Regional production and consumption emissions associated with the Danish livestock products – a CGE multi-regional input-output approach

Authors
Osei-Owusu Kwame Albert 1*, Thomsen Marianne1*, Javakhishvili Larsen, Nino 2, Caro Dario 1

Affiliations of authors:
1 Department of Environmental Science, Aarhus University, Frederiksborgvej 399, DK-4000, Roskilde, Denmark

2 CRT - Center for Regional -og Turismeforskning, Rolighedsvej 25, Bygning A 1958 Frederiksberg C

Corresponding authors contact details:
Email: akoo@envs.au.dk : mth@envs.au.dk:
Tel: (+45) 71 84 71 06 : (+45) 22 29 26 27;
Abstract

Global protein consumption is expected to rise with the predicted increase in the global population from 7.6 to 9.5 billion in 2050. While production emissions will rise accordingly, they will also partly be driven by higher consumer demand for goods and services. Recent studies have shown the importance of allocating emissions to final consumers based on international trade. Both inter and intra-regional sectoral interactions to satisfy consumer demand result in environmental repercussions such as greenhouse gases emissions embodied in trade. Using a CGE multi-regional input-output model for Denmark, this study presents an environmental extension of the Local interregional (LINE) economic model, a regional input-output model using regional environmental accounts. Denmark is renowned for its agricultural orientation and high production and consumption of animal products. Our analysis comparatively evaluates the regional production and consumption emissions associated with different livestock products in Denmark. We investigate the carbon footprint of different livestock products with the two separate accounting methods (production- and consumption-based accounting) for five Danish regions. The results achieved constitutes the basis for revealing the hotspots for livestock demand-driven regional emissions and provide grounds for local climate policies that may contribute to the reduction of national greenhouse gas emissions and carbon leakages between local regions thereby mitigating climate change (SDG 13) and acidification marine and freshwater systems (SDG 14). Most important, the model will allow for future regional planning of support for more sustainable food production and consumption (SDG 12), by implementing local circular bioresource management and technology systems for local biofertilizer and alternative protein supply chains lowering the CO₂ footprint of consumption contributing directly to SDG 13 on climate actions by delivering GHG emission reductions but also mitigating acidification and eutrophication of marine and freshwater systems (SDG 14).

Keywords: Multi-regional input-output model, CGE, carbon footprint, livestock products
1. Introduction

Climate change has become one of the greatest threats to the global economy and ecosystems (Breitburg et al., 2018; Xu, Ramanathan, & Victor, 2018). The recent report by the IPCC (2018) suggests modest and insufficient progress is being made globally towards limiting global warming to 1.5°C above pre-industrial levels. Despite the global consensus to reduce global CO₂ emissions by 45% from 2010 levels by 2030, global CO₂ emissions continue to rise (Quéré et al., 2018). Although the political rhetoric of reducing emissions has mainly focused on the transport and energy sectors, the agricultural sector is one of the sectors that generate the greatest amount of greenhouse gas emissions (Lenka et al., 2015). In particular, agriculture is the single largest source of anthropogenic non-carbon dioxide (non-CO₂) emissions mainly released from enteric fermentation and manure management in the livestock industry (Frank et al., 2018; Herrero et al., 2016). Moreover, the expansion of pasture for livestock production, especially required to produce feed (Caro et al., 2018), is mainly responsible for CO₂ emissions from land-use change (Gerber et al., 2013). In Europe livestock production accounted for 41% of agricultural output in value terms, representing 1.2% of the European Union’s GDP (Leip et al., 2010). Total greenhouse gas (GHG) fluxes of European livestock production amount to about 850 Mt CO₂eq, of which about 60% are due to cattle and 25% to pork production (Weiss & Leip, 2012). Overall, more than 80% of the agricultural sector's emissions according to IPCC classifications, is due to livestock production (Weiss & Leip, 2012). Denmark's vibrant economy thrives on agriculture with 62% of Denmark's land area used for intensive agricultural activities (Landbrug & Fødevarer, 2015). The agricultural exports comprise 25% of Denmark's exports while live animals and meat products contribute to about 17% of this share (UN Comtrade, 2018). Moreover, livestock production especially pork and dairy products are the main contributor to Denmark's agricultural output, exports and GHG emissions. In 2017, the share of GHG emissions of Denmark's agriculture sector was 21% compared to the energy sector (28%) and transport sector (26%) (Danish Centre for Environment and Energy, 2017). A large share of Danish agricultural emissions are mainly related to livestock production; methane emissions from enteric fermentation and manure management is the largest single source of about 80% of national agricultural emissions (Statistics Denmark, 2018). However, compared to 1990 methane emissions from enteric fermentation have decreased by 8.1% in 2016 largely because of a decrease in the number of dairy cattle (Danish Centre for Environment and Energy, 2017). Whereas there is greater awareness of emissions associated with the production activities of the livestock sector, less policy attention is placed on emissions induced by the consumption of livestock products.
Part of the global debate on GHG mitigation and climate policies is centred on how national emissions monitoring is effectively translated into measures at the global level (Davis & Caldeira, 2010; Kanemoto et al., 2012; Lin et al., 2015; Minx et al., 2009). A growing number of studies have argued that the traditional production-based accounting (PBA) method adopted by the IPCC (2006, 2014) which assigns GHG emissions to the producer country regardless where the final product is consumed (Boyd et al., 2018; Caro et al., 2014; Fezzigna et al., 2019), may incentivize the import of cheaper pollution-intensive goods from other countries and the ever-growing relocation of industrial activities thus promoting the carbon leakage (Barrett et al., 2013; Larsen & Hertwich, 2009; Lenzen et al., 2007). In recent times, a large body of research has focused on the allocation of GHG emissions embodied in international trade by complementing the traditional PBA with a consumption-based accounting (CBA) in which emissions are attributed to the final demand actors (Lenzen et al., 2007; Peters & Hertwich, 2008b; Kanemoto et al., 2012). These studies often use environmentally extended input-output (EEIO) and hybrid input-output (IO) life cycle assessment (LCA) models to estimate the emissions associated with final demand using CBA (Davis & Caldeira, 2010; Minx et al., 2009; Peters et al, 2011; Wiedmann, 2009). CBA offers a different and interesting way of allocating emissions to final users of products (Giovanni & Minx, 2010; Hertwich & Peters, 2009). Despite the increasing number of studies where GHG emissions from consumption are assessed from a global and national perspective, only a few provide information on how local and regional structures within a country influence the emissions associated with the production and consumption of goods and services (Cohen & Muñoz, 2016; Dias et al., 2014; Moran et al., 2018; Su & Ang, 2011). More than half of the world’s population live in cities (UN-Habitat, 2016). Moreover, urban areas are predicted to be inhabited by about 60% of the global population by 2030 due to rapid urbanisation (UN-Habitat, 2014). Regional differences influence the distribution of the environmental impact burdens in a country together with economic indicators such as growth and employment. These differences have necessitated studies on and support for local climate policies for counties and cities (Hoornweg et al., 2014; Minx et al., 2013; Moran et al., 2018; Ramaswami et al., 2012). For instance, regions in countries that are noted for intensive primary activities such as agriculture and mining are often held most responsible for environmental impacts of their output which are rather consumed in large quantities in other regions of the same country or exported to the rest of the world.

