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LETTER

Impact of cutting meat intake on hidden greenhouse gas emissions in an import-reliant city

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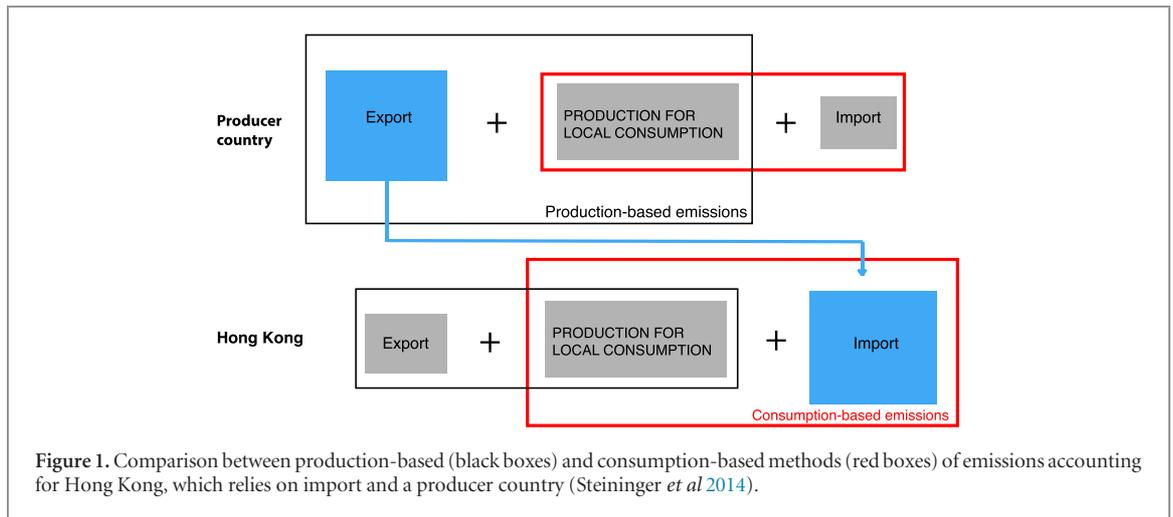
Abstract

Greenhouse gas emissions embodied in trade is a growing concern for the international community. Multiple studies have highlighted drawbacks in the territorial and production-based accounting of greenhouse gas emissions because it neglects emissions from the consumption of goods in trade. This creates weak carbon leakage and complicates international agreements on emissions regulations. Therefore, we estimated consumption-based emissions using input-output analysis and life cycle assessment to calculate the greenhouse gas emissions hidden in meat and dairy products in Hong Kong, a city predominately reliant on imports. We found that emissions solely from meat and dairy consumption were higher than the city's total greenhouse gas emissions using conventional production-based calculation. This implies that government reports underestimate more than half of the emissions, as 62% of emissions are embodied in international trade. The discrepancy emphasizes the need of transitioning climate targets and policy to consumption-based accounting. Furthermore, we have shown that dietary change from a meat-heavy diet to a diet in accordance with governmental nutrition guidelines could achieve a 67% reduction in livestock-related emissions, allowing Hong Kong to achieve the Paris Agreement targets for 2030. Consequently, we concluded that consumption-based accounting for greenhouse gas emissions is crucial to target the areas where emissions reduction is realistically achievable, especially for import-reliant cities like Hong Kong.

1. Introduction

The standardized greenhouse gas (GHG) calculation framework provided by the Intergovernmental Panel on Climate Change (IPCC) captures the emissions occurring within country's geographical boarder and usually adopts a producer-oriented approach (e.g. IPCC 2006, Caro *et al* 2015, Druckman *et al* 2008, Bastianoni *et al* 2014). The national GHG estimates are the foundation in binding international agreements such as the Kyoto Protocol and the Paris Agreement from the 21st Conference of Parties (COP21; Rogelj *et al* 2016, UNFCCC 2015, Kanemoto *et al* 2014). However, the production, or territorial-based accounting, ignores emissions embodied in

international trade (e.g. Peters 2008, Lenzen *et al* 2004). In a globalized and highly-connected economic system, country's emissions are intimately linked with each other because international trade divides production and consumption in different geographical regions (Schmitz *et al* 2012, Su and Ang 2010, Wiebe *et al* 2012, Lenzen *et al* 2004). Therefore, the economic activities and consumption of one country have impacts beyond its geographical boundary. There is an increasing trend of emissions transfer via international trade and thus emissions are shifted from one country to another (Peters *et al* 2011). Neglecting international trade in the global GHG estimation lead to an incomplete understanding of emissions nationally and undermine the emissions reduction targets



(e.g. Davis and Caldeira 2010, Peters *et al* 2012, Weinzettel *et al* 2013, Peters and Hertwich 2008, Scott and Barrett 2015, Athanassiadis *et al* 2016).

A number of studies have examined another type of GHG accounting, *consumption*-based accounting (figure 1), which allocates emissions to the final consumers (e.g. Barrett *et al* 2013, Peters *et al* 2011, Su and Ang 2010, Chen and Chen 2011, Caro *et al* 2014a, Su and Ang 2011, Gavrilova and Vilu 2012, Marin *et al* 2012, Caro *et al* 2015). It considers emissions embodied in local production and global trade, which are thought to better reflect the actual geographical distribution of emissions characteristic of international trade (e.g. Caro *et al* 2015). For instance, consumption-based accounting revealed that more than 30% of emissions from the UK and France were unaccounted for under the production-based accounting (Davis and Caldeira 2010). As such, it has been suggested that using production-based accounting to estimate emission from a city is ‘insufficient and even misleading’ (Athanassiadis *et al* 2016).

The objective of this study is to evaluate the importance of using consumption-based accounting in cities with limited local production like Hong Kong. Food consumption, especially livestock products, have been identified as a significant contributor to anthropogenic GHG emissions, accounting for 7%–20% of the total emissions depending on the accounting method and system boundary (Steinfeld *et al* 2006, Gerber *et al* 2013, Rojas-Downing *et al* 2017). GHG emissions associated with animal production originate mainly from land use change (carbon dioxide), enteric fermentation (methane) and manure management (nitrous oxide) (FAO 2011). Caro *et al* (2014b) estimated that 32.8 Megatonnes CO₂-equivalent (Mt CO₂-e) were embodied in international traded livestock between 1990 and 2010. Here, we use a life cycle assessment (LCA) approach to highlight the contribution of livestock emissions on the city’s consumption-based emissions and evaluate the mitigation potential of a low-meat diet. To assess the

consumption-based GHG emissions in meat and dairy, a hybrid of input-output analysis and life cycle assessment was used, the former one focusing on the economic and the latter on the emissions in production process (Andrade *et al* 2018, Jones *et al* 2016, Peters 2008, Davis and Caldeira 2010, Su and Ang 2010, 2011, Wiebe *et al* 2012, Athanassiadis *et al* 2016).

