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The Swedish footprint: A multi-model comparison

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ABSTRACT

Sweden has a large per capita carbon footprint, particularly compared to the levels recommended for maintaining a stable climate. Much of that footprint falls outside Sweden's territory; emissions occurring abroad are “embodied” in imported goods consumed in Sweden. In this study we calculate the total amount and geographical hotspots of the Swedish footprint produced by different multi-regional input-output (MRIO) models, and compare these results in order to gain a picture of the present state of knowledge of the Swedish global footprint. We also look for insights for future model development that can be gained from such comparisons. We first compare a time series of the Swedish carbon footprint calculated by the Swedish national statistics agency, Statistics Sweden, using a single-region model, with data from the EXIOBASE, GTAP, OECD, Eora, and WIOD MRIO databases. We then examine the MRIO results to investigate the geographical distribution of four types of Swedish footprint: carbon dioxide, greenhouse gas emissions, water use and materials use. We identify the hotspot countries and regions where environmental pressures linked to Swedish consumption are highest. We also consider why the results may differ between calculation methods and types of environmental pressure. As might be expected, given the complexity and modelling assumptions, the MRIO models and Statistics Sweden data provide different (but similar) results for each footprint. The MRIO models have different strengths that can be used to improve the national calculations. However, constructing and maintaining a new MRIO model would be very demanding for one country. It is also clear that for a single country's calculation, there will be better and more precise data available nationally that would not have priority in the construction of an MRIO model. Thus, combining existing MRIO data with national economic and environmental data seems to be a promising method for integrated footprint analysis. Our findings are relevant not just for Sweden but for other countries seeking to improve national consumption-based accounts. Based on our analysis we offer recommendations to guide future research and policy-making to this end.

1. Introduction

1.1. Environmental footprints

Current levels and patterns of consumption in developed countries are unsustainable, using too many raw materials and producing too much waste and pollution (Lorek and Vergragt, 2015). This is reflected in developed countries' high carbon, land and material footprints – estimates of the global pressures on ecosystems and natural resources that are linked to a country's consumption. For most developed countries, including Sweden, much of that footprint pressure falls outside of the territory, in the countries supplying Sweden's imported goods (Schmidt et al., 2018 (this issue); Steen-Olsen et al., 2012). This paper compares the global geographic “hotspots” of environmental pressures in Sweden's consumption footprints that are identified in different models. It explores the possible underlying causes of differences between the model results. The research is motivated by the objective to support policy and decision-makers in monitoring Sweden's footprint and provide recommendations for future research to improve the accuracy of national footprint estimates.

Sweden is now one among a number of countries that have

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produced and analysed their environmental impacts of consumption. The Swedish national statistics agency (Statistics Sweden, or SCB) has published national consumption-based carbon dioxide (CO_2) emissions accounts (carbon footprints) since the end of the 1990s, with current estimates of GHG emissions per product group for 2008–2014 publicly available. In addition, a consistent time series from 1995 to 2009 of data on the CO_2 emissions from Swedish consumption was published by Statistics Sweden in 2015 (Statistics Sweden, 2015) including a comparison of calculation methods using two different models. Earlier pilot studies by Swedish government agencies and research organizations had reported comparable footprint findings (Finnveden et al., 2001; Palm et al., 2006; Naturvårdsverket, 2008).

Work to develop similar consumption-based accounts for numerous countries has also been ongoing over a number of years, examining a wide range of environmental pressures such as the carbon footprint (Hertwich and Peters, 2009; Wiedmann et al., 2010); the water footprint (Hoekstra and Mekonnen, 2012) the land footprint (Weinzettel et al., 2013); and the material footprint (Wiedmann et al., 2015). Footprint results are now publicly available for many countries (Wood et al., 2018).

1.2. *Implications for national environmental policy – the Swedish case*

While the varying results that different models produce for the same footprint indicator may be confusing for communication purposes. There are benefits in examining the outputs of models with varying designs or data sets employed; this variability can be seen as repeated analyses concerned with the same basic set of questions, demonstrating plausibility of a consumption-based accounting approach and raising new policy questions.

This is particularly relevant in Sweden, where a number of national policies and strategies aim to tackle unsustainable consumption. A central component is the Generational Goal, the overarching goal of the national system of environmental objectives. This calls for solving the major environmental problems in Sweden within a generation, without exacerbating health or environmental pressures in the rest of the world (Swedish Environmental Protection Agency, 2012). In addition, Sweden is a signatory to Agenda 2030 and Sustainable Development Goals, with sustainable consumption and production as Goal 12 (United Nations, 2015), and recently launched a national Sustainable Consumption Strategy in December 2016 (Government Offices of Sweden Ministry of Finance, 2016). Regular monitoring of the global impacts of Swedish consumption will be essential to these efforts.

2. Materials and methods

2.1. *Consumption-based environmental impact accounting*

For this study, the Swedish footprint results were compiled from five MRIO databases: EXIOBASE, WIOD, Eora, OECD and GTAP. These results were also compared with Statistics Sweden's calculations, based on an import-adjusted single-region input-output model. All of these models employ standard input-output analysis to calculate environmental pressures associated with final consumption. For the specific method behind each of the MRIOs, refer to the references listed in the short model descriptions below.

Consumption-based environmental impact (footprint) accounting provides an alternative and complementary perspective to production-based accounts. *Production-based accounts* cover the environmental impacts of production within a country's territory including of those goods and services exported. *Consumption-based accounts*, in contrast, look at environmental pressures linked to the production and delivery of all goods and services consumed in the country, regardless of where they are produced (Peters, 2008). With solely production-based accounts the benefit conveyed to consumers through international trade is ignored (Davis and Caldeira, 2010). A number of calculations and assumptions are required to estimate a consumption-based account. This is now commonly done using environmentally extended input-output analysis (EE-IOA) (Tukker et al., 2009; Tukker and Dietzenbacher, 2013; Wiedmann, 2009).

EE-IOA is based on an established national accounting and analytical method used in economics, representing the structure of the economy in a matrix of transactions between industrial sectors and final consumers (Miller and Blair, 2009). An input-output matrix quantifies the transactions that take place between industries in an economy, factoring in inputs to production like labour or capital, and delivery of outputs to the final users (for example for consumption or export) (Duchin, 1998). When compiled at the national level, an input-output model represents the supply chains of an economy and total demand for goods and services. Environmental footprints can then be calculated by “extending” the monetary tables with environmental data and then applying the Leontief model (Leontief, 1970) to reallocate pressures from the industry of production to the products of final demand.

At the international level considerable efforts have been made to expand EE-IOA analysis and calculate footprints for many nations simultaneously using environmentally extended multi-regional input-output (MRIO) models (Lenzen et al., 2013; Timmer et al., 2015; Tukker et al., 2009; Tukker and Dietzenbacher, 2013). The basic methodological principles and structure are the same as for EE-IOA, but the models cover a number of countries and country groups (all termed regions) in the same matrix, describing the specific production technology for each region and how they are linked via international trade.

As a result, there are now a number EE-MRIO databases from which consumption-based footprint results for Sweden can be extracted, covering a range of indicators and years. However, constructing an EE-MRIO is far from a trivial task, hence there are a relatively small number of models published and available internationally.

Although the underlying calculation methods used in all these EE-MRIOs are essentially the same, published studies show differing results (Moran and Wood, 2014; Owen et al., 2016; Steen-Olsen et al., 2014). Whilst this can be difficult to interpret it is to be expected as, like any model development, the modeller must make a number of important choices about the structure and data components, and these influences the result. For IOA these include: the chosen representation of the global economy (transactions between industrial sectors and countries or world regions); the environmental pressures included, source data and allocation method; and final demand by final consumers. The data and methods used to construct and align each of these components can vary, so it would be surprising if two models using different datasets and harmonization approaches would arrive at exactly the same result. Recent efforts in the MRIO community to investigate the impact of these choices have been collected and published in a special issue of the journal *Economic Systems Research*, titled *A Comparative Evaluation of Multi-Regional Input-Output Databases* (Volume 26, Issue 3, 2014, editorial by Inomata and Owen, 2014).

2.2. *Statistics Sweden (SCB)*

The model devised by Statistics Sweden is a single-country input-output database. It uses national economic data from the Swedish National Accounts with detail for 94 products and industries, along with environmental pressure accounts of emissions to air at the industry level. The GHG emission footprint is calculated in the current consumption-based accounts, while sulphur dioxide (SO_2), nitrogen oxides (NOx) and ammonia (NH_3) footprints are being developed. The footprint estimates of Swedish domestic consumption are complemented with data on the estimated environmental pressures (GHG emissions) from imported goods and services, and the quantity of goods and services imported to and exported from Sweden. As it is a single-country input-output model not an MRIO, the GHG emissions embedded in imported goods must be approximated. The factors used to calculate emissions associated with goods and services produced in Sweden are taken as a baseline and then adjusted for each country globally, using the GHG emissions from the global EDGAR (Emissions Database for Global Atmospheric Research) database and GDP per country. These data are also further benchmarked using WIOD.