Given the significant contribution of livestock sector to Danish agricultural emissions and considering the high consumption of livestock products in the country; the main goal of this paper is to calculate and compare the production-based accounts (PBA) and consumption-based accounts (CBA) emissions for four livestock products, namely milk, beef, pork and poultry for each of the 5
regions of Denmark for the year 2013. The analysis adopts a Danish interregional static computable general equilibrium (CGE) model for 98 Danish municipalities with a social accounting matrix (SAM) framework that is based on input-output modelling and data (Madsen, 2009; Madsen, 2005; Madsen & Jensen-Butler, 2004). Input-output analysis (IOA) through a life-cycle technique enables us to estimate the direct and indirect emissions associated with satisfying final demand of our chosen animal products for each sector in all regions (Miller & Blair, 2009; Tukker & Dietzenbacher, 2013). CBA emissions allow us to obtain the quantity GHG embodied in consumption for all regions. The paper identifies the emission-intensive sectors and estimates the CBA emissions for all regions associated with the selected animal-based products showing the trade flows between regions in terms of GHG emissions.

2. Methodology

2.1. The Local Interregional Economic (LINE) model
The Local Interregional Economic (LINE) model is an interregional CGE quantity and price-based input-output (IO) model for Danish municipalities constructed and maintained by the Centre for Regional and Tourism (CRT) Research. The model is based on a two-by-two-by-two principle (Madsen, 2009; Madsen & Jensen-Butler, 2005). The principal sources of data for the model are national data from the Danish Social Accounting Matrix for Kommunes (SAM-K). The model is constructed based on microeconomic data on production, income and employment by industry and regional data on the demand and supply of commodities which includes intermediate and final consumption by industries and households.

The two-by-two-by-two principle represents are two economic agents (producers/sectors and consumers/households), two markets (factor market and commodity market) and two interactions between economic agents and markets (trade and commuting). The distinguishing feature of the LINE model is its inclusion of spatial features such as commuting (from a place of production to the place of residence), shopping (from a place of residence to commodity market) and tourism (one-day and over-night tourism). Overall, four geographic concepts are embedded in 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). The links between the markets and economic agents capture the flow of commodities from an origin to a destination (from sector to market and from residence to sector/market). In the model, production activity is related to the place of production (sectors),
whereas factor income is related to the place of residence. Demand for commodities is traced to the commodity market. Production activities generate income and employment which are distributed by socio-demographic groups (age, education and gender). The factor market is the market where households offer their services for the activities of the sectors. Disposable income and commuting cost are paid is also determine the place of residence. Through commuting, factor income moves from place of production to the place of residence. Unemployment and employment are determined at the place of residence.

Fig. 1. The real circle of the Local INterregional Economic (LINE) model for Danish municipalities by Madsen and Butler (2005) that incorporates the integrated Leontief model along with spatial features and SAM characteristics. 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 demand and employment by sectors (j) at the place of production (P). The employment by sectors (j) is categorised to age, gender and education level groups (g) and from a place of production (P) to place of residence (R) through a commuting model. 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 the unemployment by age, gender and education at the place of residence (R).
The LINE model is a spatially extended version of the conventional input-output model. It is a quantity model based on the demand-driven Keynesian-type model that has a cyclical clockwise pattern (See Fig.1). Demand for commodities drives both intermediate consumptions by industries and linked to the commodity market. The model also ensures both commodity and labour market balance. On the demand side, the interregional SAM provides information that enables one trace where demand for commodities and labour originate either by household groups. From the supply side, the interregional SAM enables one to identify which sectors produce specific commodities, where they are produced and the supply of labour from different household groups. Interregional trade is modelled in the LINE model using the gravity model (Anderson & Van Wincoop, 2003; Isard, 1953; Saltzman et al., 2018). The model does not distinguish between final demand and intermediate consumption intra- and interregional trade.

2.2. The single region Leontief quantity model

Input-output tables (IOTs) show the inter-industry transactions in an economy that satisfy a given final demand bundle (Leontief, 1936, 1970). In a typical input-output model, one can observe how the output of industries serves as inputs to produce the output of other industries. The conventional input-output Leontief model is presented as follows;

\[ x = Ax + Y \] (2.1)

where the total output \( x \) in a given region is a sum of intermediate consumption \( (Ax) \) and final demand \( Y \), $, given n-by-1 vector, and \( A = Zx^{-1} \); \( A \) is the direct input requirement matrix which shows the shares of the output of one sector (selling sector) in the output of another sector (purchasing sector); \( Z \) is the inter-industry transaction matrix which shows the flow of goods between industries. The final demand of the economy comprises of private household and government consumption, gross capital formation and inventories, as well as final demand for imports and exports. Solving for total output in Eq.2.1 gives us;

\[ x = (I - A)^{-1}Y = LY \] (2.2)

where \( I \) is an identity matrix and \( L = (I - A)^{-1} \) an n-by-n matrix known as the Leontief inverse. The Leontief coefficients represent the total direct and indirect input requirements of any industry \( j \) (columns) supplied by other industries \( i \) (rows) within the region for industry \( j \) to be able to deliver DKK 1million worth of output to final demand.
2.3. Interregional Danish input-output model

Input-output tables are constructed from make/supply and use tables based on either the product technology or industry technology assumption (Eurostat, 2008; UN, 1999). Our interregional input-output model is based on accounts on regional commodity trade and shopping flows. The shopping matrix for intermediate consumption commodities reflects the fact that commodities are often purchased at the location of the wholesaler that is the place of the commodity market. In the LINE model, the Danish SAM-K axis is divided into sector and commodity dimensions represented by the make and use matrices (Miller & Blair, 2009) – See supplementary material. Our interregional input-output tables are then constructed from make-use matrices for Danish municipalities based on the industry technology assumption. The Danish Centre for Regional and Tourism Research operates an existing model for the Danish regional input-output data for 98 municipalities in Denmark that covers 117 sectors and 164 commodities based on historical data from Denmark Statistics.