Hong Kong is an excellent case study to explore the complexity of livestock emissions and consumption emissions. Hong Kong is a net importer of goods and GHG emissions, ranked second worldwide with respect to the net import of GHG emissions per capita with 9.2 tonnes of CO₂-equivalent per capita per year for a total of 64 Mt CO₂-e imported in 2004 (Davis and Caldeira 2010). In contrast, Hong Kong’s government reported total GHG emissions of 41.6 Mt CO₂-e (5.7 tonnes CO₂-e per capita) in 2015 using a production-based accounting method (Environment Bureau 2017). Under production-based accounting, the two largest contributors of emissions are electricity generation (67%) and transportation (18%). This suggests that the reported emissions from Hong Kong’s government are considerably lower than those included from international trade.

Meat and dairy consumption in Hong Kong is the highest per capita in the world (500 g of meat and 281 g of dairy products per day). The city relies heavily on imports, with less than 1% of consumption sourced from local livestock (Agriculture Fisheries and Conservation 2017, FAO 2017). Furthermore, both the environmental and health impacts of excessive meat and dairy consumption has raised increasing concerns in recent studies (Friel *et al* 2009, Godfray *et al* 2010, Bodirsky *et al* 2014). Using a consumption-based accounting method, it was suggested that the European Union could reduce agricultural-related GHG emissions by 25%–40% from halving its meat, dairy and egg consumption (Westhoek *et al* 2014). Moreover, reducing the consumption of beef and mutton, ruminant meat, was found to be necessary for the European Union to achieve climate targets

(Bryngelsson *et al* 2016). We hypothesize that a similar situation is true for Hong Kong.

Here, we highlight the importance of consumption emissions in an import-driven city by quantifying meat and dairy consumption emissions in Hong Kong using an input-output analysis and LCA. We recalculated GHG emissions and targets to achieve COP21 goals in Hong Kong using consumption-based emissions accounting. Dietary change scenarios were also modelled to estimate the emissions reduction potential of changes in meat consumption under a consumption-based accounting system. This research can help to inform policy objectives to achieve COP21 goals.

2. Materials and methods

Meat- and dairy-based consumption emissions in Hong Kong were calculated using a combination of multiple data sets and analyses; (1) meat and dairy consumption was estimated from the Hong Kong government's trade data (Hong Kong Census and Statistics Department 2017), (2) embodied GHG emissions were calculated using detailed LCA analysis from the Food and Agriculture Organization of the United Nations (FAO), (3) input-output analysis was used to trace the emissions in international trade and (4) projected GHG emissions for 2016–2030 were obtained from the Hong Kong Environmental Protection Department (HKEPD).

2.1. Meat and dairy consumption data

Consumption data were extracted from the Hong Kong Merchandise Trade Statistic published by the Hong Kong government, which compiles trade data in Hong Kong and identifies the import, domestic export and re-export of goods (Hong Kong Census and Statistics Department 2017). Food intake and wastage are considered as consumption here. The monthly report is divided based on the type, origin, value and quantity of commodity, which follows Standard International Trade Classification Revision 4 (SITC Rev. 4). Meat products include fresh, chilled, processed meat, offal and related dairy products (Hong Kong Census and Statistics Department 2017). In total, 22 meat-related commodities were analyzed in this study. The commodities were aggregated into 8 major groups (beef, pork and poultry, sheep, egg, milk, cheese and yogurt). Domestic livestock supply was extracted from the Agriculture, Fisheries and Conservation Department (Agriculture Fisheries and Conservation 2017). The trade dataset identifies the location of production between Hong Kong and other countries, which was used to build an input-output analysis. The meat consumption was calculated by summing annual amount of imports and local livestock supply, and subtracting the domestic export and re-export for each type of meat. All meat consumption is expressed in kilograms (kg). The conversion of heads of live animal

to kg were done according to the average weight of livestock (pork: 80 kg; cattle: 450 kg; poultry: 0.185 kg; USDA Foreign Agricultural Service 2015).

2.2. Greenhouse gas emissions using life cycle assessment

The Global Livestock Environmental Assessment Model (GLEAM) developed by the FAO was used to quantify GHG emissions. Emissions in the supply chains from land use change, livestock production, and processing and transportation to final retail are embodied in the exported product (Hristov *et al* 2013). GLEAM reports carbon emissions for different production systems and regions with respect to types of livestock (Opio *et al* 2013). It is a holistic model assessing the bio-physical process on livestock production using LCA (Gerber *et al* 2013). The model captures the carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) from all major emissions activities in each stage of the livestock supply chain, such as feed and animal production, processing and transport (figure 2). The dataset includes a range of livestock such as cattle, chicken, pigs, buffalos, goats and sheep. This model was previously used in the FAO report on ruminant, non-ruminant and dairy-sector emissions (Macleod *et al* 2013, Gerber *et al* 2010, Opio *et al* 2013). GHG emissions are quantified according to the IPCC guidelines as CO₂-e using 100 years global warming potential, where carbon dioxide represents one global warming potential, nitrous oxide 298 CO₂-e and methane 34 CO₂-e (IPCC 2006). Additionally, GLEAM estimates the emissions intensity per protein of meat products in different regions, which is expressed as kg of CO₂-e per kg of protein (kg CO₂-e · kg protein⁻¹). Hong Kong's livestock consumption inventory was divided into the origin countries to consider the regional differences in production methods and energy used. In order to compare the GHG emissions between various meat and dairy products, edible protein was used as the standard unit for carbon intensity (Flachowsky and Kamphues 2012). The meat consumption was expressed as protein per kilogram of edible product, assuming 0.19 kg protein/kg edible product (de Vries and de Boer 2010).

Combining the trade balance and LCA, we calculated emissions in the bilateral trade for livestock products in Hong Kong. Therefore, the GHG emissions from meat and dairy consumption were estimated by summing the product of consumption, emissions intensity derived from GLEAM and protein mass:

$$E = \sum M_i \times P_i \times I_i \quad (1)$$

where E represents GHG emissions (kg CO₂-e), M is the consumption of meat and dairy products in weight (kg), P is the protein factor (kg protein · kg⁻¹) and I is the emissions intensity (kg CO₂-e · kg protein⁻¹), summed for each product i .

