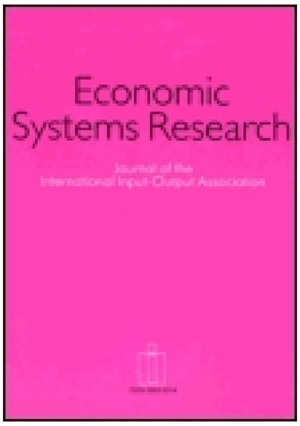

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INPUT-OUTPUT ANALYSIS AND CARBON FOOTPRINTING: AN OVERVIEW OF APPLICATIONS

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INPUT–OUTPUT ANALYSIS AND CARBON FOOTPRINTING: AN OVERVIEW OF APPLICATIONS

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This article provides an overview of how generalised multi-regional input–output models can be used for carbon footprint applications. We focus on the relevance and suitability of such evidence to inform decision making. Such an overview is currently missing. Drawing on UK results, we cover carbon footprint applications in seven areas: national emissions inventories and trade, emission drivers, economic sectors, supply chains, organisations, household consumption and lifestyles as well as sub-national emission inventories. The article highlights the multiple uses of generalised multi-regional input–output models for carbon footprinting and concludes by highlighting important avenues for future research.

Keywords: Multi-regional input–output model; Carbon footprint; Emission inventory; Trade; Consumption-based accounting

1 INTRODUCTION

Carbon Footprint (CF) has become a catchphrase in the public climate change discussion, attracting the attention of consumers, business, governments, NGOs and international organisations alike (Hertwich and Peters, 2009). Despite its ubiquitous use, a clear and commonly accepted definition of CF is missing (Wiedmann and Minx, 2008).

In agreement with the majority of the literature, we understand the CF as a purely consumption-based concept. In particular, we define CF as the direct and indirect greenhouse gas emissions – measured in tonnes of carbon dioxide equivalent using a 100-year horizon (Fuglestvedt et al., 2003) – required to satisfy a given consumption. This can be a product,

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an activity or a set of products or activities. The temporal boundary of the CF assessment will generally depend on the subject: for products it is the full life cycle, for other assessments it is usually a year, as this is the standard time frame for national and corporate financial accounting.

Given the recent interest in the CF concept, it is not surprising that many people seem to think that the CF concept is something new. While the term certainly is, the methodological frameworks to calculate CFs have been developed over a long period of time (Finkbeiner, 2009). A carbon footprint of a product, for example, is a necessary by-product of any life-cycle assessment (Weidema et al., 2008).

Products and process-based life-cycle assessment have received the most attention in the CF discussion so far. However, there are a variety of other relevant CF applications that require methodologies other than process analysis. With its focus on the direct and indirect emissions associated with a particular final demand, CFs are very intuitive for input–output (IO) practitioners. The methodological framework for input–output analysis was established in the 1970s (Daly, 1968; Leontief, 1970; Leontief and Ford, 1971; Victor, 1972) and at least since the late 1980s we find regular CF applications in the literature – albeit under different names.

In this article we provide an overview of IO applications of CFs using example evidence, mainly from the United Kingdom. Even though any list of applications within the confined space of a journal article will be necessarily incomplete, we have tried to cover some of the most common and useful ones. We focus on real-world applications and their policy relevance. For non-IO specialists this paper might serve as an introduction to allow an informed entry into the field without being sidetracked by technicalities. For experienced researchers it is a welcome reference point and provides additional momentum to the discussion of the particular contribution of IO methods to this emerging field of CF analysis.

The paper is structured in the following way. The next section provides a general introduction to IO modelling in the context of CFs. In Section 3 we introduce and discuss various CF applications in the following areas:

- national emission inventories and trade;
- emission drivers;
- products and sectors;
- supply chains;
- organisations;
- lifestyles; and
- sub-national emission accounting;

Section 4 closes with a discussion and identifies avenues for future research.

2 METHODOLOGY

Generalised input–output models (IOMs) for the analysis of environmental flows are well established in the literature (Daly, 1968; Ayres and Kneese, 1969; Leontief, 1970; Leontief and Ford, 1971; Isard et al., 1972; Victor, 1972). In principle, an environmentally extended input–output framework links environmental pressure data (e.g. direct emissions of greenhouse gases) for all economic sectors in an economy with financial transactions between these sectors (intermediate demand) and allows for an allocation of these pressures to the consumption of product groups (final demand) (Miller and Blair, 2009). It is not only the detailed and complete depiction of activities throughout an economy, but also the ability of IOMs to assess the direct and indirect environmental flows triggered by a given final demand that has attracted the attention of researchers and practitioners for decades.

Carbon footprint analysis aims to quantify all direct and indirect (embodied) GHG emissions caused by a given final demand. This requires the inclusion of emissions released worldwide to enable the production of the goods and services finally consumed and thus makes input–output analysis a suitable methodology. For simplification, generalised IOMs have frequently assumed domestic and import production to be identical and performed the analysis based only on national input–output tables and environmental accounts (the 'single-region assumption', see Turner et al., 2007; Wiedmann et al., 2007a). However, this is a restrictive assumption, which can introduce considerable error into CF analysis (Lenzen et al., 2004; Andrew et al., 2009; Hertwich and Peters, 2009).

Despite the wide range of applications covered, we only use evidence from generalised multi-regional input–output (MRIO) models here, which overcome the single-region assumption. With increasing availability of international IO databases and environmental extensions[1] such studies have become easier to undertake (see Wiedmann, 2009 for an overview). MRIO models can be set up in different ways depending on the purpose of the analysis and data availability. This issue is comprehensively dealt with in this special issue in the contribution by Andrew et al. (2009). Otherwise for a technical overview the reader is referred to Lenzen et al. (2004), Munksgaard et al. (2005, 2009), Peters (2008a), or Wiedmann et al. (2009b). Limitations of IO analysis are discussed, for example, in Suh et al. (2004), Wiedmann et al. (2006) or Minx et al. (2008a).

3 CARBON FOOTPRINT APPLICATIONS

3.1 The Carbon Footprint of Nations and Trade

A widespread environmental application of generalised IOMs is the estimation of the CF of nations (e.g. Munksgaard and Pedersen, 2001; Ahmad and Wyckhoff, 2003; Lenzen et al., 2004; Munksgaard et al., 2005, 2009; Peters and Hertwich, 2006a, 2008a; Wiedmann et al., 2007b; Hertwich and Peters, 2009; Peters et al., 2009). National carbon footprinting often goes hand in hand with the analysis of a country's carbon (GHG) trade balance or carbon leakage assessments (see below).

From a methodological point of view, IO analysis has remained largely unchallenged in the literature for the purpose of calculating national CFs (Wiedmann et al., 2009a). Only few authors have used other methods to estimate a nation's CF. However, they usually do not account comprehensively for the trade inter-linkages between regions or allocate

[1] For example, from the Global Trade Analysis Project (GTAP, http://www.gtap.agecon.purdue.edu), the European project EXIOPOL (http://www.feem.it/Feem/Pub/Programmes/Sustainability+Indicators+and+Environmental+Valuation/Activities/200703-EXIOPOL.htm) or the Organisation for Economic Co-operation and Development (OECD, http://www.oecd.org).

GHGs consistently from the global production of goods and services to consumption activities in a particular country (e.g. Harris, 2001; Helm et al., 2007; Wang and Watson, 2008).

In the international climate policy context, CFs of nations have been discussed in the wider field of responsibility for anthropogenic climate change and its implications for target setting. This discussion was prominently launched in the Brazilian Proposal (see den Elzen et al., 2005).[2] CFs are closely related to the question of whether a country's production or consumption should be the basis for this responsibility assessment (see the IO-based studies by Kondo et al., 1998; Munksgard and Pedersen, 2001; Ferng, 2003; Peters, 2008a; Peters and Hertwich, 2008a; Munksgaard et al., 2009; Peters et al., 2009).[3]

Today it is widely accepted that a fair burden sharing system is fundamental to finding a global deal on climate change (e.g. Grubb et al. 1999; World Bank, 2008). Baer et al. (2007) and Chakravarty et al. (2009), for example, present frameworks for allocating a global GHG reduction target to nations, in which the principle of 'common but differentiated responsibilities' as established in the Kyoto Protocol refers to emissions of individuals instead of nations. The CF concept fits in very naturally in such frameworks interpreting individual responsibility as any GHG emission release worldwide required in the production of the goods and services finally consumed by the individual. The use of carbon footprints in the context of a fair burden sharing system is therefore the proposition that every world citizen should have the same right to (directly or indirectly) emit carbon for satisfying their needs. Vice versa, it challenges the fact that if a purely production-based system is used to restrict the amount of GHG emissions a country is allowed to emit, some countries would have to use up some of this carbon budget for supplying resources consumed in other nations.

