The Carbon Footprint of Norwegian Household Consumption 1999–2012

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Summary

Environmentally extended input-output analysis is the prevailing method for national environmental footprint accounting; however, its practical usefulness for consumers and policy makers suffers from lack of detail. Several extensive global multiregional input-output (MRIO) databases have recently been released. A standard framework for linking such databases with the highly detailed household expenditure surveys that are conducted regularly by national statistics offices has the potential of providing analysts in countries worldwide with a powerful tool for in-depth analyses of their national environmental footprints. In this article, we combine the Norwegian consumer expenditure survey with a global MRIO database to assess the carbon footprint (CF) of Norwegian household consumption in 2012, as well as its annual development since 1999. We offer a didactic account of the practical challenges associated with the combination of these types of data sets and the approach taken here to address these, and we discuss what barriers still remain before such analyses can be practically conducted and provide reliable results. We find a CF of 22.3 tonnes of carbon dioxide equivalents per household in 2012, a 26% increase since 1999. Transport, housing, and food were the expenditures contributing the most toward the total footprint. CF per unit of expenditure increased with overall expenditure levels (elasticity: 1.14), notably owing to the correlation between overall household expenditure and transport activities (elasticity: 1.48). Household energy use, which is generally inelastic, is, in Norway, largely based on hydropower and hence contributes comparatively little to the overall expenditure elasticity of household CF.

Introduction

To achieve large-scale carbon emissions reductions, consumption-based strategies, such as demand reduction and lifestyle changes, will be required in parallel with strategies to reduce emission intensities on the producer side (Fischedick et al. 2014). Carbon-emitting industrial processes are ultimately driven by society's demand for goods and services, mostly from private household (hh) consumption (Tukker and Jansen 2006; Hertwich and Peters 2009).

Effective consumer-directed mitigation strategies require a reliable analytical framework for analyzing life cycle carbon emissions embodied in consumption, so-called carbon footprints (CFs). CFs can be calculated using various assessment frameworks that account for indirect emissions. These include process-based approaches, such as life cycle assessment (LCA); however assessments of total household environmental impacts have mostly been based on environmentally extended input-output (IO) analysis (IOA) (Hertwich 2005; Tukker et al. 2010). Though LCAs are coveted for their high level of detail, estimating complete household CFs based on LCA is challenging because there is a lack of studies for many household activities and purchases. Analyses based on IO tables (IOTs) have an advantage in that they take a top-down

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approach, thus avoiding the problem of truncation errors (Lenzen and Dey 2000; Majeau-Bettez et al. 2011).

The results of IO-based assessments are quite useful for understanding the overall CF, its relationship to the consumption pattern, and its development over time. Because of the general coarseness of IO product classifications, differences in specific products, such as organic versus conventional vegetables or mass-produced versus luxury apparel, cannot be resolved. As a result, IO-based assessments are neither able to resolve the effects of some specific lifestyle choices nor to assess the efficacy of some emission reduction proposals.

Consumer expenditure surveys (CES) are conducted regularly by national statistical offices, providing a wealth of data on household purchases at a detailed product level. Social scientists analyze CES to understand household consumption behavior (Fernández-Villaverde and Krueger 2007). CES have also been used to understand how different socioeconomic and demographic factors affect household energy use and CFs (Lenzen et al. 2006; Ornetzeder et al. 2008; Jones and Kammen 2014). By extending IOAs with CES data, more detailed analyses of household consumption can be conducted, paving the way toward further environmental analyses of specific consumption patterns or lifestyles to identify strategies for transitioning toward a sustainable society. Further, the highly detailed description of actual household characteristics and their consumption patterns contained within the CES facilitate cross-sectional analyses along the same vein of research.

Recently, several extensive global multiregional input-output (MRIO) databases have emerged, some of them freely available online (for an overview of some of the most important databases, see Tukker and Dietzenbacher [2013]). In light of this, we expect that future CES/IO studies will increasingly apply systems like these rather than single- or few-region IO systems, given that the accuracy gain of a proper and detailed trade representation is potentially significant (Proops et al. 1999; Lenzen et al. 2004; Wiedmann 2009). To encourage a coherent methodological approach by the research community, allowing comparison across studies, we here outline a practical approach for combining a standard CES data set with one such global MRIO database (see also the related work of Mongelli et al. [2010]). This approach offers two significant improvements compared to a purely IO-based environmental analysis of household consumption, with limited further investment requirements in terms of time, effort, or IO expertise. First, it allows a better understanding of the composition of household final demand in terms of specific purchases and activities, and second, depending on the CES availability, it can usually offer improved time series and various cross-sectional analyses of various households. The environmental assessment itself is performed within the IO system using the standard IO framework (equation 3); although this implies that there is a considerable degree of uncertainty for the environmental effects of detailed CES products, it still allows the assessment of the complete household footprint without complex bottom-up analyses of every single household expenditure category.

To inspire further discussion of the approach taken, and to facilitate the use and understanding of results of CES/IO analyses also to nonexperts of IOA, we offer an exposition of the practical and methodological challenges encountered and a description of the procedure taken here to combine the two data sources. We apply this method to construct a time series of CF accounts for Norwegian households from 1999 to 2012 by combining annual CES data with a global MRIO database for 2007, and discuss how such analyses can serve as a practical tool for policy makers to investigate their national footprint developments. Finally, we identify limitations and weaknesses of our approach, and outline what major methodological challenges remain to be addressed to minimize uncertainties.