For model methods see Naturvårdsverket (2016).

2.3. GTAP

The GTAP (Global Trade Analysis Project) database is one of the most widely used MRIOs in academic publications. The GTAP database is formulated principally as a representation of the world economy for use in computable general equilibrium (CGE) modelling, and while CGE and input-output modelling requires a similar foundation of data, the structure of the database is set up for input into a CGE model and a number of processing steps have to be taken to transform this into an input-output table for use in consumption-based accounting (Peters et al., 2011). One of the advantages of the GTAP database is that it has existed for a long time and is widely used and, despite a significant time-lag in publication (the most recent update was in 2015, bringing the data up to 2011), seems able to fund continuous updates and consistent publication over time.

For model methods see: Aguiar et al. (2016).

2.4. EXIOBASE3

EXIOBASE is a global, detailed environmental-extended multi-regional supply-and-use table (SUT)/input-output database. It was developed by harmonizing and detailing SUTs for a large number of countries, estimating emissions and resource extraction by industry, linking the national EE-SUT via trade to a multi-regional EE-SUT, and producing an environmentally extended multi-regional input-output table from this. This international input-output table can be used for the analysis of the environmental impacts associated with the final consumption of product groups. A main strength of EXIOBASE is that it uses a highly detailed disaggregation of economic sectors and provides a wide range of environmental extensions.

For model methods see: Stadler et al. (2018), Tukker et al. (2013), and Wood et al. (2015).

2.5. WIOD

The WIOD database is a result of an EU-funded (FP7) project and was released in 2012. It is based almost entirely on official data sources, with the main interpolation being for gap-filling years. It includes time series of world input-output tables for forty countries worldwide and a model for the rest-of-the-world, covering the period from 1995 to 2011. The database also has information on air emissions, water use, material use and energy use for the years 1995–2009 from which it is possible to calculate a variety of footprints.

For model methods see: Dietzenbacher et al. (2013).

2.6. Eora

The Eora MRIO project uses extensive automation and a data resolution engine to merge together disparate data sources into a single, composite world MRIO. The database covers 189 countries for each year in the period 1990–2012, and uses a mixed input-output table structure so that the input-output tables of individual countries are each preserved in their original detail. One drawback to this approach is that since different countries are represented in different classifications, inter-country comparison is more difficult. The advantage is that the classification supplied by each country is maintained, making it easy to combine or compare data between national statistics and the MRIO database. The database includes a number of environmental extensions including GHGs, land use, water use, air emissions, N and P emissions, and biodiversity loss.

For model methods see: Lenzen et al. (2013).

2.7. OECD

The OECD has a long tradition in creating MRIOs and calculating footprints (Ahmad and Wyckoff, 2003; Nakano et al., 2009). In the past the OECD would produce five-yearly input-output tables for 41 counties. However, with recent development work harmonized national input-output tables with inter-industrial flows of goods and services (produced domestically and imported) are now available in current prices (USD million), for all OECD countries and 27 non-member countries (including all G20 countries), from 1995 to 2011. Until recently, the database did not include any environmental data, had very aggregated industry classifications and was not freely available (Hoekstra et al., 2013). However, the input-output tables have now been made freely downloadable from the website, with more economic data and CO_2 emissions (Wiebe and Yamano, 2016).

For model methods see: Yamano and Ahmad (2006).

2.8. Model comparison

Table 1 shows a summary of the key features of the databases examined in this study, drawing on information from the table in Owen et al. (2014) and including EXIOBASE3, Statistics Sweden and OECD models.

2.9. Hotspot comparison approach

The models were all run with a Leontief demand pull model (Miller and Blair, 2009) in order to allocate production based impacts to country specific final demand. All models were run at the original resolution, before aggregating results to a common classification (Steen-Olsen et al., 2014). Such an approach avoids introducing additional aggregation error into the model (de Koning et al., 2015; Wood et al., 2014). The smallest common country classification is identical to the WIOD country classification, and we thus use that aggregation in results forthwith. As with the sectoral detail, to accomplish comparison across models the results from each model were taken for the 40 individual countries reported by all models, and the remaining countries in each model were aggregated to a “Rest of World” region. In terms of sector aggregation, in this work, we aggregate to country level totals based on the disaggregated calculation. All models are run for maximum number of years based on data availability, and where a common year (e.g. 2011) is not available for cross-country comparison (this occurs in the environmental extensions of WIOD) we take the latest available year, and explicitly note this in the results. We report both the origin of production and the region of final consumption.

Table 1
Database features, including SCB, GTAP, Eora; EXIOBASE, WIOD and OECD. Note many of the MRIO models have been updated in terms of time-series since the preparation of this work.

	Statistics Sweden (SCB)	GTAP	Eora	EXIOBASE3	WIOD	OECD
Latest available year	2013	2011	2015	2011	2014	2011
Footprints calculated for this study	1993–2012 Emissions from fossil fuel burning, GHG emissions	2004, 2007 and 2011 Emissions from fossil fuel burning, GHG emissions	1990–2012 Emissions from fossil fuel burning, material flow, water	1995–2011 Emissions from fossil fuel burning, GHG emissions, material flow, water	1995–2009 Emissions from fossil fuel burning, GHG emissions, material flow	1995–2011 Emissions from fossil fuel burning
Availability of time series data	1993–2008 in NACErev1.1 2008–2013 in NACErev2.	1990, 1992, 1995, 1997, 2001, 2004, 2007 (all years are not comparable). Harmonized 2004, 2007 and 2011 for comparison in GTAP9	1990–2015	1995–2011	1995–2011 and 2000–2014	1995–2011
Countries or regions	A single regional model with bilateral trade with 201 countries + RoW	139 + RoW in latest year (minimum 66 in earlier years)	189 countries + RoW	43 regions + 5 RoW	40 + RoW (including all EU27)	34 OECD countries and 27 non-member economies + RoW
National input-output tables	input-output table taken from Swedish National Accounts	Regional input-output tables submitted by individual GTAP contributors	74 input-output tables from national statistical offices. Other countries' data taken from the UN National Accounts Main Aggregates Database	Individual countries: SUTs from National Accounts Rest of the World regions: UN National Accounts Official Country data	SUTs from National Accounts	SUTs from National Accounts
Environmental extension availability and sources	Emissions by industry from Swedish Environmental accounts	Sector-based CO_2 emissions derived from IEA energy data	GHG emissions (from EDGAR, IEA, PRIMAP, and CDIAC), land use, water use, air emissions, materials use, nitrogen and phosphorus emissions, FAOSTAT agricultural inputs, and biodiversity loss	Material use and extraction: SERI/WU Global Material Flows Database Energy and emissions: IEA data and emission coefficients (consortium data) Land use: FAOSTAT	Energy use: IEA. Air emissions: Eurostat, UNFCCC and CLRTAP. Material extraction: Eurostat, SERI/WU Global Material Flows Database. Land use: FAOSTAT Water use: (M. Mekonnen and Hoekstra, 2011; M. M. Mekonnen and Hoekstra, 2011a, 2011b; Mekonnen and Hoekstra, 2012)	Electricity trade and energy balance from the IEA
Product/sector detail	97 product-by-product table	57 product-by-product tables	Varies by country; ranges from 26 to 511 sectors, at either product-by-product or industry-by-industry	200 products, 163 industrial sectors, at either product-by-product or industry-by-industry	35 industry-by-industry tables	34 industry-by-industry tables
Classification scheme	Disaggregated version of NACE 2 digit level. Version: NACE rev 2	GTAP classification scheme which combines International Standard Industry Classification (ISIC) with UN Central Product Classification (CPC)	Own classification system	Disaggregation of NACE 2-digit level. Version: NACE rev 1.1	Aggregated version of NACE 2-digit level. Version: NACE rev 1.1	ISIC Revision 3
Expected date of next release	Yearly update	Unknown	Yearly updates with a 2-year lag	Unknown	Funding dependent	Unknown
Accessibility	Free downloadable SIOT as Excel files at 64 products level. Footprint is calculated on commission	Licence fee payable (~£3000); data contained within proprietary software but extractable to Excel	Downloadable, free for academic use	EXIOBASE1 and 2 are both free; downloadable as txt files	Free, downloadable as Excel files	Free, downloadable as CSV files

RoW: Rest of World; IEA: International Energy Agency; SERI: Sustainable Europe Research Institute; WU: Wuppertal Institute for Climate, Environment; FAOSTAT: the statistical system of the Food and Agriculture Organization of the United Nations (FAO); NACE: Nomenclature statistique des activités économiques dans la Communauté européenne (Statistical classification of economic activities in the European Community).