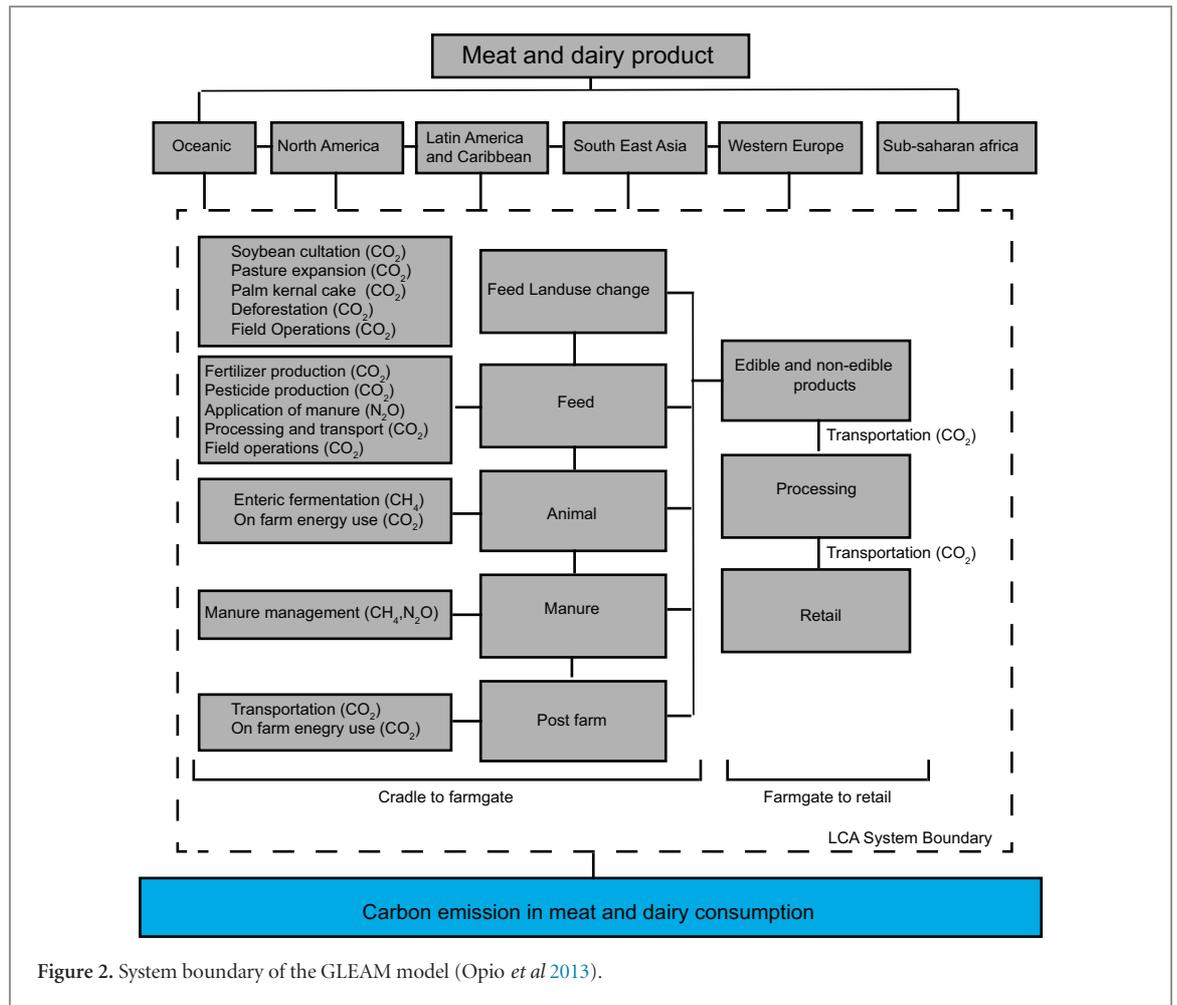


Figure 2. System boundary of the GLEAM model (Opio *et al* 2013).

To compare the relatively high meat consumption and the associated emissions in Hong Kong, we also present an input-output analysis and LCA for the United Kingdom (UK), which we consider as a typical western diet. Like those in Hong Kong, western dietary habits are also often characterized by an over-consumption of animal-based products (Röös *et al* 2016). Garnett (2007) quantified the livestock sectors' contribution on UK's consumption GHG emissions with a similar method, which allowed direct comparison with Hong Kong. It should be noted that no uncertainty on the input-output data is available and thus it is not possible to assess the accuracy of the calculated emission values. However, this is usually the case for such calculation as we followed a well-established, state-of-the-art, methodology (e.g. Wiedmann *et al* 2011, Caro *et al* 2015) and thus our results can be compared to similar study.

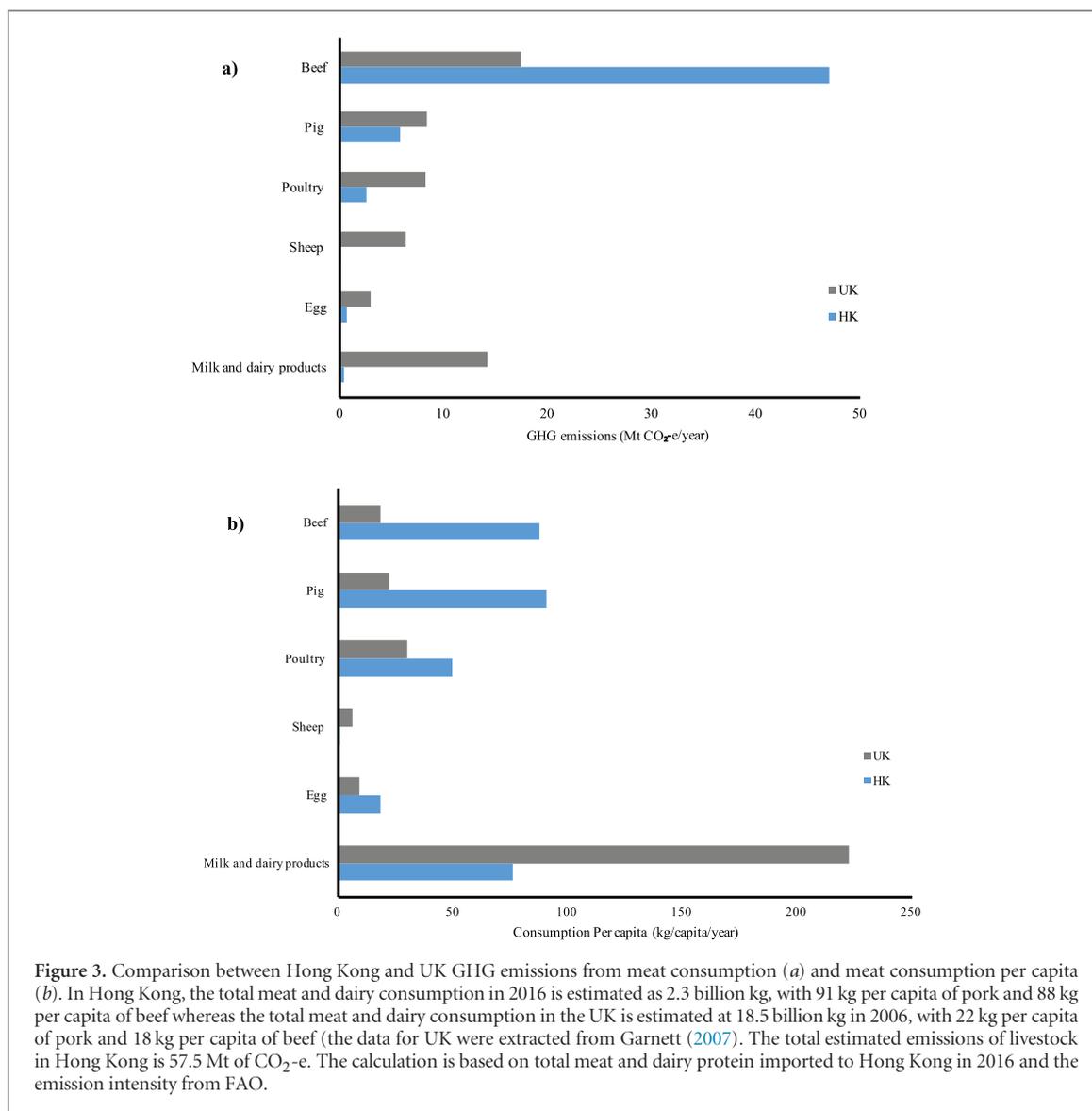
2.3. Projection of Hong Kong's emissions and new targets

Hong Kong's consumption-based emissions projection for 2016–2030 were calculated by summing the emissions from local production and trade (figure 1). The future trend was estimated using the population projection from 2016–2077 and constant per capita GHG emissions (Census and Statistics Department 2015,

Davis and Caldeira 2010). By keeping the reduction target percentage for 2020 and 2030 (20%, 26% to 36% respectively), new targets were set in accordance with the Paris Agreement (Environmental Bureau 2017).