The remainder of the article is outlined as follows. In the following section, we provide a brief methodological account of MRIO-based assessments of footprints embodied in consumption, present the IO and CES data sets used in our analysis, and discuss the main practical and methodological challenges involved in the combination of IO and CES data, in general terms as well the specific approach taken here to construct the Norwegian CF accounts. Subsequently, we present and discuss the Norwegian household carbon footprint (hhCF) development over the period, including an in-depth investigation of the 2012 hhCF. In the final section, we discuss challenges and opportunities for future research on the environmental impacts of household consumption and strategies to reduce these, and offer some concluding remarks.

Materials and Methods

Input-Output Analysis–based Footprints of Consumption

Environmental pressures caused in the production of goods and services can be allocated to final consumption activities by applying methodological frameworks such as LCA or environmental IOA. An IOT enumerates the total annual sales by n sectors of an economy to the same sectors in an interindustrial transactions matrix $\mathbf{Z}$ as well as to k groups of final consumers represented in the final demand matrix $\mathbf{Y}$, respectively. In environmentally extended IOTs, a matrix $\mathbf{F}$ tallying total direct emissions (e.g., carbon dioxide [CO_2]) by each sector accompanies the transactions matrix. In MRIO tables, domestic IOTs for $\boldsymbol{m}$ regions are interlinked with bilateral trade data to form a single composite IOT with international trade endogenized.

The central tenet in IOA is that a sector's purchases from other sectors over a year, as well as its total direct emissions, represent direct requirements to produce what was its gross output that year. Mathematically, this allows the construction of a direct requirements matrix ($\mathbf{A}$) from the transactions matrix and the vector of gross sector outputs ($\mathbf{x}$) (equation 1):

$$\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1} \tag{1}$$

By inserting this into the IO standard production balance ($\mathbf{Zi} + \mathbf{Yi} = \mathbf{Zi} + \mathbf{y} = \mathbf{x}$) which states that for each sector, total output equals sales to industries plus sales to final consumers, an expression for total output as a function of final demand can be derived (equation 2):

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{2}$$

Assuming that the requirements matrix is independent of the level and composition of the final demand, equation (2) can be used to determine the gross output by sector arising from any final demand imposed on the system.

The total emissions matrix $\mathbf{F}$ can be converted to coefficient form $\mathbf{S}$ analogously as in equation (1). The vector of total environmental impacts associated with a certain final demand, representing the environmental footprint of consumption, is then simply (equation 3):

$$\mathbf{d} = \mathbf{S}\mathbf{x} = \mathbf{S}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{3}$$

For a further and more detailed mathematical account of IOA in general and of IO-based footprint accounting in particular, the reader is referred to Miller and Blair (2009) and Peters and Hertwich (2004), respectively.

In this analysis, we apply the EXIOBASE 2 MRIO database (Wood et al. 2013), which represents the global economy in 2007, distinguishing 43 countries plus an additional five aggregate regions constituting the rest of the world.[1] Each region consists of 163 industries and 200 products, yielding a total of 9,600 unique region-products. The very high level of product detail was the rationale behind the choice to use EXIOBASE 2 over other available global MRIO systems (see Dietzenbacher and Tukker [2013] for an overview), none of which model the Norwegian economy with more than around 60 industries/products. We deemed this factor to be more important to the present analysis than the advantage of a time series of MRIO tables offered by some other systems.[2] EXIOBASE 2 also includes an extensive set of environmental extensions. For our case study, we focus on greenhouse gas (GHG) emissions, aggregated to the common unit of CO_2 equivalents (CO_2-eq).[3]

The Norwegian Consumer Expenditure Surveys

The Norwegian CES is organized by Statistics Norway (SSB), and is publically available on the SSB website (SSB 2012). The survey was compiled for the first time in 1958, and from 1974 to 2009 it was conducted annually. In each survey, approximately 2,200 individuals were randomly[4] selected from the Norwegian population, and the households they belonged to made up the survey sample. Since 2009, a new scheme has been adopted with more comprehensive surveys with longer intervals. So far, there has been one, conducted in 2012 with an original sample consisting of 7,000 households instead of 2,200. Each household participating in the survey is provided with a diary to record all their purchases over a 14-day period. The households are assigned different 14-day periods over the year in order to even out seasonal variations. Additionally, participating households are invited to an in-depth interview after the reporting period to complement the survey (Holmøy and Lillegård 2014). For surveys up to and including 2009, because of limited sample sizes, the survey presented for each year is a 3-year average with the previous 2 years' surveys; for instance, the presented survey results for 2009 is, in fact, composed of data from 2007 to 2009, converted to 2009 prices.