For the objectives of our study, primary attention is given to the agricultural sector and other sectors associated with its supply chain. We disaggregate the agriculture industry into more detailed subsectors, especially for livestock sector for our estimations (See Supplementary material). As a result, we obtain a total of 40 industries in our model aggregated from 117 industries in the national accounts and 83 commodities. In this study three regions are considered for our multi-regional input-output model; the region in question, other regions and the rest of the world. Regional demand data, including intermediate consumption, household consumption and tourism consumption, are also applied to regional environmental accounts. The demand for commodities is obtained from National Consumer Expenditure Surveys and varies among regions (https://www.dst.dk/en.aspx).

Applying the partitioned inverse of Miyazawa’s quantity model (Miyazawa, 1968 & 1976), our general quantity IO model is presented as follows;

\[ x = (I - DTS_{IC} B_{IC} b_{IC})^{-1}Y^* = LY^* \]  

(2.3)

where \( A = DTS_{IC} B_{IC} b_{IC} \); \( Y^* = DTY \), \( L = (I - DTS_{IC} B_{IC} b_{IC})^{-1} \) from Eq. 2.3 is the Leontief inverse of the industry-by-industry type of a technical coefficient matrix constructed on the basis of the fixed

---

1 We have a total of 40 sectors, number of subsectors under each sector is in brackets: Agriculture (8), Food (processing/manufacturing) industry (7), Energy (5) and Water Supply (5), Transportation (5), and 20 other sectors. See supplementary material for full list.
product sales structure. D is the make matrix of a particular region with dimension n x m (n, m ∈ N). T is the intra and inter-regional trade matrix; S_{IC} is the shopping matrix for intermediate consumption, B_{IC} is the intermediate consumption by commodity as a share of intermediate consumption by sector and place of production while b_{IC} is the intermediate consumption as a share of gross output by place of production and sector. Our multiregional input output model for Danish regions linked through interregional trade is discussed further in the Supplementary material. Our model calculation and simulations are carried out using ADAM model (Danmarks Statistik, 2013) and ALFRED computer software.

2.4. Production and Consumption-based accounting of regional emissions

We obtain detailed production (farm-to-farm gate) emissions data associated with crop and livestock production for all municipalities in Denmark from the Danish Centre for Environment and Energy. The other air emissions data for non-agricultural industries were obtained from EXIOBASE v.3. Since we were unable to obtain air emissions data for all industries specific to each Danish municipality. We assumed that similar industries in all regions except agriculture have the same air emissions patterns although different industries should discharge different amounts of emissions in different regions due to differences in energy consumption levels. Detailed information on data sources is available in the supplementary material.

We construct an environmental satellite account F_r^PBA for each region r. Each row of F_r^PBA represents the total amount of a pollutant generated from each “i” industry in 2013. Greenhouse gas (GHG) emissions from industries for each region are represented in four satellite rows corresponding to the 40 sectors in the supply and use tables (SUT) for carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O) and carbon dioxide equivalents (CO2e). Each column n represents the amounts of all pollutants generated from a particular sector in the given year. The production-based accounting (PBA) emissions are obtained as the row sum across industries as shown below;

\[ F_r^{PBA} = \sum_{i}^{40} F_r^{PBA}_i \]  

(2.4)

F_r^{CBA} is the consumption-based accounting emissions for each region, r. Here, we allocate all direct emissions from livestock production to households at the point of residence, and not where emissions are physically released into the atmosphere (production perspective). The consumption-based accounting emissions for each region is calculated as;

\[ F_r^{CBA} = S_r(1 - A_{rr})^{-1} Y_r^* \]  

(2.5)
where $S_r$ refers to the direct emission intensity for region $r$ for each type of stressor and $A_{rr}$ is the direct input coefficient matrix for region $r$. The direct emission intensity is calculated from environmental satellite account as the ratio of the annual total emissions of an industry to value of the total economic output of the industry in question (ton/million DKK).

We obtain the total environmental impact by commodity categories $\overline{F_r^c}$ as follows;

$$\overline{F_r^c} = S_r(I-A_{rr})^{-1}\overline{Y_r^r}$$

(2.6)

where $\overline{Y_r^r}$ is the diagonally final demand vector. We estimate the direct and indirect carbon footprint of consumption along the entire supply chain for each region.

$$F_{r}^{\text{direct}} = S_rY_r^*$$

(2.7)

$$F_{r}^{\text{indirect}} = S_r(I-A_{rr})^{-1}Y_r^* = S_rY_r^* + SA_{rr}^2Y_r^* + SA_{rr}^3Y_r^* + \cdots + SA_{rn}^nY_r^*$$

(2.8)

where $F_{r}^{\text{direct}}$ denotes the direct emissions induced by private consumption/final demand for livestock products; $F_{r}^{\text{indirect}}$ refers to indirect emissions upstream driven by intermediate consumption by sectors to satisfy final demand for livestock products. We do not account for emissions from households in the use phase in this study.

3. Results

NB: This section will be later updated with the results which will be presented at the conference.

The paper will present the environmental impact of livestock consumption in municipalities and hence regions in Denmark.

Tables & Figures to presented

1. Consumption per capita for all livestock products for all regions
2. Direct GHG emissions (PBA) for each livestock sector for all regions
3. Consumption-based emissions (CBA) by final demand components for all regions
4. Consumption emissions (CBA) for all products by category for all regions
5. Consumption emissions for livestock products for all regions
6. Indirect GHG emissions (total and by industry) associated with livestock consumption for all regions

From our crude preliminary results, we find that the carbon footprint of livestock products is higher in the urban regions than in peripheral municipalities and on the islands. This finding corresponds
with the high shares of livestock consumption in the urban regions than on the islands and in the peripheral municipalities. Production emissions for livestock products are higher in rural municipalities than in urban municipalities. This is because primary livestock activities and other manufacturing activities mostly occur outside urban municipalities. Urban municipalities are noted for economic activities related to services

Generally, we expect that the environmental impacts for production to be relatively higher in North and South Jutland where the primary livestock production and food processing activities occur. On the other hand, we expect the CBA emissions to be relatively higher in regions with higher population densities and income levels in Sjælland and Copenhagen. However, we expect to find that the environmental effects are greater in absolute magnitude in larger cities than in peripheral destinations.