2.4. Dietary change scenario

Dietary change scenarios were designed to investigate the mitigation potential of dietary change on GHG emissions. Here, we focused on meat consumption (beef, pig, poultry and sheep). Four scenarios were assessed as; 1) 25%, 2) 50%, and 3) 80% reduction in the consumption of meat relative to 2016 consumption in addition to four) a healthy diet in compliance with the nutritional guidelines of the Hong Kong Department of Health. These guidelines recommend an average daily intake of 180 g for meat, fish, egg and alternatives, in addition to two portions of milk and alternatives for a normal adult (equivalent to 480 ml of milk). Following the current diet composition, we defined the healthy diet scenario as 72 g of beef, 72 g of pork, 36 g of poultry, 133 g of cheese, 187 ml of milk, 3 g of yogurt per day (Department of Health 2015). It is assumed that the reduction of livestock consumption will proportionally reduce the livestock production in the exporting country. These scenarios were only tested considering a consumption-based accounting method as there are virtually no



GHG emissions related to the production of livestock in Hong Kong (~ 0.03 Mt CO₂-e).

3. Results

3.1. Livestock consumption and embodied emissions

Total meat and dairy consumption in Hong Kong was approximately 2.3 billion kilograms in 2016 ($992 \text{ g day}^{-1}/\text{capita}$), with pork and beef consumed the most (figure 3). Compared to the UK, Hong Kong consumed over nine times more beef and pork per person each day (Garnett 2007).

Using consumption-based accounting, we estimated that 57.5 Mt CO₂-e per year (7.8 tonnes CO₂-e per capita) can be attributed to Hong Kong's meat and dairy consumption. Beef (47 Mt CO₂-e) produced the highest total GHG emissions followed by pig (5.8 Mt CO₂-e) and poultry (2.5 Mt CO₂-e) (figure 3). Since the carbon intensity per protein of

beef is the highest (276 kg CO₂-e per kg of protein supplementary material, figure S1 available at stacks.iop.org/ERL/13/064005/mmedia), it translates to much higher meat and dairy consumption-derived GHG emissions per year in Hong Kong compared to the UK.

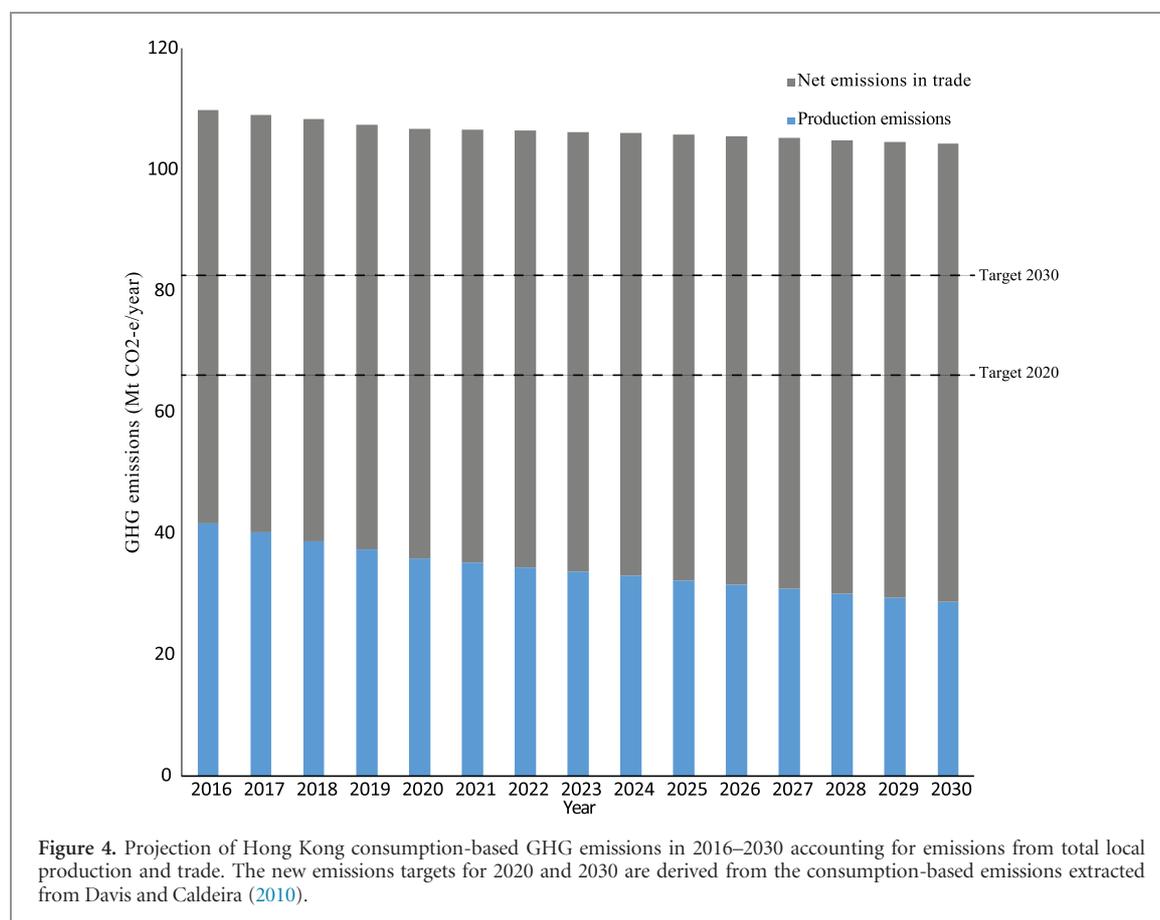
Hong Kong's is an import-oriented city where the local production is minimal (Harris *et al* 2012). As mentioned earlier, less than 1% of the meat and dairy products were produced in Hong Kong (USDA Foreign Agricultural Service 2016, FAO 2017, Agriculture Fisheries and Conservation (AFCD) 2017). In total, Hong Kong imported livestock products from 97 countries with the top three importers being Brazil, the US and China (supplementary material, figure S2). By calculating the embodied emissions of such imports, 57.5 Mt CO₂-e were outsourced to other countries, and are therefore missing from the Hong Kong's emissions inventory. From our estimation above, meat and dairy consumption (57.5 Mt CO₂-e) alone exceeds production emissions

Table 1. Comparison of the government-reported emissions and targets and the consumption-based emissions in Hong Kong.

Method	Category	Carbon emissions	Target 2020	Target 2030
Production-based	Total emissions	41.6	32.8	26.2
	Meat and dairy ^a	0.03	/	/
Consumption-based	Total emissions	109	82.4	65.9
	Meat and dairy	57.5	/	/

Note. All data are expressed as Mt CO₂-e per year.