What difference the application of a production or consumption concept can make for national emission accounting is shown in Table 1 using the UK as an example. While the UK reduced territorial GHG emissions – as accounted for under the UNFCCC[4] – by more than 10% between 1992 and 2004 and thus achieved its Kyoto targets ahead of schedule, the UK's carbon footprint was not only generally larger in all years but also increased by more than 8% over the same period (Wiedmann et al., 2008; Wiedmann et al., 2010). As a result, the carbon trade balance (BEET: export minus import related emissions) almost tripled from an import deficit of 70 to 201 Mt CO_2e.

An increasing gap between GHG emissions associated with production and consumption through international trade can cause further problems in the context of the current

[2] The Kyoto Protocol applies a target-setting approach with uniform reductions subject to differentiation for special circumstances (EU differentiation). The Brazilian Proposal introduced the issue of responsibility into the Kyoto negotiations by suggesting that target setting should be based on the relative contribution of countries to anthropogenic climate change.

[3] Various mathematical approaches, based on input–output frameworks, for sharing the responsibility between production-based and consumption-based national emission inventories have been discussed (Andrew and Forgie, 2008; Peters, 2008a; Serrano and Dietzenbacher, 2008). These trade-specific considerations are part of a wider effort to conceptualise the notion of shared responsibility between producing and consuming entities, using input–output analysis (see e.g. Gallego and Lenzen, 2005; Lenzen et al. 2007; Lenzen 2008b; Rodrigues and Domingos, 2008a, 2008b; Rodrigues et al., 2010).

[4] United Nations Framework Convention on Climate Change (http://unfccc.int).

TABLE 1. UK carbon footprint 1992–2004 and other relevant statistics (ROW = rest of world, BEET = balance of emissions embedded in trade)

	Unit	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	Change 1992–2004 abs.	Change 1992–2004 %
Carbon footprint	Million tons CO2e	863.6	855.3	844.3	815.4	862.3	876.2	895.8	868.9	895.3	952.5	951.4	930.5	934.2	+70.5	+8.2%
of which																
UK	Million *tons CO2e*	*604.2*	*575.5*	*562.0*	*556.3*	*586.3*	*582.9*	*575.5*	*565.1*	*568.6*	*572.8*	*562.0*	*562.4*	*560.1*	*−44.1*	*−7.3%*
EU	Million *tons CO2e*	*67.7*	*82.1*	*81.0*	*76.7*	*79.3*	*95.4*	*89.8*	*91.3*	*93.5*	*101.4*	*103.6*	*90.9*	*89.3*	*+21.6*	*+32.0%*
non-EU	Million *tons CO2e*	*59.0*	*61.1*	*60.2*	*59.1*	*64.3*	*69.9*	*72.5*	*66.8*	*84.1*	*88.0*	*90.4*	*80.7*	*76.0*	*+17.0*	*+28.7%*
ROW	Million *tons CO2e*	*132.7*	*136.6*	*141.3*	*123.4*	*132.4*	*128.0*	*158.1*	*145.8*	*149.1*	*190.3*	*195.4*	*196.5*	*208.8*	*+76.1*	*+57.3%*
BEET	Million tons CO2e	−71.1	−81.9	−82.5	−61.8	−81.9	−117.2	−137.8	−141.4	−162.8	−212.4	−230.3	−200.4	−200.7	−129.6	−182.3%
BEET	% of terr. emissions	9%	11%	11%	8%	10%	15%	18%	19%	22%	29%	32%	27%	27%		
Carbon Leakage	Million tons CO2e	129.4	128.6	132.3	115.6	124.3	120.7	148.3	138.1	142.7	178.2	182.0	181.7	189.8	+60.4	+46.7%
Carbon Leakage (U.S.)	Million tons CO2e	184.0	185.3	188.0	169.4	181.9	182.8	212.8	196.1	214.6	254.7	260.2	251.9	254.4	+70.4	+38.3%
Total Output	£billion	1216.1	1248.2	1309.2	1356.7	1437.6	1511.1	1595.4	1694.4	1770.2	1810.7	1874.3	1929.1	1985.1	+769.1	+63.24%
Final demand	£billion	644.2	656.2	675.5	689.5	722.3	766.3	792.4	851.9	888.0	916.8	959.9	989.1	1027.2	+383.0	+59.46%
Population	Million	57.59	57.71	57.86	58.03	58.16	58.31	58.48	58.68	58.89	59.11	59.32	59.56	59.85	+ 2.3	+3.93%
Households	Million	23.11	23.29	23.47	23.65	23.84	24.02	24.20	24.39	24.57	24.75	24.99	25.23	25.47	+ 2.4	+10.24%
Household Size	population/ household	2.49	2.48	2.47	2.45	2.44	2.43	2.42	2.41	2.40	2.39	2.37	2.36	2.35		

international climate change regime as established under the Kyoto Protocol. The shift of emissions associated with production from Annex B countries with emission targets to non-Annex B countries is sometimes referred to as 'weak' carbon leakage (Peters and Hertwich, 2008b). This is different from the concept of 'strong' carbon leakage as defined by the Kyoto Protocol which relates to the shift of emissions due to climate policies implemented in Annex B countries.

Weak carbon leakage associated with UK consumption (see Table 1) is a growing problem, with emissions from non-Annex B countries embedded in UK imports increasing from 129 to 190 Mt CO_2e per year between 1992 and 2004. This was driven by steep increases in imports from emerging economies such as China and India. If one adds emissions embodied in trade with the United States – a country that has not ratified the Kyoto Protocol – weak UK carbon leakage in 2004 would have accounted for 254 Mt CO_2e or 35% of all territorial GHG emissions in the UK.

The UK-specific trends are supported by other international evidence. Peters and Hertwich (2008a) and Wilting and Vringer (2009) show in their global MRIO models covering 87 countries and world regions that industrialised nations tend to be net importers of CO_2 emissions in general, exceptions are countries with a large extraction of raw materials such as Australia and Canada. This means that those countries who are responsible for the majority of historical GHG emissions and who have the capacity to take strong climate change actions (Baer et al., 2007) benefit from the way emissions are allocated to countries in the Kyoto Protocol.

Similarly other evidence suggests that weak carbon leakage is not a UK-specific phenomenon, but a general trend. The increased export of emissions from countries without binding emission targets to industrialised countries drives up global GHG emissions under the current UNFCCC agreement and undermines its effectiveness (Peters and Hertwich, 2008a; Peters, 2008b; Weber et al., 2008; Guan et al., 2009). This contributes to the reality that GHG emissions are growing faster today than at the beginning of international climate change negotiations (Raupach et al., 2007).

China has taken trade-related issues on board and recently asked for carbon relief for their exported products.[5] So far, there is little consensus in the policy discussion on how emissions in trade should be considered. In the literature, suggestions have been made about how the problems of carbon leakage, international trade and responsibility could be dealt with (see Peters and Hertwich, 2006a, 2008b; Peters, 2008a, 2008b; Weber and Peters, 2009; Peters et al., 2009). By highlighting this important issue, generalised IOMs have brought further crucial evidence to the table for negotiations of a post-2012 climate change regime.