4. Discussion

4.1. Comparison with other related studies

Denmark has a target of reducing Danish greenhouse gas emissions by 40% by 2020 (Danish Government, 2013). The Danish government has special plans to transition to renewable energy sources for electricity and heating supply by 2035. The ambitious goal is that by 2050, all forms of Danish energy demand will be met with renewable energy. The agricultural sector is the third highest emitter of Danish greenhouse gases. Several studies have linked food consumption with the current strain on natural resources (Ripple et al., 2014; Springmann et al., 2018). About 22% of global GHG emissions are attributed to the food industry (Hertwich & Peters, 2009; Sato, 2014). A high share of global food-related emissions is associated with livestock production (Gerber et al., 2013; Tubiello et al., 2014). The food industry could be responsible for about 50% of the total emissions by 2050 if global warming is kept below 2°C (Springmann, Godfray, Rayner, & Scarborough, 2016). However, agriculture and food climate policies are often less prioritized or excluded from comprehensive national and local climate policies for political reasons or technical difficulties in measuring agricultural emissions (Lassey et al., 2007; Snyder, Bruulsema, Jensen, & Fixen, 2009).

Many local Danish climate policies are focused on reducing consumption emissions from transport and energy by encouraging the use of electric vehicles, public transport, investment into cycling lanes on roads and eco-taxes (Miljø Metropolen, 2013; Realdania & Sustainia, 2018; The City of Copenhagen, 2012). Local climate policies related to food are skewed towards reducing food waste
making policies aimed at promoting sustainable food production and consumption systems selective. Little attention is given to consumer food choices, especially livestock products whose demand and environmental impacts are equally high and damaging. The current pressure on the local natural resources due to increasing domestic and foreign food demand calls for sustainable consumption practices. Curtail rising emissions related livestock consumption will require climate policies on multiple scales (global, national and subnational) aimed at encouraging changing diets or reducing consumption of animal products. In this paper, we argue for local climate policies for local municipalities in Denmark aimed at reducing food production and consumption emissions. This study is relevant since consumption is highest in larger cities or counties with high-income levels and population densities. Primary production like livestock farming often takes places in remote regions where consumption levels are often low.

4.2. Comparison with other related studies

A number of studies have addressed and estimated the environmental impacts of household consumption using EE MRIO at both global (Andrew & Peters, 2013; Davis & Caldeira, 2010; Hertwich et al., 2009) and national scales. Studies on carbon footprint for household consumption have been conducted for Sweden (Dawkins et al., 2019; Minx et al., 2008), for Australia (Levitt et al., 2017; Wood & Dey, 2009) and for New Zealand (Andrew & Forgie, 2008), for United Kingdom (Baiocchi et al., 2010; Barrett et al., 2013; Wiedmann et al., 2010), for Norway (Lenzen et al., 2004; Peters & Hertwich, 2006a; Peters et al., 2009) and for Denmark (Boyd et al., 2018; Ghosh et al., 2009; Munksgaard et al., 2000). Recent studies combine EE MRIO models with regression techniques and spatial emissions modelling to calculate the carbon footprint of counties and cities (Dias et al., 2014; Jones & Kammen, 2014; Larsen & Hertwich, 2009; Moran et al., 2018).

Previous studies on Danish production and consumption emissions carried out at the national level focused on highly aggregated levels of commodities such as food, energy and transport (Munksgaard et al., 2000; Schmidt & Muños, 2014). Some authors ascertained the environmental impact associated with pork, milk and beef production in Denmark and Sweden using Life Cycle Assessment (LCA) tools (Cederberg et al., 2009; Dalgaard et al., 2014, 2016; Hutchings et al., 2014; Kristensen et al., 2015). However, the effective implementation of local climate-resilient food supply chains necessitates insight on the carbon hotspots of existing local food production systems. Such information can be useful to create awareness of the carbon footprint of local food consumption. It will also inform policy
makers and facilitate the execution of policies that support efficient local resources management systems close the nutrient and prevent carbon emission leakages.

4.3. Uncertainty about results

We will interpret our results in the context of uncertainties due to assumptions on regional emissions data and the low sectoral resolution of our model. For input-output analysis, the level of detail in sectors affects the accuracy of results to a degree (Steen-Olsen et al., 2014). The level of sectoral detail often depends on the objective of the study and the availability of data. In our case, our primary focus is on the agriculture sector (livestock sector) and the other sectors indirectly related to it. We would have preferred to carry out the analyses with the complete Danish IO model of 117 sectors instead of 40 sectors to may completely capture all of the inter-sectoral resource and material flow of inputs for Danish livestock production. However, with our present model capacity, this was not an option and our model has a limit of 40 sectors. To optimize the model under the stated limitation, we disaggregated the most relevant sectors into sectors that best fits the objective of the paper (See supplementary material). We prioritized and disaggregated sectors to ensure consistency in matching regional emissions data to the economic sectors in the most reasonable manner. A number of authors have addressed the implications of aggregating and disaggregating sectors in IOA (Bouwmeester & Oosterhaven, 2013; Steen-Olsen et al., 2014). Lenzen (2011) argues that the disaggregation of IO data is preferable to the aggregation of environmental extension data. Su et al. (2010) posit a 40 sector IO model was sufficient to evaluate embodied emissions in a study on Chinese trade. Several other MRIO studies have used IOTs with less 40 sectors per region. Ahmad & Wyckoff (2003) used a 6 sector model for European countries and Lenzen et al. (2004) used 10 sectors per region to investigate the trends in Denmark’s CO₂ accounts in a five-region MRIO table but found significant errors. Another limitation of this study is that we assumed the same emission intensities for non-agricultural sectors across municipalities and regions. In the absence of detailed information about regional emissions by sectors, it was reasonable to assume that all regions use the same inputs for making electricity and other kinds of energy. When regional emissions data are available for all sectors in all regions, it would be possible to improve our regional emissions accounts and the accuracy of our results. We can also apply other novel methods used by other authors to surmount the challenge in obtaining regional emissions data. A number of recent studies on household carbon footprints suggest the use of regression analysis and carbon hotspots maps based on Zip Code Tabulation Areas (ZCTAs) (Jones & Kammen, 2014; Lenzen et al., 2012). Work is ongoing
to improve and expand our model as well as better the accuracy of our results by accounting for interactions between the Danish regions and the rest of the world. In our model, we use the average emissions intensities for the 5 rest of the world regions (Europe, Asia, Africa, North and South America). We intend to adopt an embedded input-output analysis used by Minx et al. (2013) where we combine our IO model with an MRIO database to rightly account for global carbon input and flows of Danish municipalities.

5. Conclusion

This paper presents the results of an environmental-economic analysis of the regional production and consumption emissions associated with Danish livestock products using the Danish Local Interregional Economic model. We first extended the IOTs for 98 Danish municipalities with regional environmental satellite accounts based on a number of assumptions and emissions data from different sources. The national emissions data are assigned to municipalities by applying regionalized intermediate consumption and regionalized private consumption. In other words, the amount of regional emissions depends on the amounts of intermediate consumption and private consumption in each municipality. The Danish interregional macroeconomic model provides a framework for both regional tourism accounts and regional environmental accounts.