^a Data from Environment Bureau (2017).



reported by Hong Kong government of 41.6 Mt CO₂-e in 2015 (table 1).

3.2. Projection of Hong Kong emissions for 2016–2030

Here, we projected Hong Kong's emissions for 2016–2030 using consumption-based accounting (figure 4). The emissions in trade contributed 62% of the total emissions. Moreover, consumption-based emissions are likely to increase due to the projected population growth (+9% from 2016–2030; Hong Kong Census and Statistics Department 2017), assuming per-capita consumption emissions remains constant (figure 4). Thus, despite the government actions to reduce production-based emissions, Hong Kong's total carbon emissions will only decrease by 11% from 2016–2030 if the emissions in trade are included. In

addition, the COP21 objectives would not be met (20% reduction of absolute emissions by 2020 and 26%–36% reduction by 2030 using 2005 as base year) if we consider the consumption-based data (figure 4). It is important to note that there is a difference between the absolute quantity of emissions if we consider only the production or if both local production and consumption are taken into account (figure 4). Therefore, we set new consumption-based reduction targets for 2020 and 2030 as 82.4 Mt CO₂-e and 65.9 Mt CO₂-e and 20.6 Mt CO₂-e respectively using 2005 as base year, which are two times higher than the production-based targets of 35.8 Mt CO₂-e by 2020 and 28.6 Mt CO₂-e by 2030 (table 1). Therefore, different emissions accounting may lead to different emission targets and policy. The new targets were applied to examine the mitigation potential of dietary change.

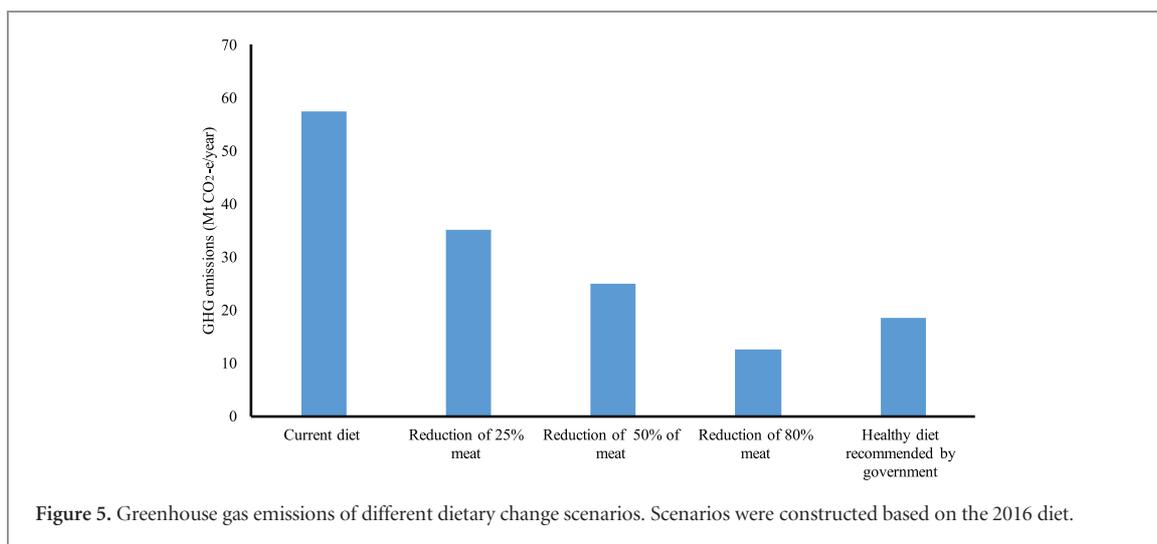


Figure 5. Greenhouse gas emissions of different dietary change scenarios. Scenarios were constructed based on the 2016 diet.

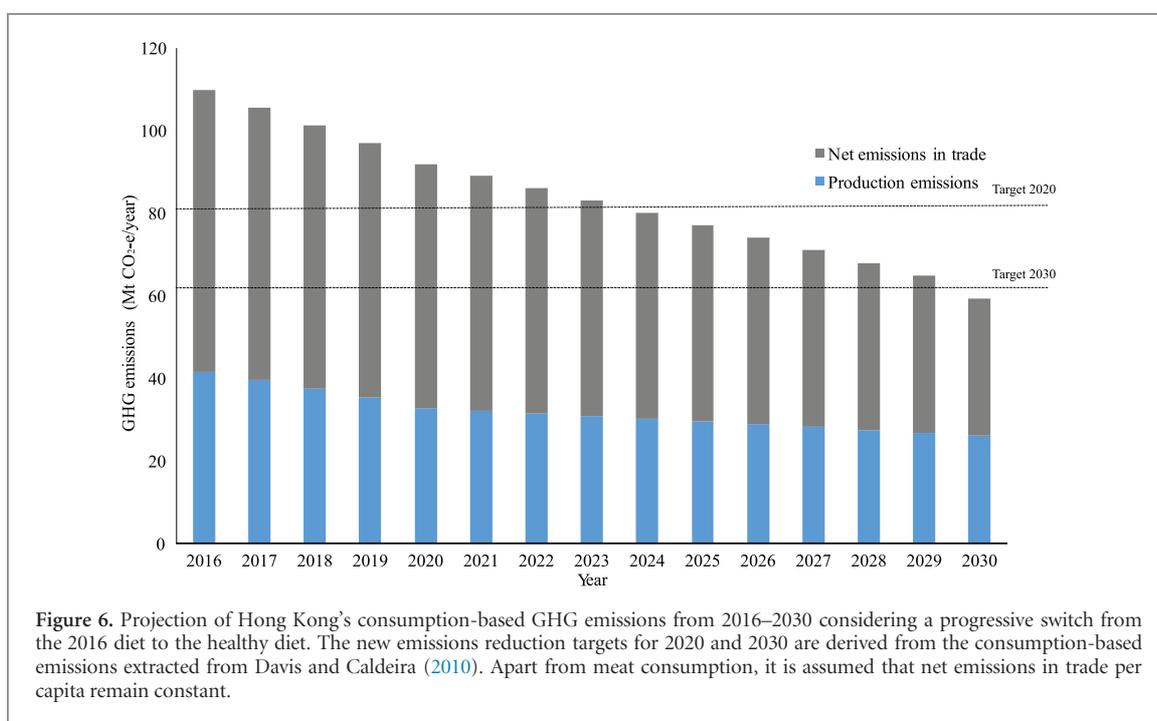


Figure 6. Projection of Hong Kong's consumption-based GHG emissions from 2016–2030 considering a progressive switch from the 2016 diet to the healthy diet. The new emissions reduction targets for 2020 and 2030 are derived from the consumption-based emissions extracted from Davis and Caldeira (2010). Apart from meat consumption, it is assumed that net emissions in trade per capita remain constant.