Since 1999, the expenditures in the Norwegian CES have been classified according to the UN Classification of Individual Consumption by Purpose (COICOP) classification system. Under COICOP, household consumption is classified within 12 divisions, which, in turn, are subdivided into groups, classes, and subclasses. This hierarchical system allows individual countries to adopt custom COICOP sets with varying levels of detail while still subscribing to a common framework. At its most detailed level, the CES data set published by SSB distinguishes 183 unique COICOP commodities (see table S2-1 in supporting information S2 available on the Journal's website). In addition, the database contains results for households grouped according to various characteristics, such as household size and income, though these breakdowns come with a somewhat reduced level of product detail in order to maintain statistical confidence.

Combining Consumer Expenditure Surveys and Input-Output Data

The idea of combining CES and IO data to quantify the environmental impacts of household consumption is not new. In a seminal article, Herendeen and Tanaka (1976) utilized the highly detailed 1960–1961 U.S. CES together with the U.S. IOT to analyze the direct and indirect energy requirements of various types of households and found an energy elasticity of income <1, mostly resulting from relatively stable levels of direct energy use. In a follow-on article, Herendeen (1978) adopted this method for a similar analysis for Norwegian households using the 1973 CES and found the same tendencies.

Since then, a range of studies have been published that attempt to reap the benefits of detail and accuracy of CES with the complete upstream analysis capabilities of IOA to analyze household environmental impacts from various angles (Sastry et al. 1989; Wier et al. 2001; Lenzen et al. 2006; Roca and Serrano 2007; Weber and Matthews 2008; Wood and Garnett 2009; Grainger and Kolstad 2010; Jones and Kammen 2011); see also the overviews provided by Kok and colleagues (2006) and Lenzen and colleagues (2006). These have mostly been cross-sectional analyses, attempting to unearth correlations between environmental pressures embodied in consumption and various explanatory variables available in the CES, such as income, age, household size, or level of education. For want of any standard framework, the combination of the data sets has mostly been performed ad hoc, often with limited details provided on the procedure chosen. Given that IOTs are assembled by national statistical offices to represent a single national economy, they do not reflect increasingly globalized patterns of production. Because of significant differences between energy systems and production patterns, national-level assessments can be misleading (Peters and Hertwich 2006).

General Challenges

In attempting to reconcile CES data with IOTs, several practical and theoretical challenges must be considered. In the following, we discuss these in general terms, while the subsequent section contains a description of the approach taken here, including how these challenges were addressed.

I. An immediately apparent challenge for analysts is the use of different commodity **classification** schemes. CES data are usually available in a very detailed format, whereas economies can be represented in IOTs with anywhere from a couple of dozen to several hundred commodities. Even if the IOT is fairly detailed, constructing the link between CES and IO commodities can be difficult, because IO commodities are not defined with household purchases in mind. Rather, they represent economic sectors, of which potentially only a few deliver goods and services directly for final consumption.

II. Just as CES are typically more detailed than IOTs, they are typically also more up to date and often available on an annual basis. The compilation of IOTs, especially fully trade-linked multiregional tables, is time- and labor-consuming, which often means that they are released with a **time lag** of several years and are not always updated annually. This, in turn, means that an analysis for a particular year might be forced to use an older IOT together with more recent CES data, which entails additional reconciliation steps and additional uncertainties.

III. IO and CES data sets typically apply different **valuation** schemes. In CES tables, purchases are reported as perceived by the consumer, for instance, a purchase of a 1,000 Norwegian crowns (NOK) pair of shoes is recorded as a 1,000 NOK payment in the "Footwear" commodity group. The standard in IOTs is to record the (trade and transport) margins component of a purchase separately as payments to the margins sectors. Further, direct taxes on products are deducted from the purchase sum. With a tax rate of 25%, the purchase in this example would be recorded as a final demand of 800 NOK, distributed as (for example) payments of 500 NOK to the "Clothing and footwear" sector and 300 NOK to the "Trade" sector. These two valuation schemes are referred to as *purchasers' prices* (pp) and *basic prices* (bp), respectively. The practical implication is that CES consumption data must be converted from pp to bp before the IOA can be conducted. Such a conversion requires detailed information on tax and margin rates, both of which are often available in IO statistics, but also are only available at the aggregated product group level.

IV. Several factors can lead to mismatches in the data sources' report of overall household consumption levels. Among these are different methods to estimate national totals from survey samples, as well as mismatched definitions of households and their consumption. A third important factor is a well-known problem of significant and biased **under-reporting** in CES. In other words, the sum of all expenditures according to the CES will usually be significantly less than the total household consumption as given in macroeconomic statistics. This under-reporting is typically biased toward certain product categories, where the products are of such a nature as to make the respondents less likely to correctly report that particular purchase, or less likely to complete the survey at all (Mørk and Willand-Evensen 2004; Heinonen et al. 2013; Holmøy and Lillegård 2014). Examples include purchases of sweets, of alcohol and drugs, and expenses related to medical emergencies, funeral services, and various infrequent purchases.

V. Though the lion's share of a household's CF is embodied in the products it consumes, there is also a significant portion that consists of **direct emissions** by the household, notably residential fuel use and tailpipe emissions from private cars. In IO systems, the households sector is usually modeled as exogenous to the industrial-economic system. In practice, this means that direct emissions are not calculated in the model, they are simply given as a static quantity. Typically, the direct emissions accounts accompanying an IOT are only provided as economy-wide totals. Thus, any calculations of the direct emissions component of hhCF with any detail beyond the national household average must be added separately by the analyst.