Although production-based emissions located within regional borders are somewhat easy to measure, supplementary consumption-based emissions are useful and provide a distinct way of accounting for emissions. CBA methods assign responsibility for the production emissions to the consumers in the location where the final consumption goods occurred. GHG emissions from production processes located within the regional borders can be leaked from one region to another when an industry relocates all or part of its operations to another. This means a reduction of GHG emissions in one region may not signify national progress in GHG mitigation. Some studies suggest that CBA inventories are better suited to evaluate the effectiveness of climate mitigation measures and to tracking the development of the responsibility for greenhouse gas emissions (Munksgaard and Pedersen, 2001; Peters, 2008; Peters and Hertwich, 2008).

The discussion in this paper focuses on making a strong argument for consumption-based emission inventories for municipalities. Our results provide direct and total impacts of livestock consumption on GHG emissions. This result should draw the attention of policy makers and regional planners when they develop regional policies. Finally, we would like to draw attention to the fact that the
environment is a global issue in that pollution does not affect only one country but has global effects on the world environment. In the long term, the global factors of CO2 and other emissions should be added to the analysis.

The results and implications of the study can be applied to other future studies focusing on reducing high intensive CO2 emission inputs and processes within the Danish meat production value chains, hence consumption, performing business transformation scenarios into climate-resilient value chains and products expected to influence future consumer habits/demands to the Danish livestock production sector as well as changing consumer food preferences. Firstly, econometric regression analyses can be used to ascertain the connection between regional socio-demographic characteristics and our calculated consumption-based emissions for livestock products. The outcomes of such studies can also be used to inform local climate policies based on social and demographic considerations. Secondly, it will also be interesting to analyse and ascertain the regional environmental and health impacts of meat taxes and diet changes towards plant-based foods.
References


IPCC. (2014). *Climate Change 2014. THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE.* https://doi.org/10.1073/pnas.1116437108


Tukker, A., & Dietzenbacher, E. (2013). GLOBAL MULTIREGIONAL INPUT-OUTPUT FRAMEWORKS:


Regional production and consumption emissions associated with the Danish livestock products – a CGE multi-regional input-output approach

Osei-Owusu, K.A., Thomsen, M., Javakhishvili Larsen, N., Caro, D.

Supplementary information

1. Overview of Danish municipalities and regions

Table S1. The 98 Danish Municipalities and 5 regions

<table>
<thead>
<tr>
<th>Region</th>
<th>Municipalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sjælland (Zealand)</td>
<td>Greve, Køge, Roskilde, Solrød, Odsherred, Holbæk, Faxe, Kalundborg, Ringsted, Slagelse, Stevns, Sorø, Lejre, Lolland, Næstved, Guldborgsund, Vordingborg</td>
</tr>
<tr>
<td>Syddanmark (Southern Denmark)</td>
<td>Middelfart, Assens, Faaborg-Midtjyn, Kerteminde, Nyborg, Odense, Svendborg, Bogense, Langeland, Ærø, Haderslev, Billund, Sønderborg, Tønder, Esbjerg, Fanø, Varde, Vejen, Aabenraa, Fredericia, Kolding, Vejle</td>
</tr>
<tr>
<td>Midtjylland (West and East/Central Jutland)</td>
<td>Horsens, Helsingør, Holstebro, Lemvig, Struer, Syddjurs, Norddjurs, Favrskov, Odder, Randers, Hedensted, Silkeborg, Samsoe, Skanderborg, Århus, Ikast-Brand, Ringkøbing-Skjern, Skive, Viborg</td>
</tr>
<tr>
<td>Nordjylland (North Jutland)</td>
<td>Frederikshavn, Vesthimmerland, Læsø, Rebib, Mariagerfjord, Jammerbugt, Aalborg, Hjørring, Morsø, Thisted, Brønderslev- Dronninglund</td>
</tr>
</tbody>
</table>

2. Multiregional input-output model

For our multi-regional input-output (MRIO) model, we derive a technical coefficient matrix, $A_{ij}$ for each region from Danish municipality supply and use tables for the year 2013 (See figure S1) with a dimension of 83 commodities and 40 industries in basic prices as provided by CRT. We apply the domestic technology assumption (DTA) for interaction between each region and the rest of the world (ROW). Generally, we consider three regions for modelling, the region in question ($r$), other regions in the country (or) and the rest of the world. We consider 5 rest of regions from EXIOBASE for Africa, Europe, North and South America and Asia.
**Fig.S1.** The structure of the environmentally extended municipal make-use tables of 40 industries and 83 commodities. Also, \( g \) is the column sums of the use table, \( U \); \( x/q \) is the column sums of supply table, \( V \).

\( V_r \) is the supply matrix (the transpose of the make matrix, \( D \)) of region \( r \) and shows the supply of \( m \) commodities by \( n \) industries. The row sums of \( V_r \) gives us \( q_r \), the total output of each commodity produced while, \( g_r \) the total output per industry is obtained from column sums. \( U_r \) is the use matrix of region \( r \) with dimension \( m \times n \) (\( m, n \in \mathbb{N} \)). \( U_r \) shows the use or intermediate consumption of \( m \) commodities by \( n \) industries. The column sums give us \( q_r \), the total use of each commodity produced by each industry. Similarly, \( V_{or} \) and \( V_{row} \) are the make matrices for other regions and the rest of the world respectively with their corresponding \( q_r \) and \( q_{row} \). \( U_{or} \) and \( U_{row} \) are the use matrices for other regions and the rest of the world respectively with their corresponding \( q_{or} \) and \( q_{row} \). For each municipality, we can obtain the final demand (\( Y \)) for 83 commodities. What is not known, however, is where these commodities originate. To approximate \( Y_r \), \( Y_{or} \), and \( Y_{row} \) we use Jensen (2007)’s ‘fixed product sales structure’ assumption, that is we assumed that the relative shares in which a product is supplied from domestic production industries and import is the same no matter to which industry or final demand component it is delivered.
Our interregional input-output model is set-up as follows:

\[
x_r = \begin{pmatrix}
A_{11} & 0 & \cdots & 0 \\
0 & A_{22} & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & A_{ss}
\end{pmatrix}
\begin{pmatrix}
x_1 \\
x_2 \\
\vdots \\
x_s
\end{pmatrix}
+ \begin{pmatrix}
y_{11} & y_{12} & \cdots & y_{15} \\
y_{21} & y_{22} & \cdots & y_{25} \\
\vdots & \vdots & \ddots & \vdots \\
y_{51} & y_{52} & \cdots & y_{55}
\end{pmatrix}
\]

where is \(x_r\) the output of region \(r\) (\(r = 1 \ldots n\)); \(A_{rr}\) represents the industry input of domestically produced products for region \(r\). For lack of data, \(A_{ij}\), the interindustry requirements of imports from region \(i\) to \(j\) is zero in our model (\(A_{ij} = 0, i \neq j\))^1; \(y_{ij}\) is the import to final demand from region \(i\) to \(j\).