3.3. Emission reduction scenario based on dietary change

The mitigation potential of dietary change scenarios was examined based on current diet and reduction scenarios. Diets with 25%, 50% and 80% reduction of meat consumption could reduce 38% to 76% of livestock-related GHG emissions in Hong Kong using consumption-based accounting (figure 5). In addition, our results show that a healthy diet saves approximately 40 Mt CO₂-e, which represents a reduction of around 67% compared to the current diet. The healthy diet scenario would require meat reduction per capita from 664 g d⁻¹ to 180 g d⁻¹ (supplementary material, figure S4). Therefore, dietary changes can manifest as considerable reductions in Hong Kong's GHG emissions. When combined with the projected consumption emissions that include

population growth and a potential progressive shift towards healthy diet, we project a 43% decrease in total consumption-based emissions in Hong Kong from 2016–2030 (from 109 Mt CO₂-e to 62 Mt CO₂-e; figure 6). If Hong Kong shifts to the healthy diet scenario by 2030, we forecast that consumption emissions in Hong Kong will meet the 2030 target (figure 6).

4. Discussion

4.1. A meat-heavy diet and its impact on consumption-based emissions in Hong Kong

We estimated that an average Hong Kong inhabitant consumed about 664 g and 258 g of meat and dairy products daily in 2016 (figure 3), which is consistent with previous reports (FAO 2017). Hong Kong's

relatively high meat consumption can partially explain its large consumption-based emissions. The estimated emissions from livestock consumption (57 Mt CO₂-e) are approximately 50% of total consumption emissions in Hong Kong (103 Mt CO₂-e) extracted from Davis and Caldeira (2010). While this number may seem unusually large, it is important to note that the GLEAM model used in this study includes a detailed life cycle assessment and the emissions associated with land use change (figure 2), as opposed to Davis and Caldeira (2010). This means that numerous sources of emissions listed under ‘meat and dairy’ consumption in our study were listed under other rubrics (e.g. transport, land use, production of goods, etc.) in Davis and Caldeira (2010). Therefore, we believe that the total amount should still be similar, as our estimate simply enlarges the boundary of what is considered ‘meat and dairy’ consumption. Moreover, we account for both food intake and wastage as consumption, which may result in a higher consumption than other self-reported meal intake studies. Our results highlight the importance of consumption-based emissions accounting in Hong Kong, as the population of Hong Kong consumes an inordinate amount of mostly-imported meat.

4.2. Potential carbon leakage due to meat consumption

Total consumption-based GHG emissions in Hong Kong were estimated to be 109 Mt CO₂-e in 2016, which is more than twice the emissions reported by the government (41.6 Mt CO₂-e) using production-based accounting (figure 6). This demonstrates that the government underestimates GHG emissions by 62% because it fails to recognize the emissions associated in trade. This large difference is consistent with Energy and Climate Change Committee (2012), in which it was estimated that Hong Kong’s actual GHG emissions should be approximately 80% greater than production-based GHG emissions. Similar results were also reported in Hertwich and Peters (2009), whereby estimates of Hong Kong’s consumption-based emissions in 2001 were 4 times higher than the government-reported emissions. This large discrepancy shows that the emissions inventory derived from production-based accounting does not provide a complete analysis in cities with considerable emissions associated with trade.

The large gap between consumption-based and production-based emissions is due to the high carbon intensity of GDP and trade imbalances (Davis and Caldeira 2010). Even within China, cities with higher GDP per capita, such as Shanghai, generally have higher consumption-based emissions than production-based emissions compared to less developed cities, such as Shijiazhuang (Mi *et al* 2016). Similar patterns were also observed in Southeast Asia, where both Hong Kong and Singapore behave as net importers with limited local resources and high GDPs. Therefore, most of the carbon emissions in Hong Kong

and Singapore are captured in international trade (Davis and Caldeira 2010). By tracing the emissions from meat consumption, we demonstrate that Hong Kong outsources considerable emissions to producer countries, yet these emissions are not allocated to Hong Kong. Therefore, a weak carbon leakage may occur because of the increasing demand driven by population growth in Hong Kong. Kanemoto *et al* (2014) observed that many developed countries such as Japan and US meet the Kyoto Protocol targets by outsourcing their emissions. The missing emissions embodied in trade will potentially undermine the climate change targets and policy, highlighting the need for more effective emissions accounting.

Currently, countries follow the IPCC guidelines to report their emissions inventory (Dahal and Niemelä 2017, European Environment Agency 2013). Hong Kong also follows the IPCC guidelines as its emissions are included within China’s inventory (Harris *et al* 2012). Territorial-based inventories neither allocate GHG emissions embodied in import beyond city borders to the consumer countries nor subtract the GHG emissions from export in the producer country (Dahal and Niemelä 2017). In order to navigate the existing caveats of the territorial-based inventory and estimate the emissions embodied in trade, Hong Kong should use a consumption-based accounting approach to calculate its GHG inventory (e.g. Lenzen *et al* 2012, Steckel *et al* 2010, Caro *et al* 2014a, Gavrilova and Vilu 2012, Marin *et al* 2012, Davis and Caldeira 2010).

4.3. The mitigation potential of dietary change on consumption emissions

In the scope of the COP21 agreements, Hong Kong committed to China’s target of reducing 20% on its absolute carbon emissions by 2020 and 26%–36% by 2030, relative to 2005 levels (Environmental Bureau 2017). In 2017, the government released Hong Kong’s Climate Action Plan 2030+, which proposed policies in reducing coal-fire electricity and increasing energy efficiency. The report focused on the emissions targets and estimated a decline in Hong Kong’s GHG emissions (figure 6) (Environmental Bureau 2017). However, when the emissions in trade are taken into account, our results demonstrate that Hong Kong no longer achieves the target despite government’s mitigation efforts (figure 6). Therefore, the existing emissions inventory could mislead policy-makers.

Therefore, we examined the potential of using consumption-based targets and dietary change to meet Hong Kong’s COP21 objective. By addressing the consumption-based targets, we formulated new targets for 2020 and 2030 to 82.4 Mt CO₂-e and 65.9 Mt CO₂-e. At the same time, we applied dietary change scenarios to estimate the mitigation potential of a reduction in meat consumption. In line with other studies, we found that decreasing meat consumption can manifest in extensive GHG emissions

reductions (De Boer *et al* 2014, Hallström *et al* 2014, Tilman and Clark 2014, Springmann *et al* 2016). Our results demonstrated that following the protein intake recommended by the government (healthy diet) can reduce livestock-related emissions by 67% (figure 6). By comparing different scenarios, adopting government-recommended nutritional guidelines is likely the best option to optimize both environmental and human health. Hence, increasing awareness of consumer choices and dietary habits on the environment is very important as such personal decisions may affect the producer country and even global climate change. In addition, such dietary changes will also yield health benefits for the consumer (Friel *et al* 2009). High meat consumption can notably increase the risk of obesity and cardiovascular disease (Micha *et al* 2010, Koeth *et al* 2013, WHO 2003), and in the case of red meat, the risk of colorectal cancer (WCRF/AICR 2007, O’Keefe 2016).