Environmental accounts of production by region and sector of origin **F** are normalized by gross output of each sector **x** to give emissions intensities **S.** In this work **F** and **S** is disaggregated row-wise by country (index *k1*).

$$\mathbf{S} = \mathbf{F}\hat{\mathbf{x}}^{-1} \tag{1}$$

Total emissions (**D**) (dimension *k1* (source country), by *k2* destination country) is calculated using the, Leontief production function, as:

$$\mathbf{D} = \mathbf{S}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{Y} + \widehat{\mathbf{f}^{y}} \tag{2}$$

Where $\widehat{\mathbf{f}^{y}}$ is a diagonalized vector of direct emissions of final demand (e.g. household cooking, driving) of dimension *k1,* D is a matrix (k1 x k2) with k1 rows of regions where emissions are originated and k2 columns of regions where products are consumed. We then obtain two databases of consumption account (**d)** and production account (**f**) by region, where

$$\mathbf{d} = \sum_{k1}\mathbf{D}_{k1,k2},$$

$$\mathbf{f} = \sum_{j}\left(\mathbf{F}_{k1,j\cdot} + \mathbf{f}^{\mathbf{y}}_{\mathbf{j}}\right)$$

These calculations are done for environmental pressure, and for each year, and each model *m*. A simple aggregation to the common classification of 41 regions is then $\mathbf{d^{cc}} = \mathbf{G^{cc,m}}{*}\mathbf{d}$ and $\mathbf{f^{cc}} = \mathbf{f}{*}\mathbf{G^{m,cc}}$ where $\boldsymbol{G^{m,cc}}$ is an aggregation matrix of 1's and 0's that specifies country aggregation between original country classification of each model *m*, and the common country classification. For the total footprint results for Sweden, we simply report the **d** and **f** for the index where *k1* or *k2* correspond to Sweden, for the results that show country of origin, we report **D** and **F** for all values where *k2* corresponds to Sweden (i.e. keeping *k1* disaggregated by region of origin). For more details on arrangement, see (Wood, 2017).

2.10. Data analysis

The data from each model were compiled and compared, identifying the countries where Sweden's consumption-based environmental impacts originate (hotspots). Countries (including Sweden) were ranked and compared for the different environmental indicators, according to the year and indicator available in each model. Where available, data for change in each hotspot over time were analysed to investigate any shifts from one hotspot region to another.

3. Results

3.1. Carbon dioxide from fossil fuel combustion emissions – multi-model results

All of the models include an estimate of the Swedish consumption-based emissions from fossil fuel combustion, so this is a suitable indicator to compare between models and also selected by other model comparison studies (for example Owen et al. (2014)). Ideally, the emissions inventory should also include emissions from processes such as cement production and steel production, but in practice these process emissions are not handled consistently across the MRIO models. MRIO models are therefore easiest to compare using only fossil fuel based CO_2 emissions. To demonstrate the differences in footprint, Table 1 shows the Statistics Sweden data including and excluding emissions from processes. Across the models the consumption-based emissions per capita for Sweden range from 8.3 to 11.1 tonnes per capita in 2011 (Table 2).

Over time, the consumption-based carbon footprints (Fig. 1) show a divergence in trends, with sharper declines in EXIOBASE and Eora from 2002 onwards compared to the other models. The Statistics Sweden data from the single country input-output model reports consistently lower footprints than the MRIO models between 1993 and 2007. This is to be expected due to the single region set up and the use of a domestic technology assumption, which may generate an underestimate in the emissions associated with imports. Fossil fuel combustion in the Swedish economy has a low emissions intensity compared to most other countries. Some of the largest differences are reported between Statistics Sweden and EXIOBASE and Statistics Sweden and OECD, with a range of 30–32 Mt difference in some years.

The OECD input output model gives the largest consumption-based footprint and is largely consistent with the WIOD trend. These models are designed to be true to the economic data and have fewer environmental parameters than the others. EXIOBASE is also very similar to the results of OECD and WIOD from 1995 to 2002, but diverges in the second half of the time series. Eora shows a rather stable trend from 1992 to 1998, and is similar to GTAP for the three years that are calculated in this model. All models show a sharp increase from 2009 to 2010 due to the recovery from the financial crises in 2008–2009.

For comparison, Fig. 2 shows the change in production-based fossil-fuel based CO_2 emissions, in which all models show a decline over time. The lower level of variation between the models in the production-based results demonstrates that model assumptions and data treatment is important for the consumption-based emissions result.

3.2. The hotspots of Sweden's carbon footprints

3.2.1. Sweden's footprint of emissions from fossil fuels

The origin of Sweden's carbon footprint from fossil fuel consumption is shown in Table 3 for each MRIO model for the latest year available. All models agree that Sweden itself is the main hotspot for at least one third of the Swedish footprint, with a further between 17 and 27 percent originating in the rest of the EU. There is disagreement between the models in how the remaining third of emissions are distributed between the rest of the world group,[1] China and Russia. However, all the models indicate that around 20 per cent of the Swedish carbon footprint emissions originate in the rest of the world group and China. The OECD model is the only one which identifies the largest proportion of the footprint as occurring domestically in Sweden (54%), in all other models more than 50% of Sweden's fossil fuel footprint originates abroad.

3.2.2. Sweden's footprint of greenhouse gas (GHG) emissions

The hotspots of the Swedish carbon footprint including all Kyoto greenhouse gases (CO_2, CH_4, N_2O and SF_6 using global warming potentials from the Intergovernmental Panel on Climate Change (2007)) is available for EXIOBASE, GTAP and WIOD and these data are similar to that of the fossil fuel combustion data, with Sweden

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[1] ‘Rest of world’ includes all those countries in the MRIO models that are not part of the 40 reported at this level of aggregation. These are as follows: Australia, Austria, Belgium, Brazil, Bulgaria, Canada, China, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, India, Indonesia, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Malta, Mexico, Netherlands, Poland, Portugal, Romania, Russia, Slovakia, Slovenia, South Korea, Spain, Sweden, Taiwan, Turkey, UK, USA, Rest of World. Not so convenient for a Swedish analysis, is that the neighbouring country Norway belongs to the group Rest of the World.

Table 2
Consumption-based carbon dioxide emissions from fuel combustion (tonnes per capita per year).

	Swedish consumption-based carbon footprint (CO_2) Fuel combustion
Unit	Tonnes per capita
Statistics Sweden (2011) [a]	10.0
Statistics Sweden (2011) [b]	8.3
Eora (2011)	8.8
GTAP (2011)	8.8
OECD (2011)	11.1
EXIOBASE3 (2011)	9.3
WIOD (2009)	9.3

[a] Including emissions from processes.
[b] Excluding emissions from processes.

and the rest of the EU ranked 1 and 2 for the origin of these emissions, followed by the rest of the world, China and Russia (Table 4). All models agree that the majority of Sweden's GHG emissions footprint occurs outside of Sweden.

3.2.3. Insight into the Sweden's GHG footprint origin in the rest of the EU

As the second largest hotspot for both the GHG and the fossil fuel combustion footprints the rest of the EU data for the GHG carbon footprint are presented in Table 5. All the MRIO models agree that Germany is the largest source of emissions, followed by Denmark. There is disagreement between the third ranked country though as GTAP has Poland as the third largest source, WIOD the Netherlands and EXIOBASE Finland.

3.3. The hotspots of Sweden's material flow and water use footprints

This section presents two further environmental footprints of Swedish consumption and investigates the countries of origin for each, comparing between models where data are available. This includes the material footprint (domestic extraction of biomass, fossil fuels, metallic and non-metallic mineral ores) from EXIOBASE, Eora and WIOD and water use from EXIOBASE and Eora.

3.3.1. Sweden's material footprint

Fig. 3 shows the origins of Sweden's material footprint for the latest year available in the EXIOBASE, WIOD and Eora models (2009). WIOD and Eora both report a more even spread of the origin of the material footprint, between Sweden, the rest of the world, the rest of EU and China, compared to EXIOBASE, where Sweden itself accounts for over half of the material footprint. In agreement with the other footprints considered so far, of the rest of the EU, Denmark, Germany and Poland feature as the main footprint hotspots from the EU countries, and are ranked 1, 2 and 3 by all models.

To explore the sources of the difference in material footprints across databases, we unpack the material footprint and itemize it by the four major types of material: biomass (crops, fisheries, forestry and grazing/fodder), metals (iron ores and non-ferrous metals), non-metallic minerals (which includes construction materials) and fossil fuels (coal, oil, gas, and peat). Fig. 4 illustrates the composition of the total Swedish footprint by material type, including unused material that is included in EXIOBASE and WIOD, but not in Eora. Fig. 5 shows the domestic-only portion of the footprint, also itemized by database and material type. The results are comparable for the total footprint, but for the domestic portion, there is a large difference in non-metallic minerals.