3.2 Understanding Carbon Footprint Drivers

Nations' CFs are driven by a variety of factors: the carbon efficiency of global production, changes in the global production structure, changes in the level and in the composition of final demand (including choice between domestic and imported products), as well as socio-demographic trends such as changes in household size or the number of residents. Structural decomposition analysis (SDA) can be applied to generalised IOMs in order

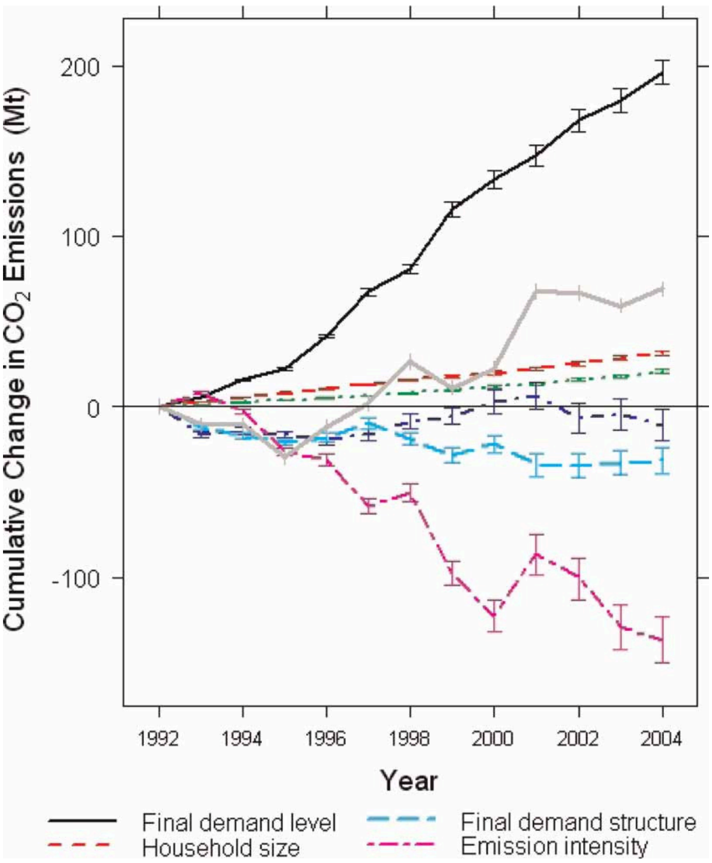
[5] See http://news.bbc.co.uk/1/hi/sci/tech/7947438.stm

to quantify the contribution of these drivers to the overall change in the CF (e.g. Dietzenbacher and Los, 1998; Dietzenbacher and Stage, 2006; Minx et al., 2009; Baiocchi and Minx, 2010; Wood, 2009).

SDA allows answering questions such as: why is the UK's carbon footprint growing? How are the UK's territorial emissions affected by changes in the global structure of production? What effect do population, affluence and technology have in relation to each other? Is the much-heralded progress on efficiency enough to compensate for growing populations or increases in imports? Are we making real progress in cutting GHG emissions?

Figure 1 shows the contributions of drivers to changes in the CO_2 component of the UK's CF between 1992 and 2004. A total of 137 Mt of CO_2 emissions were avoided through improvements in the carbon intensity of production, and a further 31 Mt through a greening of UK consumption patterns, i.e. the shifts towards products with lower climate change impacts. However, all the progress in those areas has not been sufficiently large to offset the additional 248 Mt CO_2 from growing levels of UK consumption.

FIGURE 1. Drivers behind changes in the UK carbon footprint 1992–2004 (see Baiocchi and Minx, 2010).



Only a fifth of this (52 Mt CO_2) is related to socio-demographic forces – namely additional consumption from increases in the resident population in the UK (31 Mt CO_2) as well as from decreases in household size (21 Mt CO_2). The majority (196 Mt CO_2) is a reflection of the increased per household spending levels in the UK, which has been due to a steady growth of the UK economy since the mid 1990s (see Table 1).

It is one appeal of a structural decomposition analysis that its results relate directly to the UK's environmental agenda and make CF evidence more relevant to policy makers. Whilst the government has no concrete plans to reduce the UK's CF, it has a variety of programmes aimed at improving efficiency of production as well as reducing the impacts from consumption through greener choices.[6]

The results shown in Figure 1 provide clear policy implications: in order to respond successfully to the climate challenge, countries will need to speed up their efforts to decarbonise production. This will require net reductions in domestic emissions rather than shifts in emissions between regions. In a comprehensive SDA analysis of the UK's carbon footprint, Baiocchi and Minx (2009) showed that progress in greening the domestic supply chain in the UK – triggered primarily by the shift towards a service economy – has only been achieved through an increase of emissions in foreign countries, caused by British outsourcing and re-importing of carbon-intensive, manufactured goods. For an industrialised country like the UK, the results presented in Figure 1 are also a reminder that there might be a need to question current definitions of welfare in the context of a transition to a sustainable economy, as recently highlighted in a report by the Sustainable Development Commission (SDC, 2008).

3.3 The Carbon Footprint of Sectors

There are numerous applications of IO-based CFs to industry sectors or product groups. The appeal of generalised IOMs for sectoral CF studies is that they provide a relatively detailed and complete picture of the direct and indirect GHG emissions associated with sectoral production and consumption activities. Moreover, by undertaking analyses within such a consistent accounting framework, better comparability can be achieved, relative to other bottom-up resource flow methodologies (Wiedmann et al., 2006; see also the article of Huang et al., 2009).

Therefore, applications of IOMs to carbon footprinting are often well suited for tracking sector performance in benchmarking exercises (e.g. Lenzen, 2003; Foran et al., 2005a), the identification of sectoral carbon hotspots (e.g. Lenzen, 2003; Foran et al., 2005b, Peters and Hertwich, 2006b) and priority areas for climate change research and policy (e.g. Tukker et al., 2006; Hertwich and Peters, 2009). Moreover, in hybrid models, input–output approaches can be augmented with process data to extend the applicability of IO-based carbon footprinting into areas where IO data are not specific enough. Such areas are integrated product policy, life-cycle analysis of individual products or the benchmarking of single businesses against the sector average (see Joshi, 1998; Suh et al., 2004;

[6] For example, DEFRA's product roadmaps: http://www.defra.gov.uk/environment/business/products/roadmaps

Suh, 2004; Suh and Huppes, 2005; Foran et al., 2005b; Heijungs et al., 2006; Nakamura and Kondo, 2009).[7]

Table 2 presents direct CO_2 emissions as well as the CO_2 component of the CF of broad economic sectors in the UK between 1992 and 2004. Manufacturing sectors and utilities emitted most of the direct CO_2 emissions, 323 Mt CO_2 or 68% of all emissions in UK production. In 2004 this amount decreased to 292 Mt CO_2 reflecting the ongoing decline in UK manufacturing as well as emission savings due to the switch from coal to gas in the UK energy mix during the 1990s (Minx et al., 2009).

Even though responsible for almost 56% of UK economic output, service industries just released 11% of the 474 Mt CO_2 emissions in 1992. While increasing their output share to 64% by 2004, service sectors further reduced direct CO_2 emissions in absolute terms by 3 Mt CO_2. This suggests substantial carbon benefits associated with a transition towards a service-based economy. However, direct emission sources only tell part of the story. It is the strength of CF estimates that they include the indirect emission component associated with a sector's final demand. Our results show that the global climate change impacts per unit of final demand (total CO_2 intensity multipliers – or TIMs – in Table 2, representing total embodied upstream emissions) remain low for services. However, they are larger than direct CO_2 intensity multipliers (DIMs, representing direct sectoral emissions only). While TIMs are one to three times larger than DIMs for the primary, secondary and transport sectors in 2004, they are approximately eight times bigger for construction and service industries.

Furthermore, rapidly rising demand for services in the UK are driving CO_2 emissions upwards throughout their global supply chains (see Suh, 2006; Nansai et al., 2009). Our results show that services have become the most important individual driver behind increases in the CO_2 component of the UK's carbon footprint (Table 2). Almost 38% (26 Mt CO_2) of the 69 Mt increase in the CO_2 component of the UK's carbon footprint were rooted in increased service demands. The second largest contribution with 34% (23 Mt CO_2) came from an increased demand in transport services.

This is an important finding as it challenges the often presented picture of services as being a wedge to climate change mitigation (Pacala and Socolow, 2004; ONS, 2008). Hence, unless both the direct as well as indirect emissions of sectors from upstream production are considered, it is impossible to obtain a balanced picture of the contribution of services to climate change policy (see also Suh, 2006). Direct sectoral GHG indicators in the UK must therefore be complemented with CF evidence. This example also highlights the importance of generalised IOMs for informing climate change policies; many other resource flow methodologies still struggle to depict service sector supply chains comprehensively (Wiedmann et al., 2006; Minx et al., 2008b).

A deeper understanding of the carbon trajectories of individual sectors or product groups can be gained by plotting in a graph the emission changes due to changes in production technology on the *x*-axis and emission changes due to changes in final demand on the *y*-axis. Such a two-factor decomposition is shown in Figure 2 for the UK. This not only provides information about technological advance and consumption growth, but also whether and to what extent society is shifting towards more sustainable patterns of

[7] It is not the purpose here to discuss the various advantages of such hybrid models. A good discussion is provided by Suh et al. (2004).