5. Conclusions

Using Hong Kong as a case study, this research demonstrates the differences between consumption and production-based emissions accounting. While the existing production-based accounting framework provides technical and comparable results, it does not capture the emissions embodied in trade, especially in a city with a high dependency on import. Given the large gap between conventional production-based emissions accounting and consumption-based emissions accounting, future work should focus on building a comprehensive consumption-based inventory for Hong Kong and other import-dependent cities such as Singapore. As the Paris agreement leaves flexibility for domestic-driven policies to achieve global climate goals, it is worth discussing the possibility to complement the existing GHG reporting methodology to better reflect the contribution of GHG emissions in import-reliant large cities. Moreover, our analysis indicates that Hong Kong’s trade-related emissions are partially driven by the demand of consumers for a heavy-meat diet. Therefore, the role of consumer behavior in reducing global GHG emissions is important to consider. By adopting new, climate-friendly dietary habits, Hong Kong consumers can play a non-trivial role in emissions reductions. Incentivizing the public to participate in the global effort to reduce GHG emissions may prove to be key in addressing climate change and, in the case of Hong Kong, improving public health by reducing meat consumption.

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References

- Agriculture Fisheries and Conservation 2017 Hong Kong: The Facts Agriculture and Fisheries
- Andrade J C S, Dameno A, de Andrés Almeida J M, Pérez J and Lumbreras J 2018 Implementing city-level carbon accounting: a comparison between Madrid and London *J. Clean. Prod.* **172** 795–804
- Athanassiadis A, Christis M, Bouillard P, Vercauteren A, Crawford R H and Khan A Z 2016 Comparing a territorial-based and a consumption-based approach to assess the local and global environmental performance of cities *J. Clean. Prod.* **173** 112–23
- Barrett J, Peters G, Wiedmann T, Scott K, Lenzen M, Roelich K and Le Quéré C 2013 Consumption-based GHG emission accounting: a UK case study *Clim. Policy* **13** 451–70
- Bastianoni S, Caro D, Borghesi S and Pulselli F M 2014 The effect of a consumption-based accounting method in national GHG inventories: a trilateral trade system application *Front. Energy Res.* **2** 1–8
- Bodirsky B L *et al* 2014 Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution *Nat. Commun.* **5** 1–7
- De Boer J, Schöler H and Aiking H 2014 ‘Meatless days’ or ‘less but better’? Exploring strategies to adapt Western meat consumption to health and sustainability challenges *Appetite* **76** 120–8
- Bryngelsson D, Wirsenius S, Hedenus F and Sonesson U 2016 How can the EU climate targets be met? A combined analysis of technological and demand-side changes in food and agriculture *Food Policy* **59** 152–64
- Caro D, Bastianoni S, Borghesi S and Pulselli F M 2014a On the feasibility of a consumer-based allocation method in national GHG inventories *Ecol. Indic.* **36** 640–3
- Caro D, LoPresti A, Davis S J, Bastianoni S and Caldeira K 2014b CH₄ and N₂O emissions embodied in international trade of meat to *Environ. Res. Lett.* **9** 13
- Caro D, Rugani B, Pulselli F M and Benetto E 2015 Implications of a consumer-based perspective for the estimation of GHG emissions: the illustrative case of Luxembourg *Sci. Total Environ.* **508** 67–75
- Census and Statistics Department 2015 Hong Kong population projections 2015–2064
- Chen Z M and Chen G Q 2011 Embodied carbon dioxide emission at supra-national scale: a coalition analysis for G7, BRIC, and the rest of the world *Energy Policy* **39** 2899–909
- Dahal K and Niemelä J 2017 Cities’ greenhouse gas accounting methods: a study of Helsinki, Stockholm, and Copenhagen *Climate* **5** 31
- Davis S J and Caldeira K 2010 Consumption-based accounting of CO₂ emissions *Proc. Natl Acad. Sci.* **107** 5687–92
- Department of Health 2015 Meat, Fish, Egg, Milk and Alternatives