VI. In CES, only amounts of each product consumed are recorded; no distinction is made of the share of household purchases that are **direct imports**. Though not essential, it is well known from previous MRIO analyses that emissions embodied in the same products manufactured in different countries can be widely different.[5] For this reason, an estimate of direct household imports of certain products can give non-negligible effects on results.

Approach Taken in the Present Analysis

The following is a sequential account of the practical approach taken here to reconcile the Norwegian CES with the EXIOBASE 2 database, to allow for the calculation of a CF time series for Norwegian households. The challenges listed in the previous section are addressed below in the order in which they arose; hence, for clarity, references are made to these items through their roman numerals. The reader is further referred to section S1-1 in supporting information S1 on the Web, where the procedure is shown in more detail.

A time series of the annual purchases by the average Norwegian households according to the CES was established. (II) Because the IOT was based on the year 2007, the CES purchase data were converted to 2007 prices by using price indices published by SSB (2014a). The price index data set uses its own product classification system and contains indices for 47 product groups at the most detailed level; hence, a table associating each COICOP product with a price index group had to be constructed. Following the conversion of all the consumption data to 2007 prices, a further conversion was made from NOK to EUR (Euro) using the average 2007 exchange rate (OANDA 2014).

To allow the application of CES consumption vectors on the IO system, a concordance matrix linking each CES commodity to one or more IO sectors was constructed (see item I above). Because the relation was generally many-to-many, an iterative approach was taken to populate the matrix. First, a binary many-to-one initial estimate was constructed by assigning each CES product a primary IO counterpart based on the authors' own judgment of product similarity. In a second step, possible additional links were identified. Finally, weights were manually transferred from the primary to the secondary links based on a benchmarking procedure, where the converted version of the CES consumption of the average Norwegian household for 2007 (scaled up to the national total) was compared to the Norwegian final consumption by households (available in purchasing prices) according to the Norwegian supply and use table (SUT) used in EXIOBASE 2.

The comparison showed that the total Norwegian household consumption according to the CES was 15% lower than that assumed in EXIOBASE 2, which is based on the Norwegian SUT (IV). Based on the assumption that this discrepancy was caused by under-reporting in the CES, this was added as "Consumption not captured by the CES" and allocated to a mix of IO sectors based on obvious discrepancies following the initial allocation as well as knowledge of the biased nature of CES under-reporting (Mørk and Willand-Evensen 2004). This under-reported amount was assumed to be structurally static and was scaled according to total CF values in the temporal and cross-sectional analyses.

Following the classification conversion, the CES consumption data must be converted to basic prices, which is the valuation scheme used in EXIOBASE 2 (III). EXIOBASE 2 is constructed from national SUTs, which include household consumption vectors valued in purchasers' prices, as well as broken down on its basic price, taxes, and margins components. A comparison of these was used to establish tax and margins shares of household purchases for each of the EXIOBASE 2 commodities. In the resulting algorithm used to convert CES data from pp to bp, taxes and margins for each commodity were deducted assuming these shares. Subsequently, the margins payments were redistributed as purchases from the margins sectors, according to the distribution in EXIOBASE 2.

Further, to fit the MRIO structure, the amounts and origins of consumed products directly imported by households must be estimated (VI). In an MRIO table, the household final demand of each region is given as a ($mn \times 1$) vector, that is, it lists household purchases of all n products from all m regions. By simply calculating shares from the final demand matrix, direct import shares can be estimated directly.

Finally, the distribution and temporal development of direct household emissions must be obtained from secondary sources (V). According to EXIOBASE 2, these emissions amounted to 7.8 million tonnes carbon dioxide equivalents (t CO_2-eq) for Norwegian households in 2007. In our assessment, we obtained breakdowns of direct household emissions by year and emission source from statistics Norway (SSB 2013). The direct emissions were allocated to own vehicle operation and to housing, with a distribution of 85/15%, respectively, in 1999, gradually changing to 90/10% in 2012. The shift from housing to transport was the result of the phasing out of residential oil-fired heating systems, combined with increased private car use (SSB 2014b).

Results

Norwegian Household Carbon Footprint, 2012

The average Norwegian household spent 511,000 NOK[6] on consumption of goods and services in 2012, carrying a total CF of 22.3 tonnes carbon dioxide equivalents per household (t CO_2-eq/hh). The average CF *multiplier*, that is, the carbon emissions embodied in each unit of expenditure, was 44 grams carbon dioxide equivalents per Norwegian crown (g CO_2-eq/NOK). The differences among CF multipliers of individual COICOP commodities are large, however. In figure 1, the Norwegian hhCF is broken down by the 12 COICOP divisions, with the footprint of each visualized as a product of annual expenditures per household and the average CF multiplier of the division. The overall hhCF is dominated by expenditures in the transport, housing, and food divisions, but through different mechanisms: Whereas housing contributes significantly mainly from its large share of the overall household budget, the CF related to transport is almost double, owing to the fact that every NOK spent on transport led on average to emissions of 95 g CO_2-eq, compared to only 29 g CO_2-eq/NOK for housing.