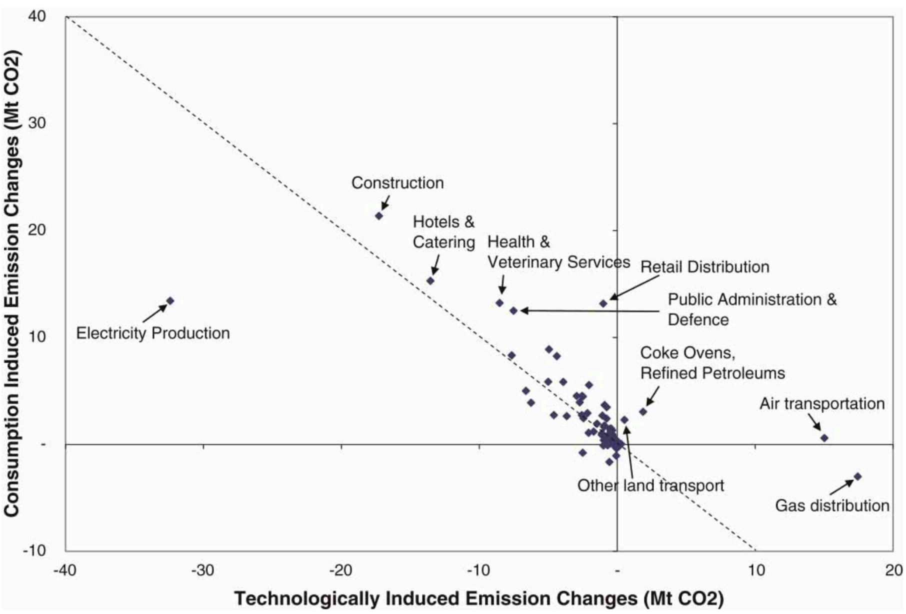
TABLE 2. CO_2 Emissions associated with UK sectors (terr. = territorial; CF = CO_2 component of carbon footprint; rk = rank; Δ = absolute change; DIM = direct intensity multiplier; TIM = total intensity (Leontief) multiplier)

	1992								2004								Change 1992 to 2004			
Unit	Terr. CO_2 1000t	rk	DIM kg /£	rk	CF 1000t	rk	TIM kg /£	rk	Terr. CO_2 1000t	rk	DIM kg /£	rk	CF 1000t	rk	TIM kg /£	rk	Δ terr. CO_2 1000t	%	Δ CF 1000t	%
1 Primary	26,998	5	0.79	3	11,141	6	1.44	3	30,138	5	0.75	3	10,275	6	0.97	3	3,140	10.42%	−866	−8.43%
2 Secondary	129,050	2	0.42	4	138,357	2	1.15	4	113,026	2	0.30	4	159,009	2	0.84	4	−16,024	−14.18%	20,653	12.99%
3 Energy	194,364	1	6.03	1	90,545	3	7.55	1	179,022	1	4.06	1	86,325	3	5.92	1	−15,342	−8.57%	−4,220	−4.89%
4 Construction	8,549	6	0.09	5	40,778	4	0.78	5	10,280	6	0.06	5	44,867	5	0.50	5	1,731	16.84%	4,089	9.11%
5 Transport	63,433	3	0.90	2	39,308	5	1.92	2	96,452	3	0.94	2	62,595	4	2.40	2	33,019	34.23%	23,287	37.20%
6 Services	51,945	4	0.08	6	191,174	1	0.44	6	48,818	4	0.04	6	217,212	1	0.31	6	−3,126	−6.40%	26,038	11.99%

consumption (Nansai et al., 2007). All points to the right of the −45° degree line indicate an increase in GHG emissions between 1992 and 2004, all points on the left side a reduction. The perpendicular distance from the line identifies the size of increase or reduction. A number of useful insights can be obtained from this analysis.

- There are a small number of sectors with large contributions to changes in CO_2 emissions and a large number of sectors with relatively small contributions. More than 70% of the product groups contributed less than 0.8% (average) to the absolute CO_2 emission changes associated with changes in technology and final consumption. From a policy perspective this might be seen as good news as it shows that by targeting a relatively small number of product groups (and their supply chains), considerable progress towards a low carbon economy could be made. According to this line of thought, integrated product policy as a systemic approach to reduce GHG emissions appears viable and manageable (Tukker et al., 2006). The targeted approach of the product roadmap work in the UK as originally recommended in a report by the Sustainable Development Commission, for example, is reinforced by these results (Sustainable Consumption Roundtable, 2006; DEFRA, 2009).
- Seventy-five percent of all product groups are located in the upper-left quadrant of Figure 2. This means that for three quarters of all product groups, CO_2 emission reductions from changes in production technology were accompanied by CO_2 emission increases from additional final consumption. For most product groups there was a net increase in emissions, because technological progress throughout the global supply chain had not been large enough to offset the increase in CO_2 emissions from rising

FIGURE 2. Two factor decomposition: technologically and consumption induced changes in UK CO_2 Emissions 1992–2004.



consumption levels between 1992 and 2004 (Hertwich, 2005a). It will be particularly important to speed up technological development in the rapidly growing sectors such as retail distribution, construction, and health and veterinary services, among others.
- Only 8% of all products are located in the upper-right quadrant, and are currently following a fully unsustainable development path in that they showed increases in CO_2 emissions from more carbon intensive production processes as well as growing levels of consumption. However, there are only three product groups (air transportation, coke oven products, and refined petroleum products) where these changes were large enough to be relevant for decision making. It might therefore be worthwhile to undertake more detailed analysis of these sectors in order to learn what caused the unsustainable trends and how they might be stopped.

There also remain challenges in the provision of detailed CF estimates for sectors in a global model, related to the various sources of uncertainties attached. A Monte Carlo analysis of our UK MRIO model (Wiedmann et al., 2008; Lenzen et al., 2010) showed that, whilst CF estimates for the whole of the economy analysis were quite robust, the uncertainty for some individual sectors can be high, meaning that results at the sectoral level cannot always be used in policy formulation. High uncertainty generally affects sectors where emissions embodied in trade are substantial, highlighting the need to improve international input–output and environmental account databases, as currently undertaken in the EXIOPOL project (Tukker et al., 2009; see also Rueda-Cantuche et al., 2009).

3.4 The Carbon Footprint of Supply Chains

Generalised IOMs can also be used to analyse the CF along the steps of production and supply. As an example, we investigated global GHG emissions associated with meat consumption in the UK (the technical details of this analysis can be found in Minx et al., 2008b). The MRIO model used allows tracing GHG emission sources associated with a particular supply chain of a sectoral final demand across 57 sectors and 87 world regions.

More than 40% of the UK's food CF (47 Mt CO_2e) were associated with meat consumption in the year 2001. Not surprisingly, CH_4 emissions from ruminants made up the largest share of the CF, with 42% or 19.5 Mt CO_2e (see Figure 3). Carbon dioxide emissions accounted for 13.7 Mt CO_2e (29%) of the CF of meat, which is almost exactly equal to the amount of nitrous oxide emitted (13.6 Mt CO_2e or 29%).

These results are largely comparable with results from LCA studies, even though the CO_2 emission component in our study is considerably higher than that reported by Foster et al. (2006). There are two likely reasons for this difference. First, as highlighted by Foster et al. (2006), most process-based studies of meat systems only analyse the emissions up to the farm gate, as they perceive the major impacts to occur during agricultural production stages. Second, as widely discussed in the literature, process LCA studies require the elimination of higher upstream production processes (cut-offs) in order to keep the system manageable (see Lenzen, 2001; Lenzen and Treloar, 2003; Suh et al., 2004; BSI, 2006). This results in truncation errors. Because CO_2 – in contrast to N_2O and CH_4 – mainly occurs in later stages of the supply chain of ruminant meat production, namely in processing and distribution, it is likely that the CO_2 estimate in LCA studies is

FIGURE 3. Composition of UK carbon footprint from meat consumption in 2001 by greenhouse gas.