- Druckman A, Bradley P, Papathanasopoulou E and Jackson T 2008 Measuring progress towards carbon reduction in the UK *Ecol. Econ.* **66** 594–604
- Energy and Climate Change Committee 2012 Consumption-based emissions reporting *Twelfth Report of session 2010–2012* (London: House of Commons, Energy and Climate Committee) (www.publications.parliament.uk/pa/cm201012/cmselect/cmenergy/.../1646.pdf)
- Environment Bureau 2017 Greenhouse gas emissions in Hong Kong by sector 2017
- Environmental Bureau 2017 Hong Kong's Climate Action Plan 2030+
- European Environment Agency 2013 European Union CO₂ emissions: different accounting perspectives
- FAO 2017 FAOSTAT
- FAO 2011 *State of Food and Agriculture 2010–2011* vol 2 (Rome: FAO)
- Flachowsky G and Kamphues J 2012 Carbon footprints for food of animal origin: what are the most preferable criteria to measure animal yields? *Animals* **2** 108–26
- Friel S *et al* 2009 Public health benefits of strategies to reduce greenhouse-gas emissions: food and agriculture *Lancet* **374** 2016–25
- Garnett T 2007 Meat and dairy production and consumption: exploring the livestock sector's contribution to the UK's greenhouse gas emissions and assessing what less greenhouse gas intensive systems of production and consumption might look like *Food and Climate Research Network, Centre for Environmental Strategy* (Guildford: University of Surrey)
- Gavrilova O and Vilu R 2012 Production-based and consumption-based national greenhouse gas inventories: an implication for Estonia *Ecol. Econ.* **75** 161–73
- Gerber P J, Steinfeld H, Henderson B, Mottet A, Opio C, Dijkman J, Falcucci A and Tempio G 2013 *Tackling Climate Change Through Livestock - A Global Assessment of Emissions and Mitigation Opportunities* (Rome: FAO)
- Gerber P, Vellinga T, Opio C, Henderson B and Steinfeld H 2010 *Greenhouse Gas Emissions from the Dairy Sector* (Rome: FAO) (www.fao.org/docrep/012/k7930e/k7930e00.pdf)
- Godfray H C J, Crute I R, Haddad L, Lawrence D, Muir J F, Nisbett N, Pretty J, Robinson S, Toulmin C and Whiteley R 2010 The future of the global food system *Phil. Trans. R. Soc. B Biol. Sci.* **365** 2769–77
- Hallström E, Rööf E and Börjesson P 2014 Sustainable meat consumption: a quantitative analysis of nutritional intake, greenhouse gas emissions and land use from a Swedish perspective *Food Policy* **47** 81–90
- Harris P G, Chow A S Y and Symons J 2012 Greenhouse gas emissions from cities and regions: international implications revealed by Hong Kong *Energy Policy* **44** 416–24
- Hertwich E G and Peters G P 2009 Carbon footprint of nations: a global, trade-linked analysis *Environ. Sci. Technol.* **43** 6414–20
- Hong Kong Census and Statistics Department 2017 Hong Kong Merchandise Trade Statistics Domestic Exports and Re-exports
- Hristov A N *et al* 2013 *Mitigation of Greenhouse Gas Emissions in Livestock Production—Review of Technical Options for non-CO₂ Emissions* ed P J Gerber, B Henderson and H P S Makkar (FAO Animal Production and Health Paper No. 177) (Rome: FAO)
- IPCC 2006 *IPCC guidelines for National Greenhouse Gas Inventories* (Geneva: IPCC) (www.ipcc-nggip.iges.or.jp/public/2006gl/)
- Jones A D, Hoey L, Blesh J, Miller L, Green A and Shapiro L F 2016 A systematic review of the measurement of sustainable diets *Adv. Nutr. An Int. Rev. J.* **7** 641–64
- Kanemoto K, Moran D, Lenzen M and Geschke A 2014 International trade undermines national emission reduction targets: new evidence from air pollution *Glob. Environ. Change* **24** 52–9
- Koeth R A *et al* 2013 Intestinal microbiota metabolism of l-carnitine, a nutrient in red meat, promotes atherosclerosis *Nat. Med.* **19** 576–85
- Lenzen M, Moran D, Kanemoto K, Foran B, Lobefaro L and Geschke A 2012 International trade drives biodiversity threats in developing nations *Nature* **486** 109–12
- Lenzen M, Pade L L and Munksgaard J 2004 CO₂ multipliers in multi-region input-output models *Econ. Syst. Res.* **16** 389–412
- Macleod M, Gerber P J, Opio C, Falcucci A, Tempio G, Henderson B, Mottet A and Steinfeld H 2013 *Greenhouse Gas Emissions from Pig and Chicken Supply Chains—A Global Life Cycle Assessment* (Rome: FAO)
- Marin G, Mazzanti M and Montini A 2012 Linking NAMEA and Input output for 'consumption vs. production perspective' analyses. Evidence on emission efficiency and aggregation biases using the Italian and Spanish environmental accounts *Ecol. Econ.* **74** 71–84
- Mi Z, Zhang Y, Guan D, Shan Y, Liu Z, Cong R, Yuan X C and Wei Y M 2016 Consumption-based emission accounting for Chinese cities *Appl. Energy* **184** 1073–81
- Micha R, Wallace S K and Mozaffarian D 2010 Red and processed meat consumption and risk of incident coronary heart disease, stroke, and diabetes mellitus: a systematic review and meta-analysis *Circulation* **121** 2271–83
- O'Keefe S J D 2016 Diet, microorganisms and their metabolites, and colon cancer *Nat. Rev. Gastroenterol. Hepatol.* **13** 691–706
- Opio C, Gerber P, Mottet A, Falcucci A, Tempio G, MacLeod M, Vellinga T, Henderson B and Steinfeld H 2013 *Greenhouse Gas Emissions from Ruminant Supply Chains—A Global Life Cycle Assessment* (Rome: FAO)
- Peters G P 2008 From production-based to consumption-based national emission inventories *Ecol. Econ.* **65** 13–23
- Peters G P, Davis S J and Andrew R 2012 A synthesis of carbon in international trade *Biogeosciences* **9** 3247–76
- Peters G P and Hertwich E G 2008 Post-Kyoto greenhouse gas inventories: production versus consumption *Clim. Change* **86** 51–66
- Peters G P, Minx J C, Weber C L and Edenhofer O 2011 Growth in emission transfers via international trade from 1990–2008 *Proc. Natl Acad. Sci.* **108** 8903–8
- Rogelj J, Den Elzen M, Höhne N, Fransen T, Fekete H, Winkler H, Schaeffer R, Sha F, Riahi K and Meinshausen M 2016 Paris Agreement climate proposals need a boost to keep warming well below 2 °C *Nature* **534** 631–9
- Rojas-Downing M M, Nejadhashemi A P, Harrigan T and Woznicki S A 2017 Climate change and livestock: impacts, adaptation, and mitigation *Clim. Risk Manage.* **16** 145–63
- Rööf E, Patel M, Spångberg J, Carlsson G and Rydhmer L 2016 Limiting livestock production to pasture and by-products in a search for sustainable diets *Food Policy* **58** 1–13
- Schmitz C, Biewald A, Lotze-Campen H, Popp A, Dietrich J P, Bodirsky B, Krause M and Weindl I 2012 Trading more food: implications for land use, greenhouse gas emissions, and the food system *Glob. Environ. Change* **22** 189–209
- Scott K and Barrett J 2015 An integration of net imported emissions into climate change targets *Environ. Sci. Policy* **52** 150–7
- Springmann M, Godfray H C J, Rayner M and Scarborough P 2016 Analysis and valuation of the health and climate change cobenefits of dietary change *Proc. Natl Acad. Sci.* **113** 4146–51
- Steckel J C, Kalkuhl M and Marschinski R 2010 Should carbon-exporting countries strive for consumption-based accounting in a global cap-and-trade regime?: A letter *Clim. Change* **100** 779–86
- Steinfeld H, Gerber P, Wassenaar T, Castel V, Rosales M and De Haan C 2006 Livestock's Long Shadow: Environmental Issues and Options *FAO pp 1–377* ([ftp://ftp.fao.org/docrep/fao/010/A0701E/A0701E00.pdf](http://ftp.fao.org/docrep/fao/010/A0701E/A0701E00.pdf))
- Steininger K, Lininger C, Droege S, Roser D, Tomlinson L and Meyer L 2014 Justice and cost effectiveness of consumption-based versus production-based approaches in the case of unilateral climate policies *Glob. Environ. Change* **24** 75–87
- Su B and Ang B W 2010 Input-output analysis of CO₂ emissions embodied in trade: the effects of spatial aggregation *Ecol. Econ.* **70** 10–8

- Su B and Ang B W 2011 Multi-region input-output analysis of CO₂ emissions embodied in trade: the feedback effects *Ecol. Econ.* **71** 42–53
- Tilman D and Clark M 2014 Global diets link environmental sustainability and human health *Nature* **515** 518–22
- UNFCCC 2015 *Adoption of the Paris Agreement*
- USDA Foreign Agricultural Service 2016 *Hong Kong Livestock and Products Annual Report 2016*
- USDA Foreign Agricultural Service 2015 *Hong Kong Livestock and Products Annual Report 2015*
- de Vries M and de Boer I J M 2010 Comparing environmental impacts for livestock products: a review of life cycle assessments *Livest. Sci.* **128** 1–11
- World Cancer Research Fund/American Institute of Cancer Research 2007 *Food, Nutrition, Physical Activity, and the Prevention of Cancer: a Global Perspective* (Washington, DC: AICR)
- Weinzettel J, Hertwich E G, Peters G P, Steen-Olsen K and Galli A 2013 Affluence drives the global displacement of land use *Glob. Environ. Change* **23** 433–8
- Westhoek H, Lesschen J P, Rood T, Wagner S, De Marco A, Murphy-Bokern D, Leip A, van Grinsven H, Sutton M A and Oenema O 2014 Food choices, health and environment: effects of cutting Europe's meat and dairy intake *Glob. Environ. Change* **26** 196–205
- WHO 2003 Diet, nutrition and the prevention of chronic diseases *World Health Organ. Tech. Rep. Ser.* **916** 1–8
- Wiebe K S, Bruckner M, Giljum S and Lutz C 2012 Calculating energy-related CO₂ emissions embodied in international trade using a global input-output model *Econ. Syst. Res.* **24** 113–39
- Wiedmann T, Wilting H C, Lenzen M, Lutter S and Palm V 2011 Quo vadis MRIO? methodological, data and institutional requirements for multi-region input-output analysis *Ecol. Econ.* **70** 1937–45