Of the total household CF, direct emissions by households constituted 16.5% or 3.7 t CO_2-eq/hh. Direct emissions in the housing category are very low in Norway, compared to most other industrialized countries, given that Norwegian households predominantly use electricity for cooking and space heating. The fact that the Norwegian electricity mix is largely based on hydropower serves to further lower the overall CF intensity of housing.

The result that food, transport, and housing are the consumption groups contributing the most toward the total hhCF is in agreement with the findings of several previous studies (Tukker and Jansen 2006; Hertwich and Peters 2009; Tukker et al. 2011). Transport is relatively more important in Norway than in other countries for the reasons mentioned above, combined with several factors that serve to increase the travel distances of Norwegians, including low population density, limited rail network, and high affluence. In recent years in particular, there has been a tremendous increase in air travel by Norwegians (Denstadli and Rideng 2012). Because of the nature of the CES, however, some emissions are allocated differently than in standard CF analyses. Notably, food consumed in restaurants and similar are counted in the "Restaurants & hotels" rather than the "Food" division here. Further, the "Recreation and culture" division includes the expenditure group "Package holidays," which means that some air travel CF is counted in this division insofar as households do not purchase flight tickets separately.

The MRIO framework allows the tracking of where the emissions embodied in any consumption activity occur. The trend of increased globalization of supply chains has caused consumers in developed countries, although sustaining high

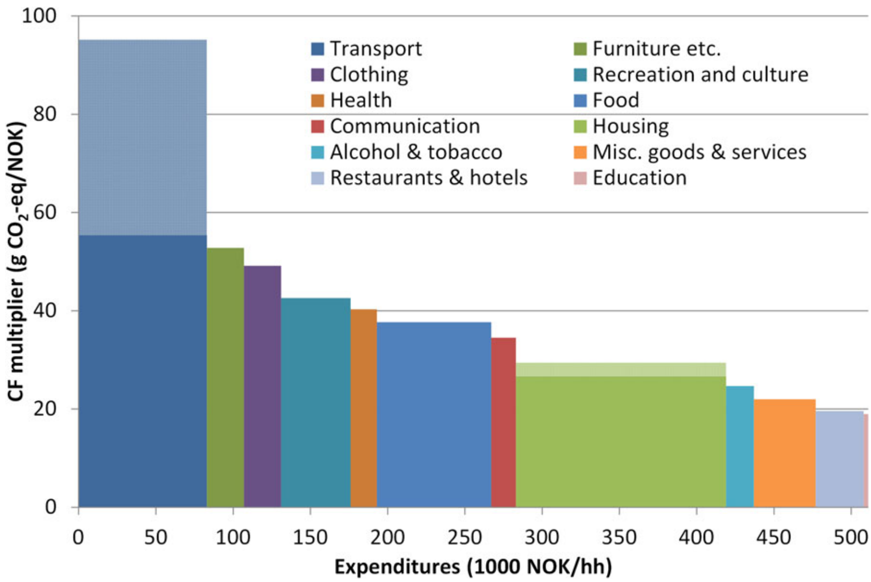

Figure 1 Norwegian household expenditures and the average carbon footprint intensities of each COICOP division, 2012. The lighter shaded parts of the "Transport" and "Housing" columns constitute direct emissions by households. In the input-output tradition, these are defined as emissions directly brought about by household members, for example, from gas stoves or private vehicles. COICOP = UN Classification of Individual Consumption by Purpose.

Table 1 Consumption-based account of Norwegian household purchases: regional distribution of effects

	Value-added generation (%)	*Greenhouse gas emissions (%)*
Norway	70	40
EU	15	22
USA	5	4
China	1	12
Other	9	22

Note: EU = European Union; USA = United States of America.

environmental footprints, to be geographically separated from the effects of many of the environmental burdens of consumption, which may occur far upstream. A substantial share of the processing and manufacture of final and intermediate products ultimately delivered for consumption by Norwegian households has been shifted to developing countries, notably China: In 2012, 12% of the emissions contributing to the Norwegian hhCF took place in China (table 1). By comparison, a very small amount of the value generation occurs in China. The analysis of effects occurring in the United States from Norwegian household consumption showed a quite different picture, with value added and emissions contributing similarly toward the total. Overall, 70% of the value added embodied in Norwegian household consumption was generated domestically, whereas this share was only 40% in terms of embodied carbon emissions.[7] Among the emissions occurring abroad, the largest contributing emitter was China; however, the emissions in the combined European Union (EU) region were considerably larger still, with Germany being the most contributing emitter by a large margin (see table S2-3 in supporting information S2 on the Web for a complete breakdown of emissions by region).

The big geographical difference observed here between value added and GHGs embodied in final consumption is owing to the fact that they largely accumulate at different stages of the supply chains. Whereas embodied CF is typically associated with emissions in secondary (manufacturing) sectors, the majority of value added is generated closer to the end user. A contribution analysis of the GHG emissions and the value added embodied in Norwegian household demand showed that whereas 60% of upstream emissions occurred in secondary sectors, 71% of the value added was generated in tertiary sectors (see table S2-4 in supporting information S2 on the Web).