3.3.2. Sweden's water footprint

Only EXIOBASE and Eora data were available for the Swedish water footprint hotspots analysis (2011 as the comparison year). This is the only indicator where Sweden is not ranked as the first hotspot; instead both models identify the rest of the world region as the largest hotspot for Sweden's water footprint, followed by

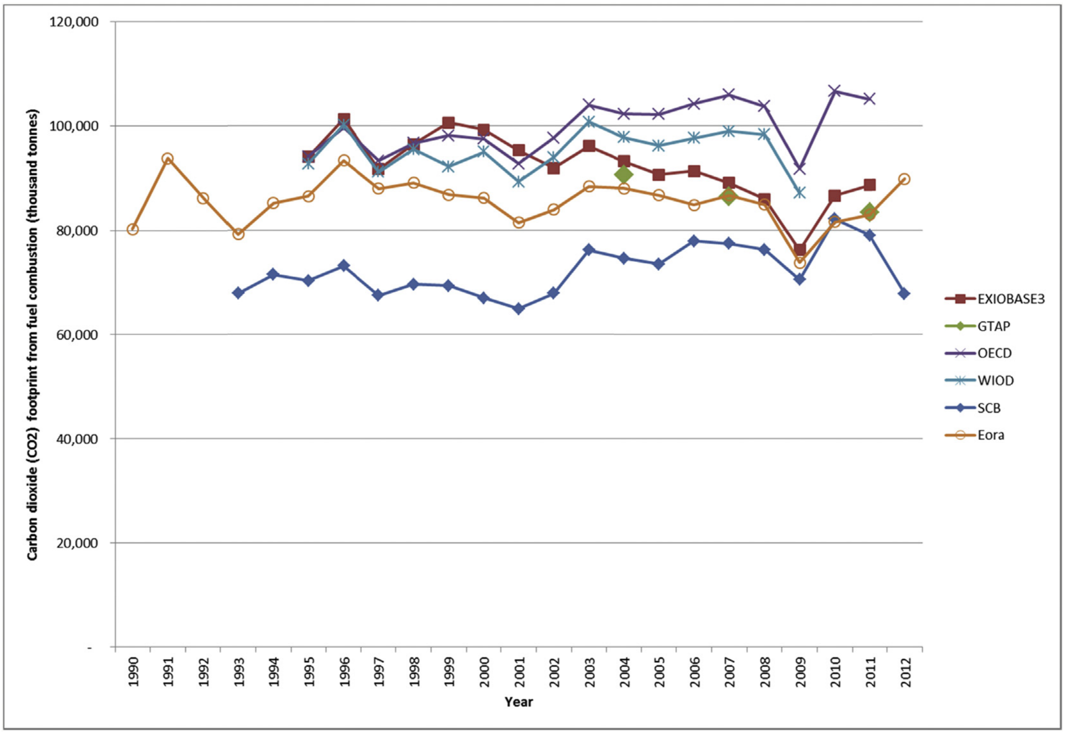

Fig. 1. Consumption-based carbon footprint for Sweden (carbon dioxide emissions from fossil fuel combustion), 1990–2012, EXIOBASE3, GTAP, OECD, WIOD, SCB and Eora.

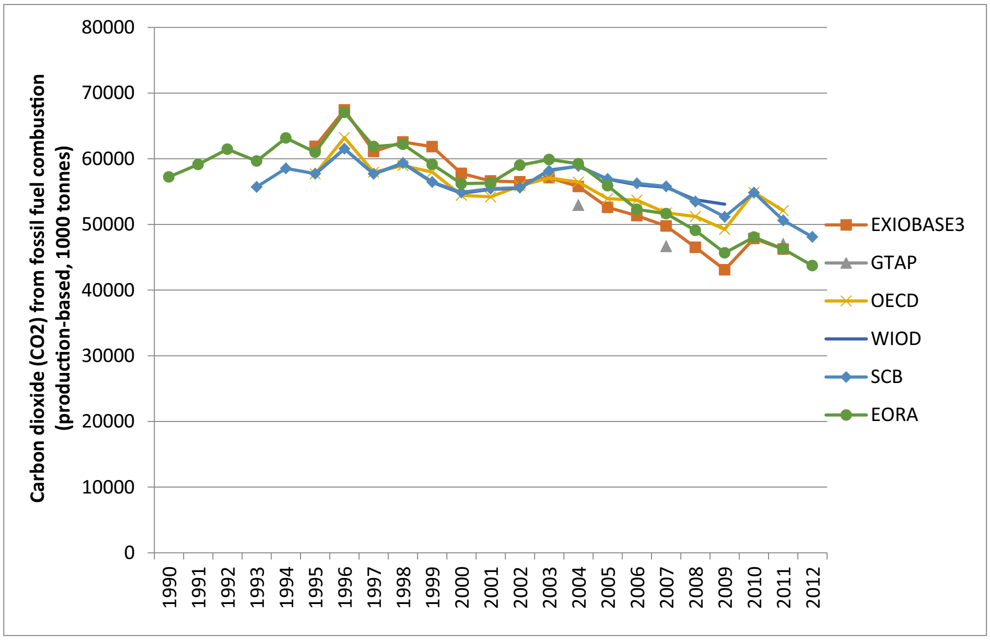

Fig. 2. Production-based carbon footprint for Sweden (carbon dioxide emissions from fossil fuel combustion), 1990–2012, EXIOBASE3, GTAP, OECD, WIOD, SCB and Eora.

Table 3
The major contributing regions of the Swedish carbon footprint from the emissions of fossil fuel combustion.

Country of origin of fossil fuel emissions footprint	Eora (2011)	EXIOBASE3 (2011)	GTAP (2011)	OECD (2011)	WIOD (2009)
Sweden	31%	44%	41%	54%	47%
Rest of EU total	27%	20%	23%	17%	21%
Rest of World	11%	13%	11%	7%	10%
China	13%	9%	10%	7%	10%
Russia	5%	5%	4%	7%	4%
USA	6%	3%	4%	3%	3%
India	3%	2%	2%	2%	1%

Table 4
The major contributing regions of the Swedish GHG carbon footprint.

Country of origin of GHG footprint	EXIOBASE3 (2011)	GTAP (2011)	WIOD (2009)
Sweden	41%	43%	44%
Rest of EU total	19%	21%	20%
Rest of World	16%	11%	13%
China	9%	9%	10%
Russia	6%	5%	5%
USA	3%	4%	3%
India	2%	2%	1%

Table 5
Ranking of ‘rest of Europe’ major contributors to the Swedish GHG carbon footprint.

Country of origin of GHG footprint	EXIOBASE3 (2011)	GTAP (2011)	WIOD (2009)
Germany	1	1	1
Denmark	2	2	2
Finland	3	5	5
UK	4	4	4
Netherlands	5	7	3
Poland	6	3	6
Belgium	7	12	7
France	8	6	8
Italy	9	8	10
Spain	10	9	9
Ireland	11	13	14

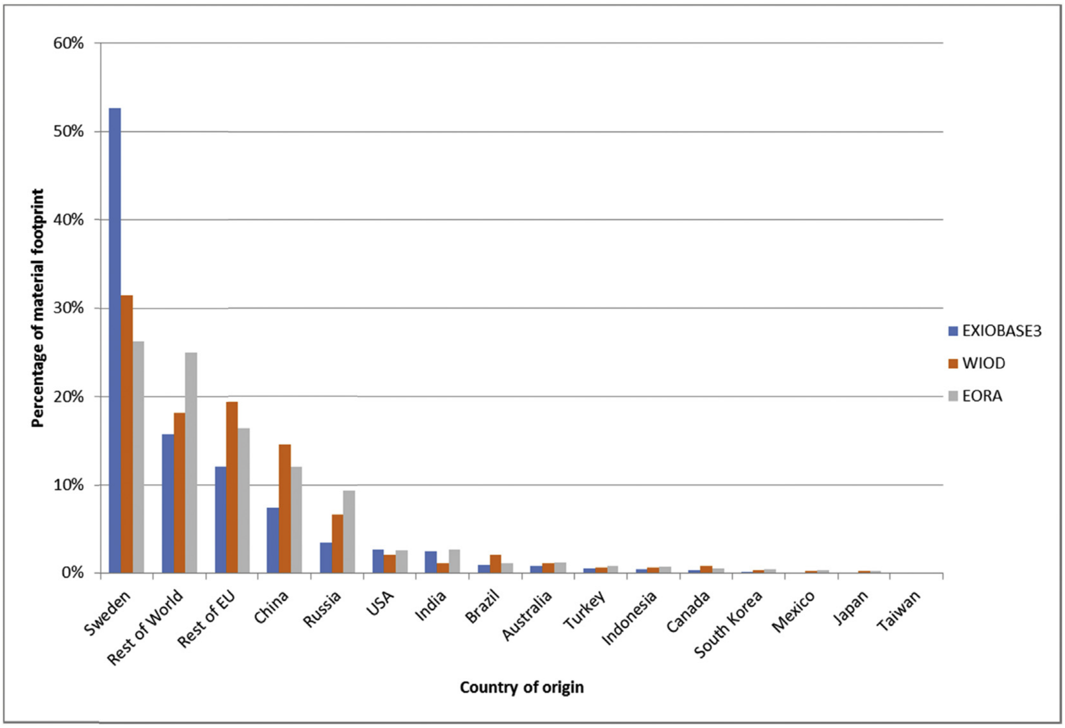

Fig. 3. Hotspot of Sweden's material footprint (used material only), 2009.