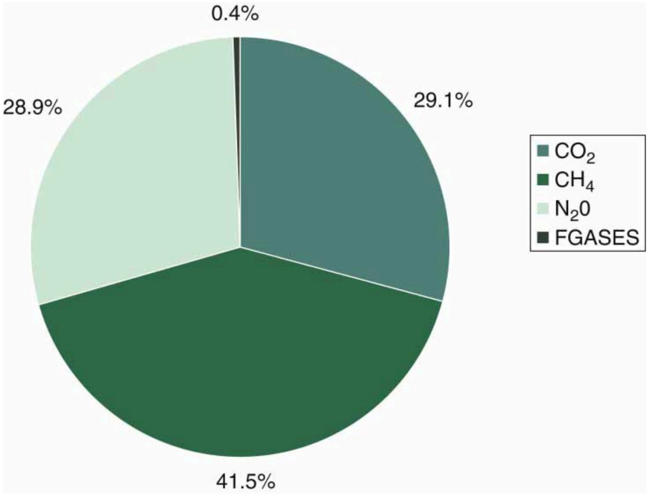
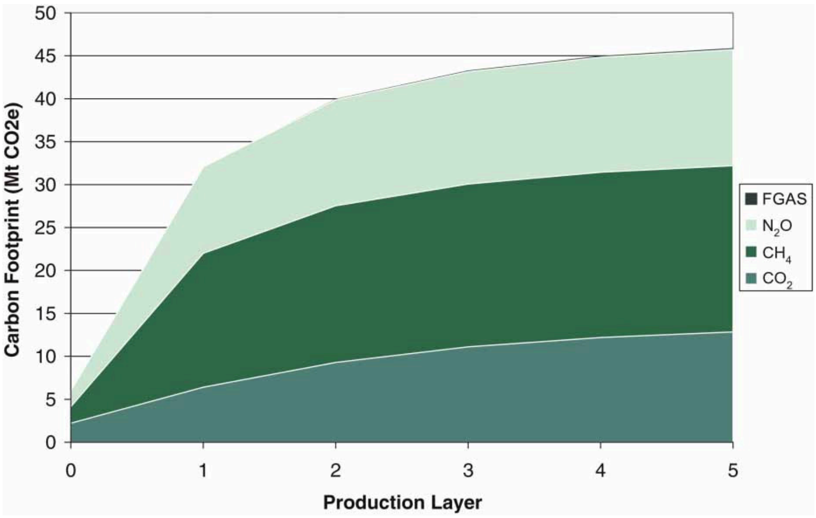


FIGURE 4. Build-up of the carbon footprint from UK meat consumption along production (supply chain) layers.



more heavily affected by this truncation (see Figure 4, where the CF of UK meat consumption is decomposed into layers of production along the supply chain). While more than 90% of CH_4 and N_2O are located in the first production layer, it takes until the fifth production layer for CO_2 until 90% of the emissions are covered. Hence, one important advantage of generalised IOMs in the context of supply chain analysis is that truncation is avoided and that emission sources throughout the entire global supply chain are covered, leading to more accurate CF estimates (Minx et al., 2008a).

FIGURE 5. Carbon footprint of UK meat consumption by sector and world region (in million tonnes of CO_2e).

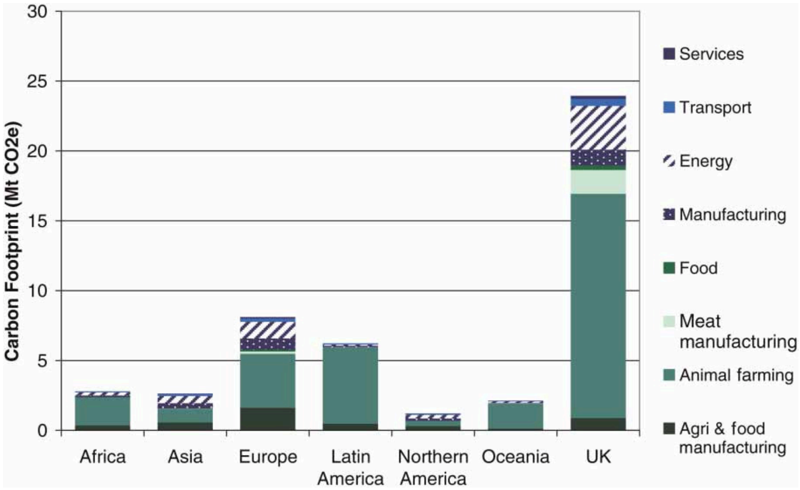


Figure 5 shows the CF of UK meat consumption in 2001 by emitting sector and world region. Sixty-five percent of the emissions (30.5 Mt CO_2e) came from the animal farming sector. Agriculture and Energy both contributed approximately 10% (4.3 Mt CO_2e, and 5.5 Mt CO_2e respectively), meat and other food manufacturing with 5% (2.5 Mt CO_2e) and the remaining sectors together 10% (4.2 Mt). The difficulties of mitigating emissions in agriculture and animal farming, particularly non-CO_2 emissions, suggest the need for dietary changes in order to achieve the ambitious emission cuts envisaged in the climate change policy community (Weber and Matthews, 2008; Stehfest, 2009).

Only 50% of the CF of meat occurred within the UK, while the rest was released elsewhere in the world (Figure 5). The regional aggregation hides some interesting detail. The single most important foreign country in the UK's supply chain of meat was Brazil, where 12% or 5.5 Mt CO_2e were released in 2001. This is a cause for concern, because Brazil is a deforestation hotspot and our analysis does not include emissions from land use change. Even though Brazil does not have the highest rate of deforestation in the world, it still has the largest area of forest removed annually (FAO, 2007). Between 2000 and 2006, Brazil lost 150,000 square kilometres of forest, an area larger than Greece. Seventy percent of formerly de-forested land in the Amazon, and 91% of land deforested since 1970, is used for livestock pasture (Margulis, 2004; Steinfeld et al., 2006).

When animal farming is linked to deforestation, the carbon footprint has been reported to be at least 30–40% higher (Steinfeld et al., 2006; Weber and Matthews, 2008). Our study (Minx et al., 2008a) did not cover emissions from deforestation, although they are potentially very important. However, a detailed multi-regional model for supply chain analysis immediately highlights which part of the carbon footprint emissions from land-use change might play a role. Our results show that emissions from major land-use change might at least be relevant for 20–30% of the GHG emissions. This implies that, in the case of meat, the region of origin is important, not because of the emissions associated with transportation, but rather because of the potential emissions from land-use change.

Generalised multi-regional IOMs can be used for the identification of sector and regional emission hotspots in global supply chains of products. Much more detailed pictures of trade linkages throughout the global supply chain can be obtained by applying decomposition techniques such as structural path analysis (SPA, e.g. Sonis et al., 1997; Lenzen, 2003; Peters and Hertwich, 2006b). SPA can provide more specific guidance to decision makers in their efforts to reduce emissions. Furthermore, our analysis highlighted the potential of MRIO models to establish a link to issues such as deforestation and land-use change, and to stimulate thoughts about further economic, environmental and social implications.

3.5 The Carbon Footprint of Organisations

Carbon footprint accounting of organisations has received a great deal of attention in recent years. The GHG Protocol (WRI and WBCSD, 2004) distinguishes scope 1, 2 and 3 emissions: scope 1 includes the GHG emissions from sources owned or controlled by the organisation – equivalent to direct emissions in the language of generalised input–output analysis, scope 2 includes indirect GHG emissions associated with the generation of electricity purchased by the organisation, and scope 3 includes all other indirect GHG emissions associated with the operations of the organisation. A full CF estimate for an organisation must comprise all these three components.

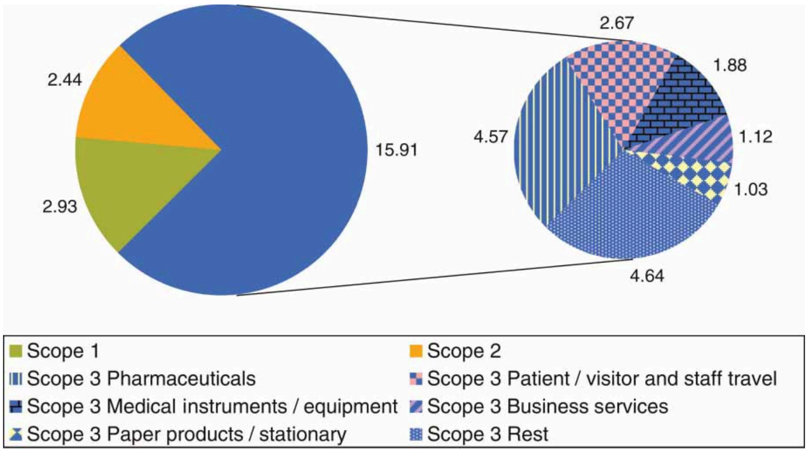
A problem for many organisations is that the establishment of a comprehensive carbon footprint account, including all scope 3 emissions, can be an administratively complex, expensive and methodologically challenging task. Linking generalised input–output models with the financial accounts of an organisation in a hybrid framework can provide a consistent, comprehensive and cost-effective way of estimating the organisation's upstream scope 3 emissions (Joshi, 1998; Suh, 2004; Suh et al., 2004; Foran et al., 2005a; Lenzen et al., 2007; Lenzen, 2008a; Wiedmann et al., 2009b). For this reason, generalised input–output analysis is currently considered as a methodological option by an international working group for a corporate/scope 3 emission accounting standard.[8,9]

Let us focus on a brief example on the CF of a government organisation. Governments can make a considerable difference in climate mitigation through climate friendly procurement choices and through minimising emissions from own activities. In the UK climate change discussion, 'leadership by example' has been highlighted as a pre-condition to engage other stakeholders in (voluntary) climate change action (HM Government, 2005). The UK government has defined ambitious targets for reducing GHG emissions associated with its own activities as defined in the 'targets for sustainable operations on government estate' (Home Office, 2006).