Across the population, total CF per household increased rapidly with overall expenditure levels (table 2). In the most affluent decile, the average expenditures per household were 4.1 times those in the poorest decile, whereas their average CFs were 5.1 times higher. Overall, we estimate an expenditure elasticity of CFs of 1.14 ($R^2 = 0.999$). This was owing to the fact that affluent households spent relatively more on carbon-intensive commodities; in fact, the top three elasticities in table 2 coincide with the three most CF intensive commodities in figure 1 (transport, furniture, and clothing).

The two lowest-income groups in table 2 exhibit some interesting differences. The households in the poorest decile of Norwegian households typically do not own a car, nor do they own their house, both in contrast to the large majority of Norwegian households overall (see tables 10444 and 10448 in SSB [2012]). For this reason, the hhCF in the lowest-income decile is disproportionally small for these consumption categories. The reduced transport CF in particular contributes to a low CF per NOK spent overall for the lowest-income cohort. Lower car

Table 2 Total expenditures and carbon footprint by COICOP division, 2012

	All hh	*Decile 1*	*Deciles 2+3*	*Deciles 4+5*	*Deciles 6+7*	*Deciles 8+9*	*Decile 10*	ϵ_{CF}	R^2
Exp. per hh (10^3 NOK)	*511*	*229*	*342*	*410*	*535*	*678*	*949*		
CF per hh (kg CO_2-eq)	22,170	8,557	14,081	16,964	23,448	30,207	43,524	1.14	0.999
01 Food	3,018	1,390	1,862	2,386	3,376	4,145	5,209	0.98	0.986
02 Alcohol & tobacco	333	198	257	265	356	412	551	0.72	0.983
03 Clothing	1,162	529	536	771	1,152	1,730	2,717	1.26	0.932
04 Housing	4,088	1,744	2,713	3,720	4,215	4,879	8,041	1.02	0.976
05 Furniture, etc.	1,280	408	788	983	1,325	1,763	2,666	1.29	0.994
06 Health	632	421	470	581	679	758	915	0.57	0.978
07 Transport	7,864	1,776	5,083	5,569	8,421	11,335	15,923	1.48	0.955
08 Communication	589	457	383	434	640	762	995	0.65	0.791
09 Recreation	1,883	1,091	1,139	1,242	1,957	2,596	3,884	0.97	0.906
10 Education	26	26	13	17	24	37	51	0.70	0.475
11 Restaurants	484	212	316	383	471	676	937	1.05	0.995
12 Misc.	811	305	523	614	832	1,116	1,635	1.17	0.998

Note: Results for all households, as well as by expenditure levels. The two rightmost columns show expenditure elasticity of CF (ϵ_{CF}) and associated R^2 values. The CF of each COICOP division *i* (as well as the total) is regressed to $CF_i = ax^{\epsilon_{CF}}$, where *x* represents total expenditures per household. COICOP = UN Classification of Individual Consumption by Purpose; Exp. = expenditure; hh = household; NOK = Norwegian crowns; CF = carbon footprint; t CO_2-eq = tonnes of carbon dioxide equivalents; Misc. = miscellaneous.

and house ownership rates leave more income disposable for other consumption, which reduced this effect to some degree: For the COICOP divisions Clothing (03), Communication (08), and Recreation (09), the CF of decile 1 is similar or even higher than those of deciles 2 and 3.

The observed CF elasticity of expenditures of 1.14 is an unexpected result, in contrast with the findings of Herendeen (1978) and most studies since, which have generally found elasticities less than 1 (Lenzen et al. 2006). Two limitations of the present cross-sectional analysis could potentially affect our result: First, the CES broken down by income deciles as published by SSB features less product detail than the full survey because of reduced sample sizes, and the deciles are aggregated so our elasticity calculation is performed over only six income groups. Further, the emissions model applied here does not distinguish luxury products; a luxury car at twice the price of an average car is, for example, assumed to carry twice the CF (Hertwich 2005).[8] The same limitations, however, also affect most other studies reviewed by Lenzen and colleagues (2006). On the other hand, some important factors support the result of a high elasticity. First, in stark contrast to most countries, emissions from direct household energy use are almost negligible in Norway, where energy for cooking and space heating is mostly based on electricity from hydropower. Direct energy use in households is generally inelastic; this has been an important reducing factor for the overall CF elasticity of income in previous studies (Vringer and Blok 1995; Lenzen et al. 2006; Jones and Kammen 2011). Second, consumption in the travel and transport category is associated with high carbon intensities and high elasticities; in a recent case study on German consumers, Aamaas and colleagues (2013) found much higher climate impact from travel for the higher-income cohorts, with an elasticity of 1.17 for air travel.

Footprint Development 1999–2012

The time series analysis shows that the overall changes in consumption from 1999 to 2012 led to an increase in the CF of Norwegian household consumption by 25%, corresponding to an average of 340 kilograms CO_2-eq per year. Over the same period, consumption volumes rose by 26%. Because our analysis is based on a detailed consumption time series coupled with a static technology-emissions model, we expect the overall CF development to match that of the real expenditures fairly well; however, the detailed results show that the increase was neither linear nor monotone (figure 2). Much of the growth occurred over 3 years, from 2004 to 2007, whereas 2 years (2003 and 2008) had slightly reduced CF compared to the previous year.