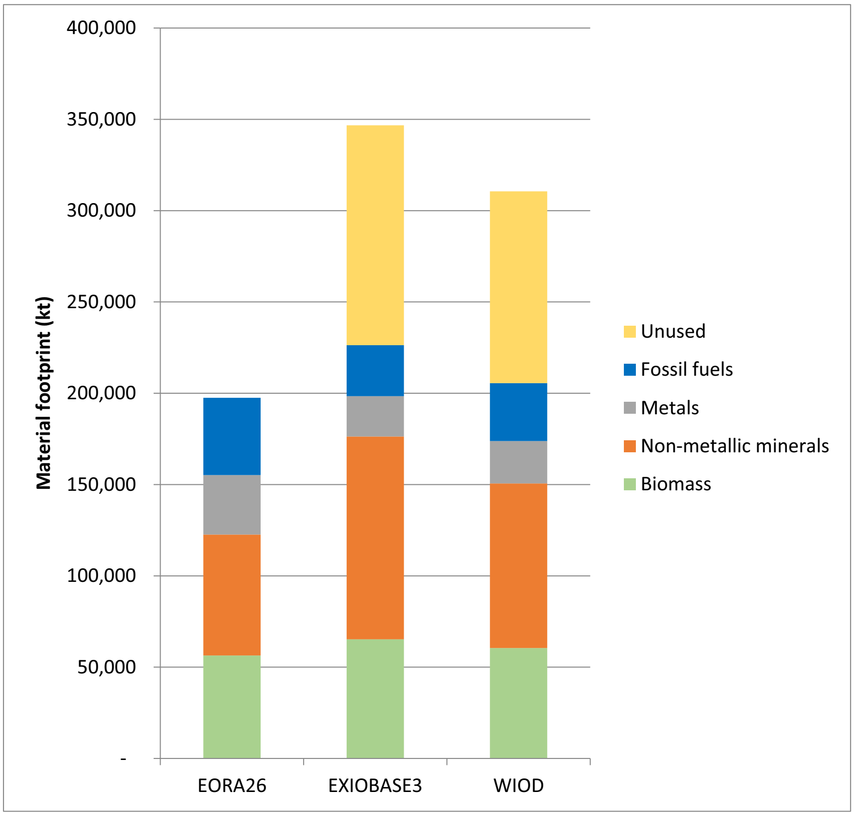

Fig. 4. Breakdown of Sweden's total material footprint in kt, 2009.

Sweden and the rest of the EU (Fig. 6). EXIOBASE shows a large difference between the rest of the world and Sweden, but Eora reports a similar percentage of the footprint between the rest of the world, Sweden and the rest of the EU. The rest of the EU accounts for only 10 per cent of the footprint in total from EXIOBASE and Spain is identified as the main footprint hotspot for Sweden within

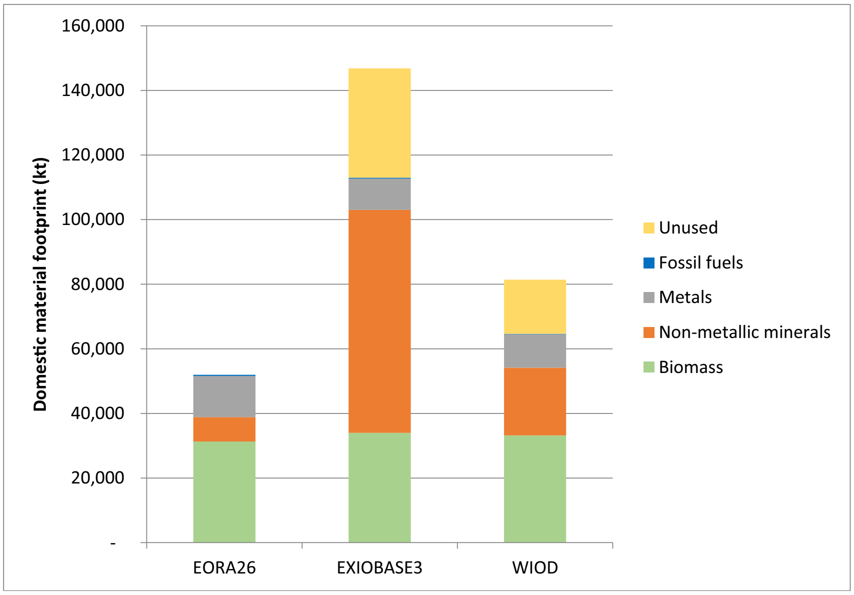

Fig. 5. Breakdown of Sweden's domestic material footprint in kt, 2009.

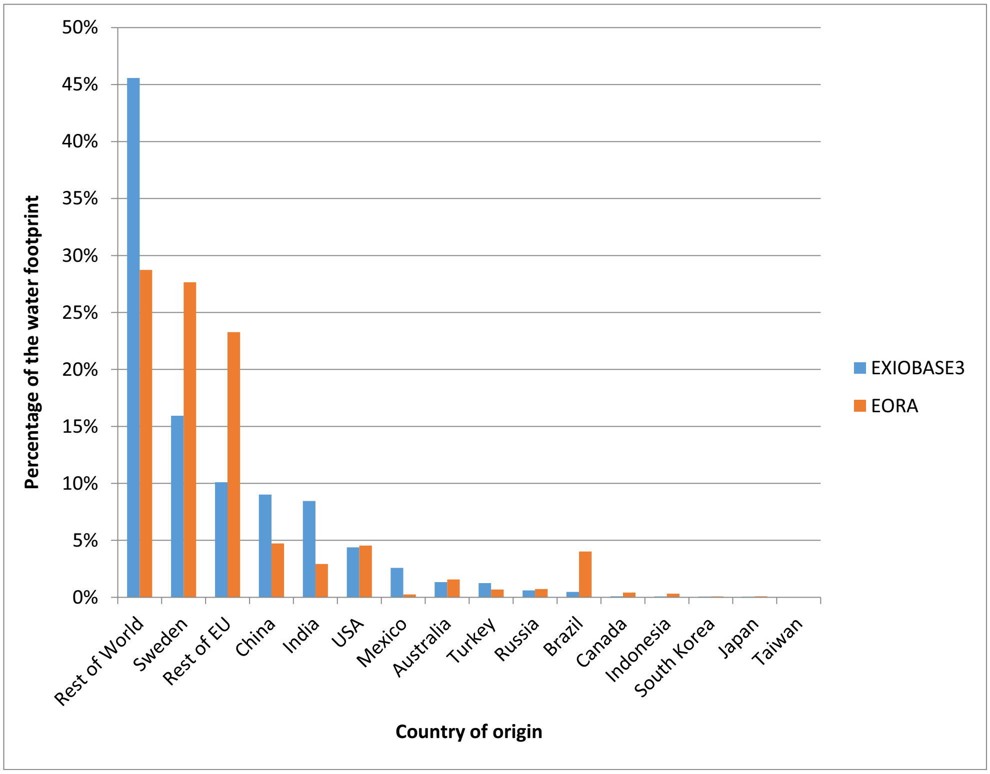

Fig. 6. Hotspot of Sweden's water footprint, 2011.

the EU, followed by Italy. However, this is not the same as Eora where Germany and Denmark are ranked highest.

3.3.3. *Hotspots of value added*

It is interesting to explore the footprint of value added to compare economic data with the environmental footprints from different regions. This gives insight into whether the economic impacts are similar to the environmental pressures in each hotspot. Table 6 shows the hotspots of Swedish value added footprint (including only those regions above 0.5 per cent). Sweden accounts for over 70 per cent of value added, and when ‘rest of EU’ is an aggregated this amounts to between 13 and 18 per cent in the models. The ‘rest of the world region’ often accounts for a higher proportion of the environmental pressures than value added for example, over 10 per cent of the carbon footprints, 16–25 per cent of the material footprint and a large proportion of the water footprint, occur in the ‘rest of the world’ region, but a much smaller percentage of the value added, at around 4–5 per cent. For the

Table 6
Swedish footprint of value added, by country/world region with 'rest of EU disaggregated', year as specified.