These reduction targets usually only consider scope 1 and scope 2 emissions for the reasons outlined above. However, a study of the National Health Service (NHS) in England (SDC, 2008) based on a generalised IOM, showed that excluding scope 3 from the analysis would mean neglecting more than 70% of the total CF of 21 Mt CO_2e, as

[8] See http://www.ghgprotocol.org/standards/product-and-supply-chain-standard
[9] The article by Huang et al. in this issue deals explicitly with the methodological discussions during the update of the GHG Protocol standard.

FIGURE 6. Carbon footprint of the National Health Service 2004 (in Mt CO_2e).



shown in Figure 6. Almost 30% (4.6 Mt CO_2e) of scope 3 emissions were associated with the purchase of pharmaceutical products, 17% (2.7 Mt CO_2e) with patient, visitor, and staff travel and 12% (1.88 Mt CO_2e) with the purchase of new medical instruments and equipment.

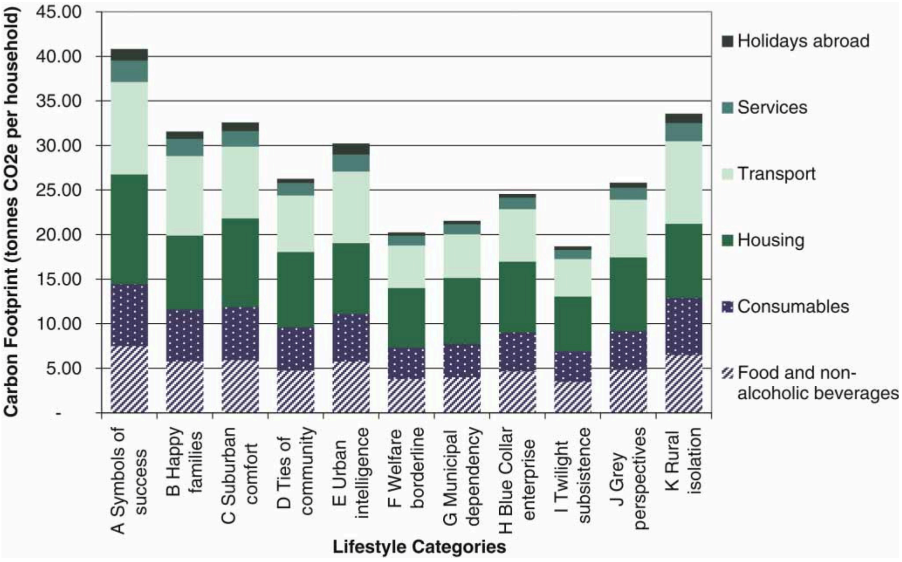
The NHS – as with any other organisation – not only has influence over its scope 1 and 2 emissions but also some influence over its scope 3 emissions. It has been argued in the literature that the responsibility to reduce emissions along supply chains, i.e. between producers and consumers, should be shared (Lenzen et al., 2007). In response to the current study (SDC, 2008), the NHS officially committed, as the first government organisation in the UK, to reduce its carbon footprint in a supply chain partnership with an initial reduction target of 10% from 2007 levels (NHS, 2009). Generalised IOMs will help to keep track of progress made and to prioritise CF reduction efforts.

3.6 The Carbon Footprint Associated with Consumption Patterns and Lifestyles

Using generalised IOMs to understand consumption patterns and lifestyles provides a whole new avenue for CF applications. It is widely accepted that the deep cuts in carbon emissions are unlikely to come from technological change alone. There is also an important role for changes in consumer behaviour and lifestyle. Generalised IO models can make an important contribution in this context by tracking progress, identifying hotspots and removing barriers to lifestyle change.

In IO analysis, a ‘lifestyle’ is usually assumed to be reflected in the expenditure pattern of a group of people or households with a well-defined set of socio-demographic characteristics (Duchin, 1998; Minx and Baiocchi, 2009). Expenditures by different socio-economic groups trigger different carbon emissions throughout the world. We found comparative studies in the literature with the shared motivation to identify consumption bundles and/or lifestyle groups with carbon saving potential (Hertwich, 2005b; Druckman et al., 2008; Hertwich and Peters, 2009) or to identify the underlying factors driving emissions (Lenzen et al., 2004, 2006; Baiocchi et al., 2009). Sometimes,

FIGURE 7. Carbon footprint associated with 11 lifestyles categories in the UK in 2004 (tonnes of CO_2e per household).



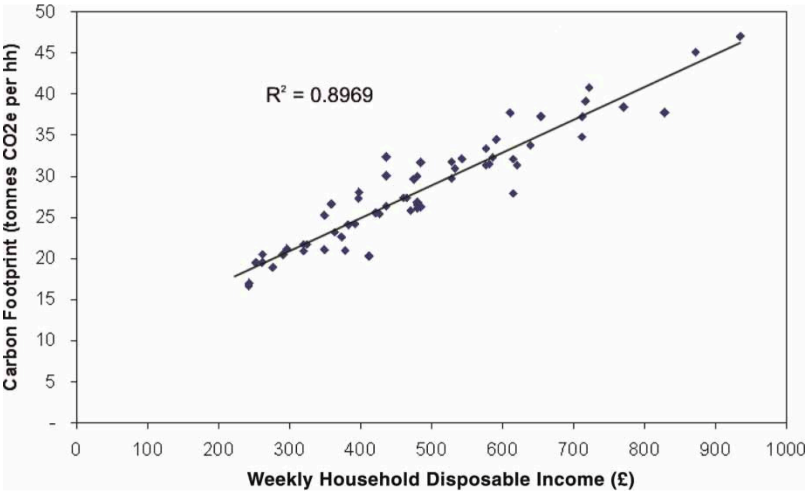
authors are also interested in the added pressures generated by changing lifestyles (Guan et al., 2008) or demographics (Haq et al., 2007). All methodological details required for a comprehensive understanding of this Section are presented in Minx (2009).

Differences in the carbon footprint of 13 lifestyle groups in the UK as distinguished by the MOSAIC classification (Experian, 2009) arising from they ways they spend their money on goods and services are shown in Figure 7. For the purpose of illustration we distinguished spending across seven major household consumption categories. The areas housing, travel and food are the hotspots in the emission patterns across all lifestyle groups (a finding confirmed by Hertwich, 2006; Tukker et al., 2006; and Druckman and Jackson, 2009). Overall, these areas are responsible for 60% of the UK households' carbon footprint. It can be shown that the share in transport emissions rise and the share in housing emissions seems to fall with a group's income level. Moreover, transport emissions are more prominent for lifestyle groups living in rural areas (Baiocchi et al., 2009).

Overall, the climate change impacts of lifestyles differ by more than a factor of two (or 18.7 t CO_2e per household) between of lifestyle group I ('Twilight Subsistence') and category A ('Symbol of Success'). This factor becomes three once we look at a more detailed breakdown of 61 lifestyle groups.[10] In Figure 8, we map per-capita carbon footprints against weekly household income of these groups and find a strong linear relationship between the two. Even though richer groups might be more likely to buy energy-efficient

[10] Note that these refer to average lifestyle groups derived from average national data. A study by Weber and Matthews (2008) suggests that we could expect considerable in-group variability if individual responses from surveys were used.

FIGURE 8. Carbon footprint and weekly household income per household of 61 lifestyle groups in the UK in 2004 (in million tonnes of CO_2e per household and £ per household).



appliances and live in better insulated houses, bigger houses, cars and fridges are driving their carbon footprint upwards.

The relationship between household income and carbon footprint of lifestyle groups has an important implication for climate change policy. Ultimately, governments need to make sure that the costs of cutting carbon are born by those who have contributed most to driving climate change, on the one hand, and by those who have the capacity to act, on the other hand. This is not only key for a reasonable burden sharing between countries (see World Bank, 2008), but also within countries. Unfortunately, this has often been neglected in climate change discussions to date. Generalised input–output models are therefore crucial for tracing GHG emission contributions of different lifestyle groups and informing fair, intra-societal climate change policies.