The CF of the three consumption categories highlighted here and in previous studies as the main contributors toward the total hhCF (food, shelter, and mobility) all grew significantly over the period. Despite an overall standstill in consumption levels over the first 5 years, the CF of housing expenditures still increased by a total of 8%. The CF of transport, despite an overall growth, showed some fluctuation; this was mainly found to be caused by annual variation in private car sales. The CF of food grew steadily, owing in part to a dietary shift from staple foods toward meat and processed food. For a more in-depth discussion of the developments by category, the reader is referred to the Supporting Information on the Web.

The ceteris paribus assumption implied in the present analysis might entail substantial errors for certain product types, given that changes in technology or international trade and consumption patterns can vary significantly over a period of 13 years. Hence, it must be stressed again that the temporal development observed is from changes in consumption volumes

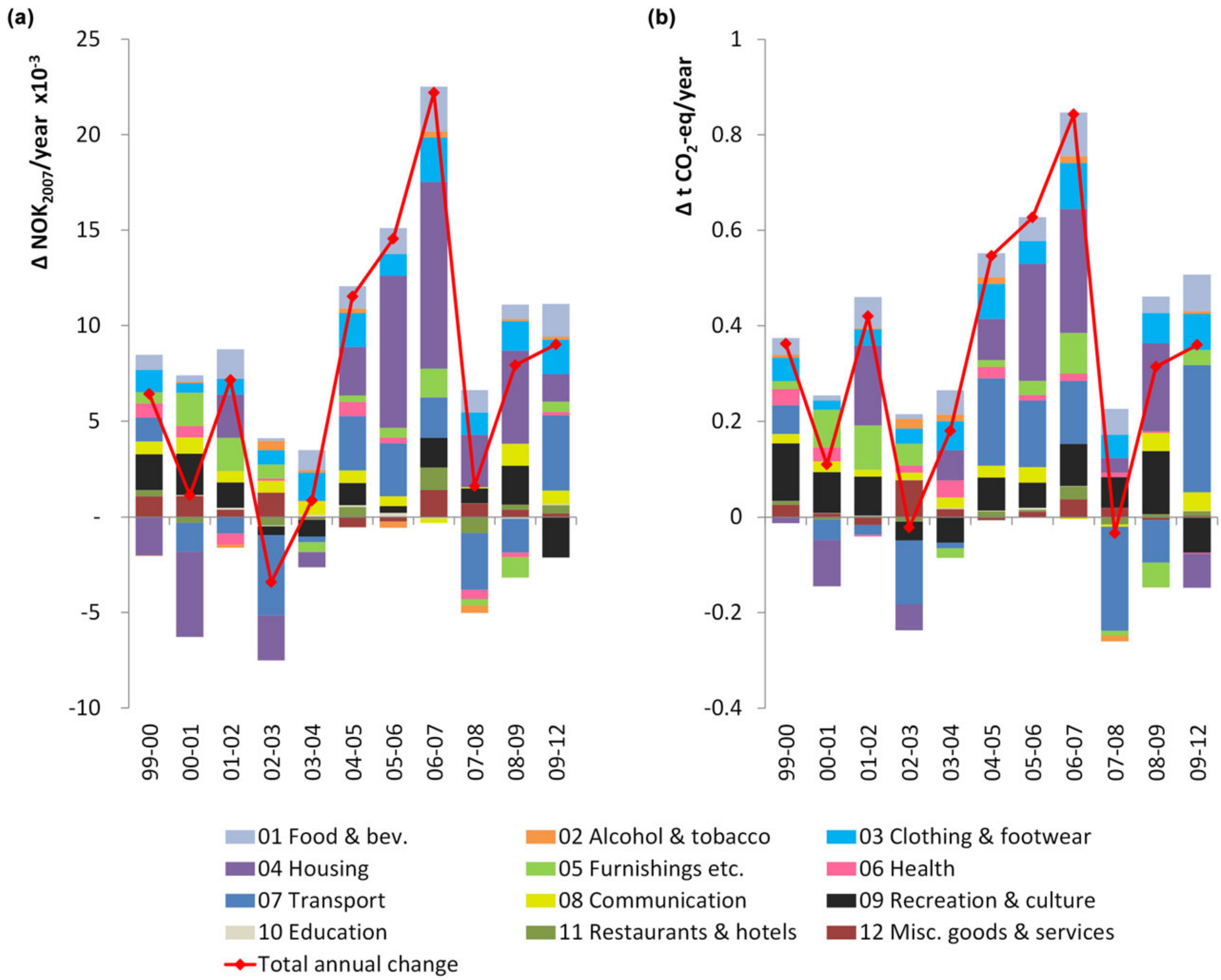

Figure 2 Annual change in expenditures (a) and their associated carbon footprints (b) by COICOP division, 1999–2012. Changes in the final 3-year period were divided by 3 to get average annual change. Average household size fluctuated from 2.19 persons per household (p/hh) in 1999 through a maximum of 2.24 p/hh in 2002 to a minimum of 2.12 p/hh in 2012. COICOP = UN Classification of Individual Consumption by Purpose.

and patterns alone. Previous structural decomposition analyses have found that technological improvements have generally led to reduced carbon emissions intensities, but that these have not been sufficient to offset the emission growth caused by increased affluence (Peters et al. 2007; Guan et al. 2008).