	EXIOBASE (2011)	Eora (2011)	OECD (2011)	WIOD (2009)
Sweden	74.34%	71.15%	70.71%	72.91%
Rest of World	5.80%	4.40%	4.93%	3.74%
Germany	3.33%	5.33%	4.08%	3.85%
USA	1.54%	1.95%	2.56%	2.39%
UK	1.40%	1.89%	2.10%	1.83%
China	1.31%	1.54%	1.41%	2.21%
Denmark	1.13%	1.51%	1.72%	1.57%
France	1.12%	1.58%	1.40%	1.09%
Netherlands	0.92%	1.53%	0.71%	1.28%
Russia	0.85%	0.56%	1.24%	0.63%
Italy	0.85%	1.22%	1.16%	0.80%
Finland	0.76%	1.05%	1.22%	0.90%
Belgium	0.74%	0.91%	0.54%	0.88%
Poland	0.64%	0.50%	0.73%	0.77%
Spain	0.54%	0.57%	0.90%	0.60%
Japan	0.44%	0.91%	0.49%	0.54%
Ireland	0.39%	0.26%	0.40%	0.36%
Australia	0.38%	0.14%	0.12%	0.16%
India	0.38%	0.29%	0.60%	0.26%
Canada	0.35%	0.23%	0.29%	0.34%
Austria	0.32%	0.39%	0.33%	0.28%
South Korea	0.27%	0.24%	0.25%	0.25%
Czech Republic	0.25%	0.29%	0.25%	0.22%
Brazil	0.22%	0.18%	0.19%	0.58%

European countries and the 'rest of the world' region, those ranked highest in terms of value added hotspot tend to also appear higher ranked in the footprint hotspots (for example, rest of world, Germany, Netherlands, Denmark, Finland and the UK).

3.4. Change in Sweden's footprint hotspots over time

By running time series data it was possible to investigate if and how the global hotspots of Sweden's footprints have changed over time. The findings show that the hotspots of GHG emissions have indeed changed. In both EXIOBASE and WIOD the percentage of the GHG footprint originating in Sweden has decreased from around 60 per cent to 40, with increases reported in China and the rest of the world group, and also in the rest of the EU in EXIOBASE. This pattern is shown in Figs. 7 and 8 for the top 6 regions only. One of the top 6 is the rest of world group which is the same as in Table 3 (see footnote 1).

4. Discussion

4.1. The global hotspots of Swedish environmental footprints

All consumption requires resources, and the various stages of production often cause adverse impacts on the local and global environment, particularly when the energy system is driven by fossil fuels. With the development of global supply chains these adverse impacts can happen in locations very distant from the consumer and from the reach of environmental legislation in the country where the products are consumed. The results of this study demonstrate that MRIO analysis can provide insight into the global hotspots of consumption-based environmental footprints, and the development of a number of increasingly sophisticated global models allows in-depth comparison and analysis.

The Swedish environmental footprints have been shown to originate in a range of countries globally. This presents a challenge for both policy-makers and consumers when making efforts to reduce the impacts of consumption. Environmental pressures vary according to production methods, fuel use and environmental protection standards in different countries, and a large number of actors including governments, transporters, manufacturers, retailers and consumers are involved in each of these aspects in every product supply chain. From the perspective of the consumers – the increasing length and complexity of supply chains and the vast range of products available reduces the potential for improvements driven by consumer pressure and feedback. Similarly, governments have the capacity to directly impact the component of the footprint that originates within their own countries, but less influence over the environmental conditions in others. However, increasing awareness about the environmental impacts of consumption has opened discussions about how to influence supply chains and consumption patterns (Persson et al., 2015).

4.2. MRIO model variations in findings

The principal aim of this work was to investigate the agreement between the different MRIO models available, as well as the Statistics Sweden single-region input-output model. Any large differences in the results of the models may restrict the potential for their findings to be interpreted and utilized by policy-makers.

All of the MRIO models agree on the following:

- The consumption-based per capita carbon footprints for Sweden remain considerably higher than a per capita share of the global budget for limiting 2 °C of warming (Larsson, 2015).
- The consumption-based footprints for Sweden are higher than the environmental pressures due to production in Sweden, for all indicators. Sweden is the largest individual country of origin for the Swedish carbon footprint (both from fossil fuels and GHGs) and material footprints in all of the models, but the size of the Swedish share varies between models.
- All models find that the majority of the GHG footprint originates outside of Sweden; all except the OECD model find the same for the fossil fuel emissions footprint.
- The two models that were available for water footprint comparisons (EXIOBASE and Eora) agree that the majority of the water footprint originates outside of Sweden.
- There is general agreement between the models on the location of water and material footprint hotspots globally, but variation in the proportion of the footprint occurring domestically in Sweden versus externally.
- All models agree that the majority of the Swedish value added footprint (over 70 per cent) occurs in Sweden, with the rest of the EU accounting for between 13 and 18 per cent followed by the rest of the world (4–5 per cent).
- The WIOD and EXIOBASE models agree that the domestic share of Sweden's GHG footprint has declined over time as the share in other parts of the world (notably China and "the rest of the world" region) have increased.

Despite this agreement, there are also variations between the models, one of the biggest being whether Sweden's CO_2 footprint from the combustion of fossil fuels has increased or declined over time. In addition, individual models disagree on the extent to which the footprint pressures occur domestically or externally to Sweden. One particular example is the OECD model which reports Sweden as a much larger hotspot of pressure for the carbon footprint, particularly compared to the rest of the world. In comparison, the other models identify larger hotspots in the rest of the world. Why these variations may occur have important implications future MRIO development and policy applications.

4.3. Reasons for MRIO model variation

4.3.1. The approach to MRIO and input-output table development

Some of the reasons for variations between the results from

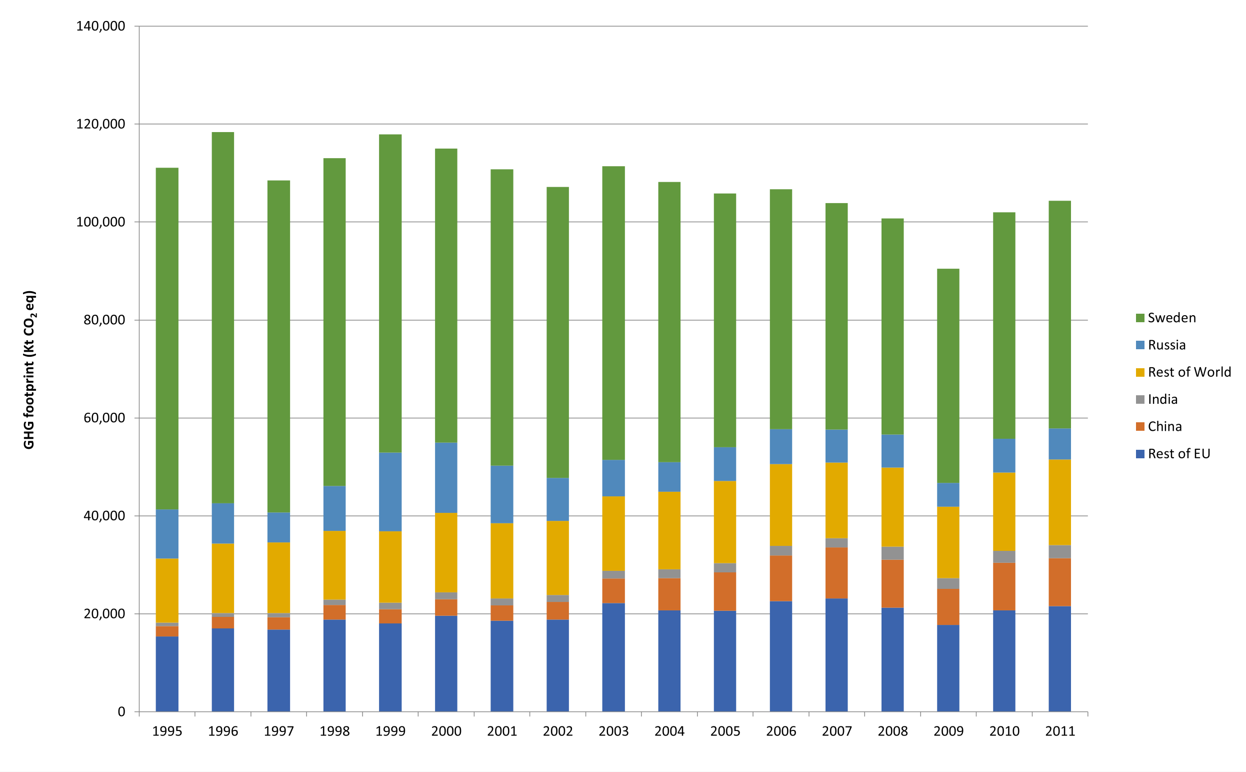

Fig. 7. Change in top 6 hotspots of Sweden's GHG footprint, EXIOBASE model 1995–2011.