The lifestyle data presented here are different from data usually applied in generalised input–output studies, as it is of geo-demographic nature taken from commercial market segmentation systems (Duchin, 1998; Duchin and Hubacek, 2003; Druckman et al., 2008; Druckman and Jackson, 2008; Baiocchi et al., 2009). The main characteristic of these databases is that all information is geographically coded – down to the post-code level – and that they contain a wealth of economic and social variables. Moreover, in the geo-demographic classifications, lifestyles are not only distinguished by characteristics such as income, occupation or gender (Weber and Perrels, 2000; Pachauri, 2004; Wier et al., 2005), but also take into account key neighbourhood and community characteristics such as the type and size of dwelling, access to services etc. Members of lifestyle group 1 ‘Symbols of Success’, for example, typically live in detached houses with four or more bedrooms in fashionable inner-city neighbourhoods of economically more successful regions of the UK such as London or the South East. Such information about the immediate physical environment and infrastructure is crucial as it helps to explain the size of carbon footprints and identify barriers to lifestyle change (Baiocchi et al., 2009). It is also essential in informing lifestyle-related climate change policies. Every lifestyle group has particular wants and needs, particular world views, acts within a particular physical environment, and has particular attitudes towards the environment. Knowing these socio-economic and geographical circumstances as well as local and social barriers to lifestyle change (such as the absence of public transport, age and condition of dwellings, lack of financial resources to improve home insulation, etc) helps to identify feasible opportunities for reducing the carbon footprint of different lifestyles. Providing information for target-group and area-specific behavioural change policies as well as communication campaigns (see e.g. Australia's online Atlas; ISA and ACF, 2007) and therefore overcoming 'one-size-fits-all' policy recommendations is the unique opportunity offered by CF evidence based on such geo-demographic lifestyle data (DEFRA, 2008). Recent examples demonstrate that generalised IOMs have an important role to play in this context (Druckman et al., 2008; Druckman and Jackson, 2008; Baiocchi et al., 2009; SEI and Experian, 2009).

3.7 The Carbon Footprint at a Sub-national Level (Regional and Local Carbon Footprints)

Generalised IOMs can also be used to calculate the CFs for small spatial areas at the sub-national level – most importantly municipalities and cities. As the importance of local mitigation and adaptation measures is increasingly recognised in the international climate change discussion, there is a considerable policy demand for such information. This is reflected in a variety of climate change programmes for cities and local government by international organisations such as the World Bank (2009), OECD (2009) or the United Nations (2009).

The need to inform this policy process with robust and comparable data and evidence has triggered initiatives to standardise the construction of local production and consumption-based GHG inventories (Dawson et al., 2007; ICLEI, 2008). However, methods for calculating CFs for small spatial areas are still in their infancy (Kennedy et al., 2009). The role of generalised IOMs is largely unexplored in this context, even though there are some notable exceptions in the literature (Lenzen et al., 2004; SEI, 2007; Larsen and Hertwich, 2009).

The main challenge associated with estimating local CFs based on generalised IOMs is the requirement to combine information on global production activities with information on local consumption activities. While the former is well researched in the input–output literature (Lenzen et al., 2004; Munksgaard et al., 2005, 2009; Peters and Hertwich, 2006a; Peters, 2008a; Wiedmann et al., 2009b), the latter has received comparatively little attention.

The basic challenge associated with the construction of local expenditure (final demand) data is the insufficient sample size of most national consumer expenditure surveys (Minx, 2009) – even when data for multiple years are combined in pooled samples. A largely undiscovered road to small area CF estimates from generalised IOMs is the use of the geo-demographically segmented expenditure data mentioned above. Consumption profiles of the 61 lifestyle groups can be combined with spatially specific estimates indicating the number of households in each lifestyle group within a particular area. This results in initial estimates of local consumption, which can then be re-scaled and updated with the best available regional and local information.

FIGURE 9. Per-capita carbon footprint for UK local authority areas in 2004 (t CO_2e).

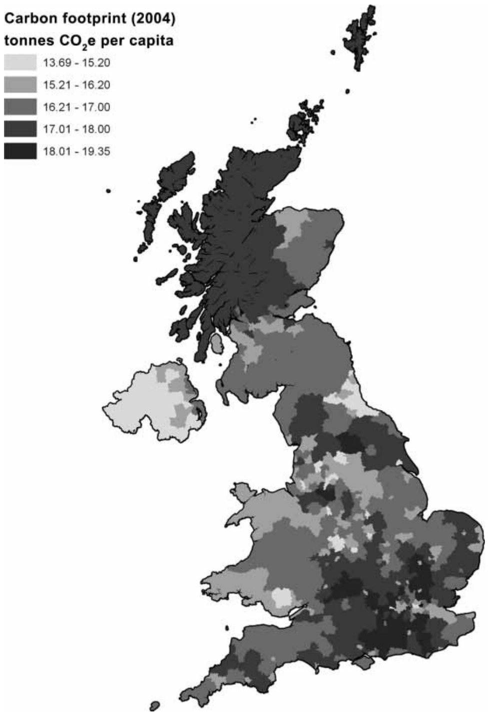


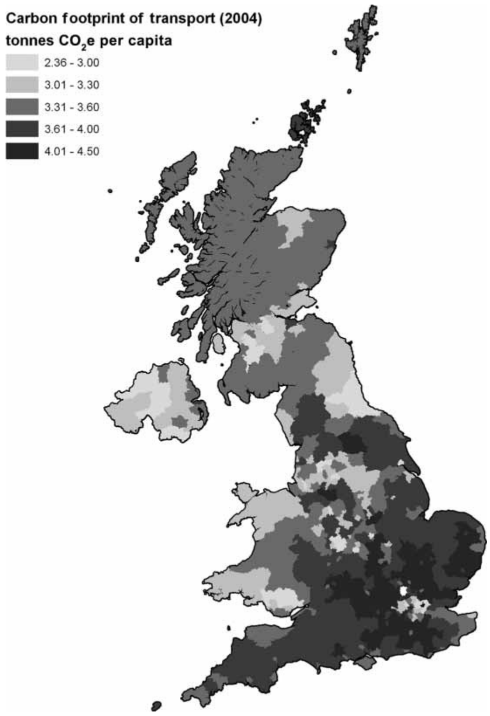
Figure 9 shows the carbon footprint of households in all 434 local authorities in the UK. The CF pattern emerging across the country is closely related to the distribution of wealth across private households in the UK. As for lifestyle groups, local authorities with richer residents tend to have a higher CF (for a more detailed analysis of factors influencing the spatial variation in CFs in the UK see SEI, 2007).

More specific local government policy issues emerge once we look at individual consumption categories. Figure 10 shows the household CF associated with private transport. The first striking feature is the comparatively high transport CF of households living in local areas bordering London. These areas belong to the 'commuter belt', inhabited mainly by people who work in central London, but who also enjoy the amenities of living in the countryside. This lifestyle often results in long commuting distances and has led to considerable urban sprawl, particularly in the South East of England and has driven the transport CF of areas with a high proportion of commuters upwards.

At the same time, the transport CFs of households living in London itself are very low. The reason for this is that London has the most restrictive private transport policy in the country and provides by far the most advanced urban public transport infrastructure. This combination ensures that London residents tend to own fewer cars, use the car less frequently, if they have one, and use public transport much more often (DfT, 2008), resulting in a lower per household transport CF.

The example of London therefore demonstrates the opportunities for reducing the transport CF through legislative policies and the provision of an adequate transport

FIGURE 10. Per-capita transport carbon footprint for UK local authority areas in 2004 (t CO_2e).



infrastructure, but also warns about the negative climate impacts associated with urban sprawl. Generalised IOMs in this context provide an important source of evidence as they can readily provide consistent and comparable CF estimates for small spatial entities within wider areas and therefore inform about the relationship between the city and its hinterland in an integrated approach to spatial planning.

Carbon footprint estimates can also be derived for very small spatial areas, such as Super Output Areas, which have a few thousand inhabitants on average.[11] Our results of CF estimates for super output areas in London (shown in Figure 11) inform about the distribution of CFs within administrative boundaries and can be used as a starting point for scoping and designing specific local policies. High CF areas can be analysed in their urban context and specific policies can be implemented, reflecting the needs and socio-demographic profile of the resident population and the local infrastructure they act in.

Finally, Australian evidence demonstrates how small-area CF evidence from generalised IO models can be used for public communication. ISA and ACF (2007) present CFs of more than 1400 Statistical Local Areas (SLAs) of Australia in an easy-access, on-line Consumption Atlas (see also Lenzen, 2009).