We assume domestic technology assumption for Danish imports from the rest of the world for each region. Given data on the emission intensities for each region and the local final demand (in each region), we calculate the carbon footprint of consumption for each region as follows;

\[
\begin{pmatrix}
F_{hh} \\
F_{ss} \\
F_{sysy} \\
F_{mn}
\end{pmatrix}
= \begin{pmatrix}
s_k \\
s_k \\
s_m \\
s_n
\end{pmatrix}
\begin{pmatrix}
I & 0 & 0 & 0 \\
0 & I & 0 & 0 \\
0 & 0 & I & 0 \\
0 & 0 & 0 & I
\end{pmatrix}
\begin{pmatrix}
A_{hh} & 0 & 0 & 0 \\
0 & A_{ss} & 0 & 0 \\
0 & 0 & A_{sysy} & 0 \\
0 & 0 & 0 & A_{mn}
\end{pmatrix}
^{-1}
\begin{pmatrix}
y_{hh} \\
y_{ss} \\
y_{sysy} \\
y_{mn}
\end{pmatrix}
\]

where \(F_{ij}, i = j\) is the carbon footprint of each region; \(I\) is an identity matrix and \(s_i\) contains the emission intensity for each region.

2.1. Production and consumption emissions in the framework of the two-by-two-by-two principle

This study aims to calculate the regional production and consumption emissions associated with the Danish livestock sector, with particular attention to dairy, beef, pork and poultry products. In this section, we graphically illustrate how we carry out calculations in the framework of the Danish Input-Output (IO) Computable General Equilibrium (CGE) Local INterregional Economic (LINE) model. The LINE model follows the circular flow principle of the Keynesian quantity model.

In the local economy, two actors (producers and households) and two markets (commodity and factor markets) can be identified. In the figure S2, producers are located in the upper \(P_j\) cell reflecting the place of production (P), and the “industries/ sectors”(j) horizontal columns on the vertical and

---

1 Technical coefficients for regions; Hovedstaden (A_{hh}), Sjælland (A_{ss}), Syddanmark (A_{sysy}), Midtjylland (A_{mn}), Nordjylland (A_{nn})
horizontal Social Accounting Matrix rows respectively. In the case of the livestock industry are “livestock activities”, that include breeding of cattle, pigs, poultry, crop production to feed animals, processing and packaging of livestock products, transportation of meat products etc. The place of production is, where these activities take place, that is farms, slaughterhouses, transport industry, processing industries. The households belong to the (Rh) cell, reflecting that households by the place of residence, column (R) and vertically the SAM-row for households (h). In the context of this study, livestock products are consumed by household types (educated, with or without children and gender) who carry out daily activities at the place of residence and provide services in the sectors through the factor market.

**Fig.S2.** Livestock production and consumption emissions in the framework of the two-by-two-by-two principle of the LINE model (Madsen & Jensen-Butler, 2005). Three elements (actors, markets and origin/destination) illustrate the two-by-two-by-two principle.

The commodity market and factor markets belong to the (Si) and (Qg) cells respectively. The commodity market is located at the place of the commodity market (S) and the SAM-axis is commodities (i). The factor market belongs to the place of factor market (Q) and the SAM-axis to labour/population by type (g). In the case of agriculture, labour/population refers to the gender, age, education and socioeconomic status of the population and the labour force for the livestock and food
industry workers and consumers. The place of labour/factor market is where contacts and eventually contracts between the employer and the employee are completed.

Between the two actors and the two markets flows with geographical and SAM origins and destinations link actors and markets together. This involves trade (in the case of the environmentally extended LINE version with livestock commodities or services and between the place of production – farms - and commodity markets – shops, supermarkets), commuting (labour by type of health care education and between place of production and place of residence) and “shopping” (consumption of governmental services by type of health, care and education and between place of residence and place of commodity market – the place of health demand).

**Standard equations of the macroeconomic quantity model applied to the LINE model**

\[
\begin{align*}
 b &= BQ \times x \tag{1.1} \quad \text{(from j to i and from P to S)} \\
l &= LQ \times x \tag{1.2} \quad \text{(from P to R and from j to g)} \\
y &= YLQ \times l \tag{1.3} \quad \text{(from g to h)} \\
c &= CQ \times y \tag{1.4} \quad \text{(from h to I and from R to S)} \\
u &= UQ \times l \tag{1.5} \quad \text{(R and g)} \\
g &= GQ \times u \tag{1.6} \quad \text{(from g to i and from R to S)} \\
m &= b + c + g + i \tag{1.7} \quad \text{(S and i)} \\
mf &= MFQ \times m \tag{1.8} \quad \text{(S and i)} \\
md &= m - mf \tag{1.9} \quad \text{(S and i)} \\
ed &= md \tag{1.11} \quad \text{(from S to P)} \\
e &= ed + ef \tag{1.12} \quad \text{(P and i)} \\
x &= e \tag{1.13} \quad \text{(from i to j)}
\end{align*}
\]

Where:
- \(x\): Gross output
- \(y\): Income
- \(b\): Intermediate consumption demand
- \(BQ\): Intermediate consumption shares of the production
- \(c\): Private consumption demand
- \(CQ\): Private consumption as a share of the income
- \(e\): Demand for domestic production
- \(ed\): Domestic demand for domestic production
- \(ef\): Foreign export demand for domestic production
- \(g\): Governmental consumption demand
- \(GQ\): Governmental consumption per capita
- \(i\): Investment demand
- \(m\): Domestic demand
- \(l\): Employment
- \(LQ\): Employment content
Disaggregation and aggregation of sectors for LINE model

National input-output (IO) models usually have highly aggregated sectors. For example, activities such as animal production and crop cultivation are all lumped into the category of agriculture, forestry and fishing sector. In order to perform an environmental impact assessment of a sub-sector like livestock production, one has to further disaggregate the agriculture sector of interest to suit the needs of the study. Sub-sectors like animal production can also further be classified into the breeding of cattle, pigs and chicken. Most IO models do not have very detailed processes and data like process LCA provides. In recent times, hybrid IO-LCA models have gained popularity since they have somewhat abated the challenges with lack of process-level data in IO models. With data, one can disaggregate aggregate any sector of interest to the most comprehensive level.
We disaggregated four sectors (agriculture, food, energy and transport) in the 117 sectors Danish input-output table. These four sectors are split up into eight, seven, five and five sub-sectors respectively. With this detailed level of disaggregation of the four sectors, our computer program\(^2\) aggregates Denmark Statistics’ 117 sectors to 40. Therefore, the remaining sectors were aggregated to 20 groups because they are “less important” for the goal of the paper. In this study, our primary sector of interest is the agriculture sector. We intend to estimate the regional production and consumption emissions associated with dairy, beef, poultry and pork products. Due to our disaggregation of the agriculture sector into more specific activities such as crop cultivation and livestock production, we collate the total greenhouse gas by type for each industry and municipality according to our disaggregation.