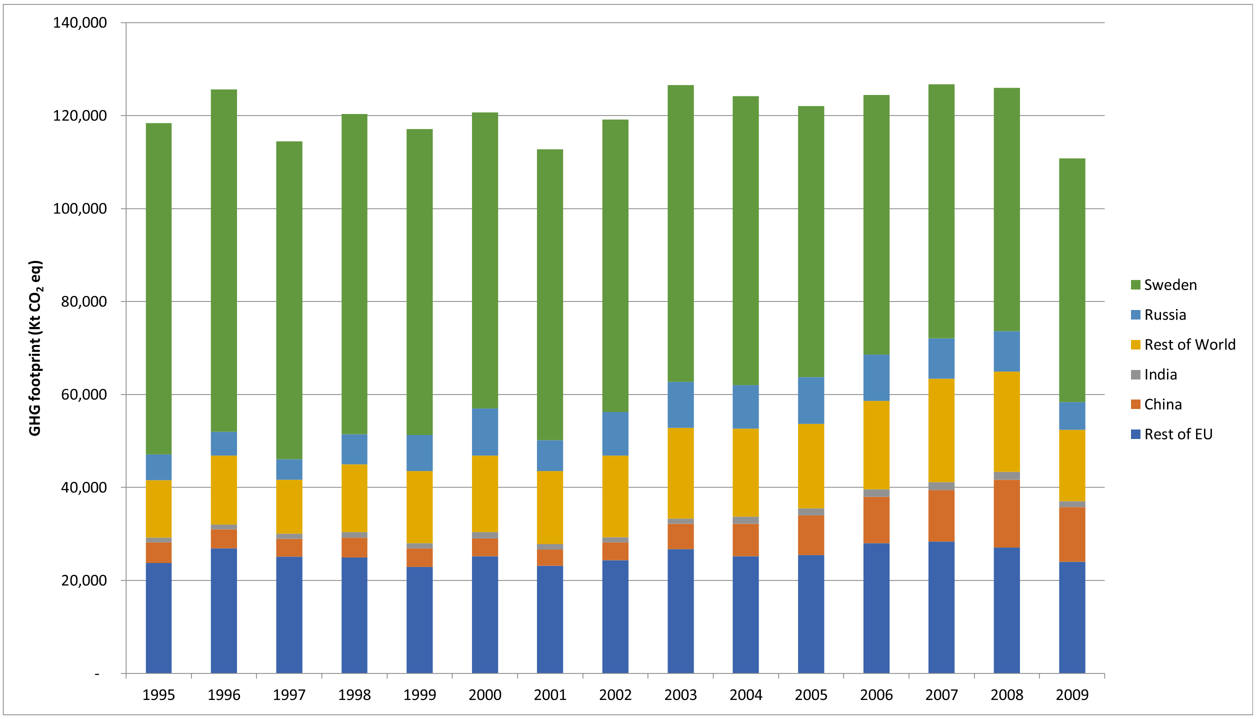

Fig. 8. Change in top 6 hotspots of Sweden's GHG footprint, WIOD model 1995–2009.

different models are relatively straightforward to identify, while others require assessment of the input data or internal workings of the model, which can be more time-intensive to complete and often requires specialist knowledge of the model being investigated. Due to the number of data points, assumptions and calculations involved in generating a single total consumption-based footprint figure, the task of disentangling individual factors would also be far beyond the scope of an investigation for a policy report or recommendation. The purpose of this paper is not to test or examine in detail the differences between the MRIO models, but instead to investigate the implications and main findings of each for Sweden, to support policy-making and other decision-making based on data from this type of model. This section discusses conclusions of previous analyses into MRIO variations (e.g. Inomata and Owen, 2014; Tukker et al., 2018) and the implications for the Swedish results and policy.

As a first step to understanding the similarities and variations between the models it is important to consider how they are constructed and the data on which they are based. One major difference to note is that the Statistics Sweden model is a single-region input-output model, meaning that the economic structure is based on Swedish input-output data; there is no representation of the production structures and international economic flows between other sectors and other countries. At the same time, the Statistics Sweden model is the only model that uses the most up-to-date economic data and the latest industry classification (NACE rev 2.), meaning that it gives the most consistent and representative view of the Swedish economy.

4.3.2. Macroeconomic data

If the global and national macroeconomic and environmental input data totals vary then the footprint results will undoubtedly vary following the calculations made to estimate the consumption-based footprints. Moran and Wood (2014) identified variance in environmental input data as one of the principle factors in inter-model variation, but as Tukker et al. (2018) note, differences in environmental data often only account for part of the variation, while the rest is due to descriptions of the economic structure, as well as the differences in the value and composition of final demand.

Wieland et al. (2018) investigated the impact of differences in the monetary data by making comparisons between MRIOs with constant environmental data. They found that it was domestic flows, rather than trade flows, that contributed to the largest differences in footprint results when they compared EU-28 carbon footprints in WIOD, EXIOBASE, Eora and GTAP (Wieland et al., 2018). Further to this, they were able to recommend that specific places and sectors such as the domestic use table of major economies like Germany and China, and high emitting sectors such as electricity are prioritized for future efforts to improve consistency between models.

Previously, Hoekstra et al. (2013) had identified issues in the compilation of the databases that gave rise to differences between carbon footprint results from Statistics Netherlands and WIOD.[2] In addition, work by Owen et al. (2014) reported that the total final demand vector is an important source of the variation between the Eora database and GTAP and WIOD, but that GTAP and WIOD were more similar in their total final demand and composition. As Tukker et al. (2018) emphasize, the share of final demand by country and product can have more of an effect than the share of emissions by country and industry. In the results of this study the Swedish total final demand is higher in EXIOBASE and Eora, with WIOD and OECD both using lower and very similar figures. This is consistent with global final demand, which is higher in EXIOBASE and Eora. This means that in all models Sweden has a very similar percentage of global final demand (around 0.7%), except in WIOD which gives a share closer to 0.6%.

4.3.3. Environmental data

The limited environmental data consistently available for the different models restricts the possibility of detailed comparisons between all environmental pressures at this time. However, studies such as Moran and Wood (2014) found that there was substantial variability in the way the carbon emissions accounts were compiled in four MRIOs (Eora, WIOD, EXIOBASE, and an MRIO model developed as part of a EU funded project OPEN:EU[3]; see Hertwich and Peters, 2010). How total pressures are allocated between particular sectors, which of the GHGs are included, which emissions sources are included/excluded, how sectoral inventories are estimated if empirical data are not available, and if included there are non-CO_2 GHGs included and converted into CO_2 equivalents, the assumed global warming potentials of each of the gases were all found to be sources of variation.

Similarly, there is substantial variation in the volume and structure of material footprints of WIOD, EXIOBASE and Eora. This could likely be due to the environmental accounts: the models may not define material use the same way, may use different primary data sources, may allocate material to responsible sectors differently, and may have differing definitions of “used” and “unused” material. Whether the material considered includes both “used” and “unused” portions is particularly important for agriculture and mineral extraction. Eora reports only on used material; WIOD and EXIOBASE report both used and unused material; WIOD does not include separate categories for fish and non-ferrous metal ores, while EXIOBASE and Eora do. National footprints and hotspots results from the different models will consequently vary due to any discrepancies in total environmental pressures, the databases selected for the analysis, the pressures included in any combined indicator, and the assumptions made in linking these to monetary flows. Table 7 shows the variation in global and Swedish data in this study.

4.3.4. Model construction and data processing

The basic conceptual principles and building blocks for input-output analysis are similar. However, MRIOs depend on whatever data are available at national level. Almost all countries follow international standards and regulations in compiling and reporting economic data. International standards exist for environmental data reporting too, but they are not yet widely implemented. They are, however, used and legislated in the EU. The variations in data availability and detail at the national level mean that modellers must make decisions and assumptions when combining the data into MRIOs. These are as follows:

1. **The data prioritized in the MRIO model construction** – the models are constructed from different datasets which often report the same thing (e.g. imports of products from one country to another) and the figures can vary between the data sources. This means that one data source may have to be prioritized over another as the correct value to assume. EXIOBASE, WIOD, Eora and OECD prioritize staying as close as possible to the numbers collected and presented by national governments in their SUTs or input-output tables in official national statistics (Hoekstra et al., 2013), but others such as GTAP focus on ensuring that the values of reported trade data remain as close to the source trade data as possible and adjust other components to match.
2. **Data processing decisions and standards** – variable quality of the input data means that a number of processing decisions must be taken, which can also lead to differences in models. SUTs and input-output tables are commonly published by

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[2] (1) the way that imports in the supply table are allocated to the different demand components (intermediate, investments and final demand) and (2) how margins are dealt with for conversion between purchasers and basic prices.

[3] http://www.oneplaneteconomynetwork.org/.

Table 7
Total global and Swedish consumption and production-based environmental pressures, by MRIO model.

