that immensely improved the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2020.106778.

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