**Table S2.** Industries in our model showing a highly disaggregated agriculture sector

<table>
<thead>
<tr>
<th>ID</th>
<th>Industry name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Production of cereal (Crop production)</td>
</tr>
<tr>
<td>2</td>
<td>Production of rice</td>
</tr>
<tr>
<td>3</td>
<td>Breeding of dairy cattle</td>
</tr>
<tr>
<td>4</td>
<td>Breeding of beef cattle</td>
</tr>
<tr>
<td>5</td>
<td>Breeding of weaners/piglets</td>
</tr>
<tr>
<td>6</td>
<td>Production of slaughter pigs</td>
</tr>
<tr>
<td>7</td>
<td>Poultry</td>
</tr>
<tr>
<td>8</td>
<td>Forestry and fishery, the rest of agriculture</td>
</tr>
<tr>
<td>9</td>
<td>Mining and quarrying</td>
</tr>
<tr>
<td>10</td>
<td>Processing of pig meat</td>
</tr>
<tr>
<td>11</td>
<td>Processing of other meat (cattle)</td>
</tr>
<tr>
<td>12</td>
<td>Processing and conservation of poultry</td>
</tr>
<tr>
<td>13</td>
<td>Production of meat and poultry products</td>
</tr>
<tr>
<td>14</td>
<td>Dairies and cheese production</td>
</tr>
<tr>
<td>15</td>
<td>Production of feed mix to agriculture</td>
</tr>
<tr>
<td>16</td>
<td>Rest of food, drinks and tobacco industry</td>
</tr>
<tr>
<td>17</td>
<td>Textile, leather, wood and paper industry, printing</td>
</tr>
<tr>
<td>18</td>
<td>Oil refineries, chemical industry, plastic, glass and concrete industry</td>
</tr>
<tr>
<td>19</td>
<td>Metal, electronic industry, preparation of electronic devices</td>
</tr>
<tr>
<td>20</td>
<td>Machine, vehicle, furniture, other industry</td>
</tr>
<tr>
<td>21</td>
<td>Electricity</td>
</tr>
<tr>
<td>22</td>
<td>Gas</td>
</tr>
<tr>
<td>23</td>
<td>Heating</td>
</tr>
<tr>
<td>24</td>
<td>Water</td>
</tr>
<tr>
<td>25</td>
<td>Rest of water supply and renovation</td>
</tr>
<tr>
<td>26</td>
<td>Building and construction</td>
</tr>
</tbody>
</table>

\(^2\) ALFRED computer software was used for our CGE MRIO modelling
There are 83 commodities aggregated from 164 commodities in our model. Each of them corresponds to a sector, with some sectors having more than one commodity (co-products). The aggregation of the commodities follows the same procedure for the aggregation of sectors. Hence our computer program has a limitation of 99 commodities and the objectives for the aggregation of commodities is to optimize the level of detail under this limitation. As a result, we disaggregate commodities under agriculture, food- and meat industry, production of fertilizer, energy- and water supply and transportation sectors.

4. Data sources

In this section, we provide an overview of the data sources used for the study presented in this paper. The first sub-section discusses the economic data used for LINE model that serves as the basis for our interregional input-output model. The second describes the environmental data sources used for calculating the carbon footprint of the consumption of livestock products for all municipality (and regions) in Denmark. All data are gathered for the study correspond to the year 2013.

4.1. Economic data

The primary source of economic data for the LINE model is the interregional social accounting matrix for Danish municipalities, Social Accounting Matrix for "Kommune" (SAM-K). The LINE model is obtained from the SAM-K based on the double spatial entry principle known as the “two-by-two-by-

---

3 Kommune is the Danish word for municipality
two principle”. Model data is collated from three main sources; Denmark’s national accounts, register data and questionnaires. Data is also available at the Danish municipality and regional levels. “TA” (“Tilgang og Anvendelse”), “KRNR”, Annual Danish Aggregate Model (ADAM), “TØBBE” and RTSA (Regional Tourism Satellite Account) make-up the register data. Input-output data is obtained from Statistics Denmark. The “TA” is the national account database that consists of Danish make and use tables. The make tables show the national supply of products by specific activities/sectors including imports from the rest of the world whilst the use table shows how specific sectors use the supplied products in their activities. Make and use tables for municipalities are generated from the national tables by the Centre for Regional and Tourism (CRT) research. The KRNR data is the regional production accounts at Danish municipalities. ADAM is a macroeconomic model that provides the conceptual framework behind the operation of the Danish economy. It is useful for predicting economic trends and for impact assessment of policy interventions. ADAM combines theoretical ideas from both Keynesian and neo-classical economics. RSTA is the regional tourism satellite accounts that provide special information related to tourism activities.

4.2. Environmental data

Our economic input-output model is extended with air emissions data by type of air emissions, industry and municipality (region). Three main greenhouse gases (GHGs) are considered in this study, CO₂, CH₄ and N₂O. The air emissions data for the Danish economy used in the study were obtained from the Danish Emissions Inventory annual reports of Aarhus University’s (AU) Department of Environmental Science (Nielsen et al., 2015), and EXIOBASE v3 (Stadler et al., 2018). We obtained air emissions data for all municipalities in Denmark for both crop and livestock production from AU’s Department of Environmental Science. The air emissions data for all other sectors except for agriculture are obtained from EXIOBASE v3. We use the same national average emission factors per industry for all other sectors with the except of agriculture for which we have detailed municipal and region air emissions data.