Global environmental pressure totals, by indicator	Eora (2011)	WIOD (2009)	GTAP (2011)	OECD (2011)	EXIOBASE (2011)
Total global GHG emissions from industry (kt CO_2 eq)		35,331,566	36,981,509		38,359,958
Total global CO_2 emissions from fuel combustion from industry (kt CO_2)	30,431,350	23,230,042	24,913,892	26,048,793	26,557,301
Total global GHG emissions from households (kt CO_2 eq)		4,284,510	4,508,263		4,648,669
Total global CO_2 emissions from fuel combustion from households (kt CO_2)	2,240,894	3,969,674	3,904,382	3,539,602	4,338,413
Total global Domestic Extraction Used (kt)	69,686,068	69,776,170			78,447,482
Domestic Extraction Used: *Biomass (kt)*	*20,294,768*	*18,664,134*			*21,828,420*
Domestic Extraction Used: *Non-metallic minerals (kt)*	*29,584,828*	*31,826,919*			*34,952,244*
Domestic Extraction Used: *Metals (kt)*	*6,982,886*	*6,615,864*			*7,864,145*
Domestic Extraction Used: *Fossil fuels (kt)*	*12,823,585*	*12,669,252*			*13,802,674*
Total global Domestic Extraction Unused (kt)		42,120,166			48,117,891
Total global Blue water (Mm^3)	2,353,987 (2007)				1,179,625 (2007)
Sweden environmental pressures totals, by indicator	**Eora (2011)**	**WIOD (2009)**	**GTAP (2011)**	**OECD (2011)**	**EXIOBASE (2011)**
Domestic Extraction Used (kt) production total	122,988	191,874			209,546
Domestic Extraction Used: Biomass (kt) production	*55,455*	*57,849*			*62,729*
Domestic Extraction Used: Non-metallic minerals (kt) production	*24,717*	*89,160*			*87,879*
Domestic Extraction Used: Metals (kt) production	*41,643*	*44,222*			*58,202*
Domestic Extraction Used:Fossil fuels (kt) production	*1173*	*643*			*736*
Domestic Extraction Unused (kt) production		59,823			94,801
Domestic Extraction Used (kt) consumption	214,404	205,976			279,214
Blue water (Mm^3) production	674				457
Blue water (Mm^3) consumption	1308				2102
GHG emissions (kt CO_2 eq) production		71,978	68,844		58,845
GHG emissions (kt CO_2 eq) consumption		119,552	118,993		112,619
CO_2 from fuel combustion (kt CO_2) production	48,070	53,082	47,020	52,096	46,240
CO_2 from fuel combustion (kt CO_2) consumption	82,980	87,117	83,371	105,131	88,622
Total Swedish final demand (million USD unless specified)	460,986	350,589	463,837	461,210	536,569 (EUR)
Total global final demand (million USD unless specified)	72,827,610	56,840,290	67,902,360	66,650,850	72,738,020 (EUR)
Total Swedish final demand, as % of global total	0.70%	0.62%	0.68%	0.69%	0.74%

national statistics agencies within their national accounts and standard accounting practices guide their formulation. These are compiled in international databases such as those maintained by the United Nations, OECD and Eurostat (Hoekstra et al., 2013). Despite the standardizations, the availability and quality of these data can still vary – European countries publish SUTs in accordance with the System of National Accounts (SNA) but other countries publish input-output tables or SUTs following different standards (Wood et al., 2014).

When developing an input-output model a number of decisions such as dealing with asymmetries in reported trade data, the level of sectoral aggregation and handling with missing data must be taken. There are also a number of factors that must be taken into account when creating MRIO tables from national SUTs and input-output tables which will undoubtedly cause variation in country level footprints (Tukker et al., 2018), including: the overall balancing of the tables (ensuring total inputs are equal to total outputs), dealing with transport and trade costs, taxes and subsidies in the economic data and converting tables into the most appropriate form (either representing industries or products for example). Any of these factors could cause variations in results when trade is taken into account, as seen in this study where the divergence between consumption-based results is greater than that of production-based results for Sweden. While there is a relatively long list of specific modelling choices to be made, previous studies such as those by Arto et al. (2014) and Moran and Wood (2014) have found that disagreement across models is often highly localized, occurring in just a few countries and sectors and a few sections of the model.

4.4. Policy implications

Following up on progress towards Sweden's Generational Goal requires monitoring the environmental pressures associated with Swedish consumption, and models are required to estimate this by combining the necessary consumption, economic structure and environmental data. It is therefore important that policy-makers understand which models are available to use and understand the implications of the choices. The differences between the single-region input-output model, which has more detailed Swedish economic and emissions data, and the MRIOs which better describe international trade flows, gives an indication that it may be necessary to combine the strengths of these different approaches. An important consideration for a country such as Sweden is that it is a comparatively small country in the global MRIO models and the model assumptions and calculation routines may not prioritize Swedish data. Consequently, the data for Sweden (and other small countries) can end up altered in MRIO models (Edens et al., 2015; Hambÿe et al., 2018). However, without detailed trade information from an MRIO, the data about the origin and pressures of imported goods is limited. Ideally, a combination of the two, such as the SNAC (Single-country National Accounts Consistent) approach given by Edens et al. (2015) or an alternative approach (as described by Wood and Palm, 2016) and referenced in Tukker et al. (2018) could provide consistent data on environmental pressures from Swedish consumption.

MRIOs are time-consuming to construct and require large amounts of data from a variety of sources; it is not practical for a small country such as Sweden to regularly construct its own independent MRIO model. It must therefore rely on what is already available internationally and as the analysis shows, the choice of MRIO model will affect the results.

The MRIO models have different strengths: in the coverage of environmental parameters, in the fullness of the inventories, in the possibility to disaggregate different product groups or regions, in the accuracy of the model over time, and last but not least, in the continuity of the work that makes it possible to anticipate when new data will be available. The choice of appropriate MRIO is not always simple, and depends on the aims of the project (Hoekstra et al., 2013), the research or policy questions. There is reasonable agreement between the data used in the models; however, it is clear from this and numerous other studies that efforts must be made to support consistent data collection and reporting internationally in order for models such as MRIO to draw on consistent input datasets.

The possibility to examine hotspots of pressure in the MRIO models is particularly important for pressures that are locally specific (such as the impacts of material extraction or water use) and further interpretation may require additional information (such as water scarcity). The impacts of emissions such as CO_2 or GHGs remain the same regardless of where they are released; however, the interpretation of the trends of the Swedish footprint can also be tricky. For example, changes in the Swedish GHG footprint may be driven by a shift in domestic energy policy, but it is common to see the interpretation that Sweden is outsourcing its production as an explanation for these types of trends.

Sweden has two separate types of consumption-focused policy analysis. The first is a time series macro approach to look at overarching patterns of the environmental pressure from national consumption to follow up the Generational Goal. This result is important for awareness raising at the policy and public level, and for increasing the understanding of the potential impacts of current consumption patterns. Policies can then take into account information about the direction of the impacts of consumption and variation in its components, such as private demand, public demand and investments.

The other policy use is a more exploratory investigation into the pressures associated with certain product groups. At the policy level, once awareness of consumption as a driving force for environmental pressure is present, questions arise about which the type of product groups and countries are the most important for the resulting environmental pressure. Here, the ability of MRIOs to identify hotspot countries and product groups in Sweden's consumption footprint is invaluable. This can help to guide policy interventions and the product groups for further detailed research, complementing the work of more detailed life cycle assessment studies.

5. Conclusion

The Swedish footprint results from five MRIO databases were compiled – EXIOBASE, WIOD, Eora, OECD and GTAP – along with the Statistics Sweden calculations that employ an import-adjusted single-region input-output model. As could be expected, given the complexity of the models, the analyses show different results, but they are similar enough to allow important general conclusions to be drawn. For example, they show that the distribution of environmental pressures due to Swedish consumption largely follows the sourcing patterns for Swedish imports (such as the rest of the EU). Most MRIO models agreed that the majority of the GHG, fossil fuel, material and water footprints of Swedish consumption fall outside of Sweden. For value added, however, the opposite is the case, with the majority of value added inside Sweden.

The agreement on the regions of origin of environmental pressures and the changes over time demonstrates the valuable insights into the footprint that MRIO can provide. However, having multiple models producing differing numbers for the same indicator undoubtedly complicates interpretation and communication of the results. It is therefore important to understand that these models are representations of complex systems of production, trade and pollution across the globe; it is hence no surprise that the exact details of the results will differ.

Overall, this study demonstrates that the different MRIOs provide largely consistent pictures of the overall patterns and hotspots in Sweden's external footprint, indicating the plausibility of this approach for consumption-based accounting. In addition, they consistently report higher carbon footprints than the results using Statistics Sweden's current calculation method, which also provides much less detail on the geographic distribution of Sweden's footprint. Our study thus supports the validity and usefulness of incorporating MRIO data into Sweden's systems for following up on policies such as the Generational Goal.

Each MRIO model has different strengths that could be used to improve and monitor national footprint calculations. The global MRIO models have been able to source, compile and harmonize national and international databases of environmental and economic data to an extent that would be very demanding for one nation to construct and maintain alone. However, it is also clear that for a single nation calculation, there will be more detailed and often more up-to-date data available nationally, that would not take priority in the design of an international MRIO model. Thus, the combination of an MRIO and the national economic and environmental data seems to be a promising analytical tool.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2018.11.023.

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