Discussion and Conclusions

Despite widespread media attention and public concern about climate-change prospects, the CF of Norwegian households increased across all COICOP divisions from 1999 to 2012. Fundamentally, this was related to the sustained growth in the real income of Norwegian households observed over the past decades, particularly since the turn of the millennium, which, for the most part, was realized as increased consumption in general (Vrålstad and Melby 2009).

In order to lessen the environmental burdens of private consumption, a solid and detailed understanding of the underlying links between consumption and overall impacts is required. With the recent efforts to construct databases that are economically, environmentally, and geographically detailed, up to date, and reliable, MRIO analysis remains the best-suited tool for consumption-based assessments of household environmental impacts including supply-chain effects. Still, pure IO-based assessments have thus far been of limited practical value for specific policy design because of a lack of detail. The approach taken here to combine consumer expenditure surveys with IO models provides a straightforward—albeit partial—solution to the traditional IO challenges of product detail and timeliness.

Detailed temporal analyses of household CFs have a significant potential for informing the public debate and policy on climate-change mitigation, and the well-established CES tradition provides a promising resource for extending IOAs and yield results that are more directly relatable to the daily activities of households. In the interest of reducing the CF of household consumption, two key challenges should, in the authors' view, be the focus of future studies in this vein. First, further efforts should be made to establish a commonly accepted standard framework for environmental footprint analyses using detailed local data combined with the comprehensive global MRIO systems that have come available as of recently. Such a framework should be straightforward enough to allow and encourage analyses by IO practitioners without the need for extensive investments of time and effort in order to understand and work with the data, in the interest of promoting consumption-based accounting of impacts to complement the territorial or production-based approach.

Second, a significant limitation to IO-based analyses of household environmental impacts still remains, concerning the level of product detail. We have here tried to improve this from the household expenditures side only, by using CES data to disaggregate the standard IO final demand. The extensions made here to the standard IO framework allow a significantly improved understanding of the various everyday household activities' contribution to overall household environmental impacts at a relatively modest cost in terms of time and effort, by capitalizing on already available official statistical data sets. It also allows, once the correspondence table from the household purchases in CES to IO classification has been established for the base case, full utilization of the various temporal and cross-sectional breakdowns that may be available in the CES data set. From the side of calculating environmental intensities, however, the analysis is still performed at the IO product level. This can be addressed by moving toward hybrid models that capitalize on product-specific results from life cycle databases, which would potentially greatly improve the ability to distinguish between functionally similar, but environmentally different, commodities. Global MRIO databases are continuously developing and becoming increasingly detailed, facilitating the construction of such models. Still, the lack of an overarching standard, potentially leading to a range of models using different data and assumptions that may produce results that are more or less in conflict, may hamper the acceptance of such analyses as a basis for policy.

The present analysis highlighted the diversity in the set of household activities that constitute the overall Norwegian household CF; most household activities contribute toward the total to a considerable degree. This reflects the pervasiveness of carbon-emitting processes in society, suggesting the need for large-scale emission abatement strategies to be economy-wide and comprehensive, aiming for overall footprint reduction through a combination of several strategies targeting a range of sectors and activities from the producer as well as the consumer side.

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Notes

1. EXIOBASE 2 is the latest version of the database presented by Tukker and colleagues (2013) in the special issue cited in Section 1.1 (Dietzenbacher and Tukker 2013).
2. The next update of EXIOBASE, scheduled to be released in 2016, will also feature a time series.
3. Note that emissions from land use, land-use change, and forestry (LULUCF) are not included in EXIOBASE and hence not in this analysis.
4. From 1974 to 2009, persons 80 years or older were excluded from the population before the sample was drawn; in 2012, this threshold was raised to 85 years. Persons living permanently in institutional households (e.g., nursing homes) were also excluded.
5. The same, of course, holds true for many domestic products which fall into the same sector in an IOT but are, in reality, very different.
6. The average exchange rate in 2012 was 7.48 NOK/EUR or 5.82 NOK/USD (www.oanda.com/currency/historical-rates/).
7. Prell and colleagues (2014) compared value added and sulfur dioxide embodied in U.S. consumption and found similar results.
8. Girod and De Haan (2010) take a different assumption, converting monetary expenditures to consumption of functional units to account for quality changes, which is also not without problems. They find that a significant portion of the expenditure increase with household income is attributable to increased price per functional unit consumed; however, it is not clear how the environmental impact scales with the price of the product.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: This supporting information is a sequential account of the practical approach taken to reconcile the Norwegian CES with the EXIOBASE 2 database, to allow for the calculation of a carbon footprint time series for Norwegian households. Additionally, this document includes a discussion related to figure 2 in the article.

Supporting Information S2: This supporting information provides the following tables: data from the Norwegian consumer expenditure survey (table S2-1); product classifications as used in the Norwegian consumer expenditure surveys and the EXIOBASE input-output tables (table S2-2); total Norwegian household carbon footprint (2012) by the regions in which the emissions occurred (table S2-3); Norwegian household carbon footprint by the aggregated regions in which the emissions occurred (2012), per expenditure group (table S2-4); and a breakdown of emissions and value added footprints by the economic sector types where the emissions/value added generation occurs (table S2-5).