EXIOBASE v3 contains a full estimation of greenhouse gas emissions across all sectors of the global economy. The GHG emissions from fossil fuel combustion are based on IEA energy balances and emission coefficients. The agricultural emissions from fuel combustion are calculated from the IEA energy balances which are disaggregated based on energy use coefficients of different types of agricultural production. Moreover, an Agrimodule is used to obtain agricultural emissions data mainly from FAOSTAT while International Fertilizer Industry Association is used to obtain technical coefficients, manure production, emissions and trade data in mass units. Methane and nitrogen-related emissions (especially nitrous oxide) estimations are based on the guidelines from the
Intergovernmental Panel on Climate Change (IPCC, 2006 a,b). The Agrimodule provides the production and emissions for individual crops, and the production, feed intake, manure production and emissions per livestock category. For the purposes of this study are the emissions by crop and livestock type which are aggregated to the two major crop groups and five major animal categories, and other 33 industries for each Danish region (See Table S2). The non-CO2 GHG emissions are transformed into CO2 equivalents using IPCC characterization factors (IPCC, 2014). The air emissions data are measured in GHG tons. We assign the annual total emissions data by type to the respective activities/industries for each region/municipality.

4.3. Livestock production emissions data

We obtain agricultural emissions data for our carbon footprint calculations at a detailed level for crop production and 5 livestock categories (See Table S2). Livestock production is associated with direct and indirect GHG emissions. These emissions may occur either directly on the farm or indirectly beyond the farm gate. Generally, these emissions result from animal feed production, husbandry, slaughtering, processing, transportation and energy use. Our principal source of cradle-to-farm-gate emissions data associated with livestock production for each municipality in Denmark is Aarhus University’s Department of Environmental Science. These air emissions associated with livestock production are calculated based on information on the number of animals, the distribution of animals according to housing type and information on feed consumption and excretion for all farms in each municipality (Danish Centre for Environment and Energy, 2017). These emissions are simply farm-to-farm gate emissions.

Table S3. Danish regional agricultural emissions by category

<table>
<thead>
<tr>
<th>Type/source of emission</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total agriculture (CO_2) emissions, tonnes</td>
<td>Animal, Crop and Soil</td>
</tr>
<tr>
<td>Enteric fermentation, CH_4, tonnes</td>
<td>Animal</td>
</tr>
<tr>
<td>Livestock manure storage, CH_4, tonnes</td>
<td>Animal</td>
</tr>
<tr>
<td>Livestock manure storage, N_2O, tonnes</td>
<td>Animal</td>
</tr>
<tr>
<td>Livestock manure spreading, applied to cropland, N_2O</td>
<td>Animal</td>
</tr>
<tr>
<td>Commercial/mineral fertilizer spreading/application, applied to cropland, N_2O, tonnes</td>
<td>Crop</td>
</tr>
<tr>
<td>Other fertilizers, applied to cropland, N_2O, tonnes /other bio-waste based (sludge)</td>
<td>Crop</td>
</tr>
<tr>
<td>fertilizer</td>
<td></td>
</tr>
<tr>
<td>Grazing, N_2O, tonnes</td>
<td>Crop</td>
</tr>
<tr>
<td>Crop residues, N_2O, tonnes</td>
<td>Animal</td>
</tr>
<tr>
<td>Atmospheric deposition from the application of manure (NH_3 and NOx from the stall-storage application), N_2O, tonnes of CO_2 eq.</td>
<td>Animal</td>
</tr>
</tbody>
</table>
5. Extension of the LINE model with air emissions data

Detailed analyses on the relationships between the economy and the environment can be conducted using environmentally extended input-output models (Kitzes, 2013; Weinzettel et al, 2014). We construct a stressor coefficient matrix for 98 municipalities based on air emissions data for three greenhouse gases (GHGs): carbon dioxide (CO$_2$), methane (CH$_4$) and nitrous oxide (N$_2$O). A stressor coefficient matrix is simply a matrix with the emissions intensities of sectors in an economy. An emission intensity ($S$) of industry “i” is calculated as the ratio of the total emissions generated by an industry to the total output of that activity.

$$S_i = \frac{\text{Total emissions related to an activity/industry (tonnes)}}{\text{Total output of an activity (in physical quantity or monetary value (million DKK))}}$$

We construct the stressor intensity matrix with three dimensions, namely; the geographical location (for all 98 Danish municipalities, later aggregated to 5 regions), industry and type of greenhouse gas. We deploy a top-down approach to distribute national crop and livestock emissions among municipalities using proxy variables/relevant allocation keys. For emissions from crop production, the hectares of cropland harvested in each municipality by crop category is used while the number of animals reared in each municipality by type of livestock is used for livestock emissions. Data for these two allocation keys were obtained from Denmark Statistics website (https://www.dst.dk/en.aspx).

For example, to obtain the methane emissions associated with the beef production (S4- Sector 4 in Table S2) for a given municipality “A”, we use data on national average for the methane intensity
associated with beef cattle production and the number of non-dairy cattle reared on the farms in municipality “A” for the year 2013. We calculate the total production emissions from the breeding of beef cattle \( F_{\text{beef cattle}}^{\text{methane}} \) in “municipality A” for the year in question as follows;

\[
F_{\text{beef cattle}}^{\text{methane}} = \text{(Methane per head per year)} \times \text{(number of beef cattle in per year)}
\]

For a given municipality, the total production emissions, \( F_{\text{animal type}}^e \) for each air emission type and livestock sector excluding feed crop production emissions was calculated as follows;

\[
F_{\text{animal type}}^e = (\text{National average emission intensity per air emission type per year}) \times \text{(number of animals in municipality per year)}
\]

where \( e \) is the type of air emission. On the other hand, the total feed crop production emissions, \( F_{\text{crop type}}^e \) for each crop category (for e.g. cereals) and air emission type is calculated as follows;

\[
F_{\text{crop category}}^e = \frac{\text{Total national emissions associated with crop production by type per year}}{\text{Hectares of cropland harvested by crop type per year by municipality}}
\]

Based on the results from our calculations, we construct a stressor matrix containing municipality specific crop and livestock production intensities. The table contains total emissions related to each agricultural sector for each municipality.

**Table S3.** Simplified structure of the stressor matrix (S) for each municipality

<table>
<thead>
<tr>
<th>Sectors</th>
<th>S1</th>
<th>...</th>
<th>S7</th>
<th>S8</th>
<th>S9</th>
<th>...</th>
<th>S40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air emissions by type</td>
<td>CO2</td>
<td>CH4</td>
<td>N20</td>
<td>C02e</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Key**

- Spatial emissions data was obtained for all 98 municipalities for the 7 agricultural sectors (from the Department of Environmental Science, Aarhus University)
- We use national emissions data for the remaining 33 sectors from EXIOBASE v3 to calculate emission intensities for all municipalities. This is because we were unable to obtain spatial data for these sectors for each Danish municipality.
References