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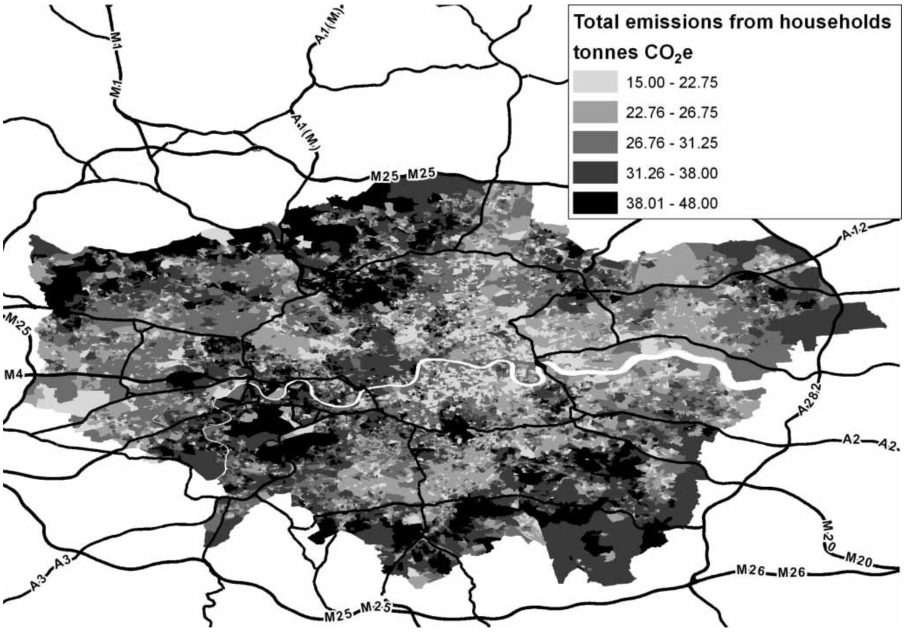
[11] http://www.statistics.gov.uk/geography/soa.asp.

FIGURE 11. Per-household carbon footprint of London by Super Output Area in 2004 (t CO_2e).



4 DISCUSSION, CONCLUSION AND OUTLOOK

In this article we have turned our attention to the potential contributions of generalised input–output models (IOMs) in the emerging area of carbon footprint (CF) analysis. Methodologically, the global system boundaries of CF analysis suggests the use of multi-regional IOMs to avoid errors associated with assuming domestic production technology for foreign economies (Andrew et al., 2009). Using evidence from the United Kingdom, exclusively derived from multi-regional input–output models, we provide an overview of applications in seven policy areas. This has highlighted the value of generalised IOMs for CF analysis and the policy relevance of the results. However, any model has its strengths and weaknesses, making it more useful to certain applications than to others. Ultimately, any model choice will depend on the policy question under consideration; the key determinants are as follows:

- *Time horizon*. The time horizon applied in the analysis provides an indication as to whether generalised IOMs might be suitably applied. IO tables and environmental accounts record all the economic and environmental flows within a given year. Unless additional data is introduced into the model, the use of generalised IOMs should be restricted to CF applications where this one-year time frame is appropriate. However, a variation in time horizon can often be achieved relatively easily by considering expenditures of a particular day or month or all spending associated with a running a car of a 20 year life cycle.
- *Type of data*. Data in generalised IOMs are averaged over 12 months and are typically a few years old. When an average representation of a technology is suitable or even

required for CF applications, such secondary data is appropriate and sufficient. Similar data from life cycle inventory databases might not always provide the same level of quality. However, certain CF applications might demand information about a specific, rather than the average, technology or might require the collection of primary data. In such a cases, generalised input–output analysis on its own is not sufficient for CF applications.

- *Costs and work effort*. Another advantage of generalised IOMs is that, once the model is in place, analyses can be carried out relatively fast – without large efforts and at low costs. In cases where an initial CF estimate is urgently required, generalised IO models will often provide a good starting point.
- *Detail and comprehensiveness*. Input–output tables describe all economic (market) activities at a (disaggregated) sector level. Whether this level of detail is sufficient depends on the focus of the analysis and the available data.[12] Studying the sector breakdown from the available IO tables will often be sufficient, when deciding how suitable an IOM is. If the emphasis is on *detail* rather than completeness, the sector breakdown provided by generalised IOMs may not be sufficient. In these cases, process-specific information will be required, ideally in the form of an integrated hybrid model, combining the strengths of process and input–output analysis (Suh, 2004; Suh et al., 2004; Minx et al., 2008). If the emphasis of the analysis is on *completeness*, generalised IOMs will often be the adequate choice (compare with Huang et al., 2009 and Nansai et al., 2009). For example, if we want to analyse the environmental impacts of trade flows, of lifestyles of groups or communities, or of global, sectoral supply chains, generalised IOMs will allow a complete assessment, whilst providing sufficient detail for avoiding grossly biased estimates.

CF applications can be extended considerably when employing a combination of generalised input–output models with process analysis (Bullard et al., 1978; Treloar, 1997; Joshi, 1998; Lenzen and Treloar, 2003; Suh et al., 2004; Suh, 2004; Peters and Hertwich, 2006c). Such hybrid models allow analyses to be undertaken with the same level of detail as in process studies, covering sub-sectors, companies and individual products. They can therefore overcome shortcomings associated with IO and process methods (Minx et al., 2008b). This is a field in its own right and one that would deserve a separate discussion beyond the scope of this paper. Further discussions of hybrid approaches can be found elsewhere (e.g. Suh, 2004; Rebitzer, 2005; Lenzen et al., 2007; Lenzen, 2008b, 2008c; Crawford, 2008).

We have not covered the capacity of generalised IOMs for CF applications in the context of scenario analysis. Even though important for supporting decision-making, scenario analyses have received relatively little attention in the literature so far (Guan et al., 2008; Hubacek et al., 2009; Wood et al., 2009). Generalised IOMs have two major appeals in this context. First, national accounts can be linked to existing macro-economic models. This allows the generation of CF appraisals that are consistent with available macro-economic policy scenarios (e.g. climate change models, fiscal models etc). Product carbon roadmaps, for example, can be used to identify priority areas for integrated

[12] The level of sectoral detail varies considerably between countries, from, for example, just over 50 sectors in Sweden to more than 500 sectors in the US and Japan.

product policies given different mitigation pathways (SEI et al., 2009). Second, even though IOMs have been widely criticised for their restrictiveness in scenario generation, Duchin (1998), for example, has challenged this argument for situations when structural shifts in the economy are of concern. She highlights the limitations of dynamic macroeconomic models for considering structural changes and proposes an alternative approach based on expert judgement for the specification of future production structures.

In terms of future research, there are a variety of avenues for the application of generalised IOMs to carbon footprinting:

- There is a need to expand, to consumption as a whole, the responsibility approach suggested in the international climate change negotiations by the Brazilian Proposal (den Elzen et al., 2005). Generalised multi-regional IO research in this context needs to explore how a time series of consumption-based GHG emission accounts could be constructed for all countries in the world. This would not only help to advance the debate on a global climate deal, but would also provide country-specific evidence on how the problem of carbon leakage has evolved over time.
- In the area of hybrid-model applications, further database development is desirable, which integrates process and IO data and minimizes the shortcomings of the two. More efforts need to be put into the development of hybrid models in a multi-regional IO framework.
- More efforts are required to integrate generalised multi-regional IO models with gridded data for a detailed geographically specific study of carbon flows (Gallego and Lenzen, 2008). This will also help when studying smaller urban and rural areas as well as their relationship.
- Finally, there is a general need for applying generalised IO models in scenario applications. Efforts should focus on linkages with established climate change models as well as on the scenario development within the IO context.

While the interest in carbon footprints and climate change clearly provides opportunities to move the environmental agenda forward, it also carries the risk that other pressing environmental problems could be neglected or shifted just to another environmental medium rather than solved. Biodiversity loss, the presence of toxic materials in humans and ecological systems or the increasing shortage of drinking water are other examples of utmost importance. However, the good news for IO practitioners is that IOMs can be versatile and useful as well in these areas.[13] We therefore stress that climate change policies must be part of a wider, integrated environmental strategy. For research and policy advice this means that the CF should only be one important indicator amongst a variety of others that inform environmental policies (Tukker et al., 2006, 2009).

Acknowledgements

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[13] See for example the studies on water footprint and input–output analysis by Hubacek et al. (2009), Wang et al. (2009) or Zhao et al. (2009).

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