

Paper prepared for the International Ecological Footprint Conference, Cardiff, 8-10 May 2007
Stepping up the Pace:
New Developments in Ecological Footprint Methodology, Policy & Practice

M0001- 37

Multiregional Input-Output Modelling Opens New Opportunities for the Estimation of Ecological Footprints Embedded in International Trade

**Thomas Wiedmann^{1,*}, Manfred Lenzen², Karen Turner³, Jan Minx¹ and
John Barrett¹**

- 1) Stockholm Environment Institute, University of York, Heslington, York, YO10 5DD, UK; www.sei.se/reap
- *) Corresponding author: Tel.: +44 (0) 1904 43 2899 , Email: tommy.wiedmann@sei.se
- 2) Integrated Sustainability Analysis (ISA), School of Physics, A28, The University of Sydney, NSW 2006, Australia; www.isa.org.usyd.edu.au
- 3) Department of Economics, University of Strathclyde, Scotland, G4 OGE, UK; www.strath.ac.uk

ABSTRACT This contribution offers a detailed review of recently described multi-region input-output models used to assess environmental impacts of internationally traded goods and services and their suitability for Ecological Footprint calculations. A large number of such environment-economic models have been described but only in the last few years models have emerged that use a more sophisticated multi-region, multi-sector input-output framework. This was made possible through improvements in data availability and quality as well as computability. We identify six major models that employ multi-sector, multi-region input-output analysis in order to calculate environmental impacts embodied in international trade. Results from the studies reviewed demonstrate that it is important to explicitly consider the production recipe, land and energy use as well as emissions in a multi-region, multi-sector and multi-directional trade model, which is globally closed and sectorally deeply disaggregated. Only then reliable figures for indicators of impacts embodied in trade, such as the Ecological Footprint, can be derived. We also describe how to enumerate the resource and pollution content of inter-regional and international trade flows with the aim to illustrate an ideal modelling framework for the estimation of Ecological Footprints. What appears to be absent from previous applications is an account of the analytical method by which Ecological Footprints should ideally be estimated in an international input-output framework. This allows an explicit analysis of the problems that prevent the application of the full method and identification of the most appropriate short-cut methods in a transparent way.

Conference Theme: Methodology - Connecting the economy and the environment

Keywords: multi-region input-output models, international input-output analysis, international trade, embodied environmental impacts, Ecological Footprint

1. Introduction

The Ecological Footprint, as introduced by Wackernagel and Rees (1996), measures human demand on bioproductivity by assessing how much biologically productive land and sea area is necessary to maintain the consumption of a given human population. The calculation of Ecological Footprints starts from the consumption of resources in terms of mass units and transforms this mass into land appropriation in a second step (Monfreda et al., 2004). A considerable share of the Footprint consists of the notional forest area that would be required to absorb carbon dioxide emitted from the combustion of fossil fuels.

The total land appropriation derived in this way can then be compared to available biocapacity, also expressed in land and sea areas. If global demand exceeds global supply of biologically productive area, this indicates an 'overshoot' situation in terms of a shortfall of bioproductivity needed for human purposes.

National Footprint Accounts (NFA) are generated annually by the Global Footprint Network for most countries of the world (GFN, 2005; WWF, 2006). They account for the consumption of land by the countries' residents wherever this land might be located. The Footprint associated with products imported from foreign countries, for example, is fully added to the consumers' Footprint account. Therefore, the concept of Ecological Footprint analysis strictly follows the principle of consumer responsibility¹, a term introduced in the context of discussions on greenhouse gas accounting (Munksgaard and Pederson, 2001).

However, in its current state the method to generate National Footprint Accounts (Monfreda et al., 2004; Wackernagel et al., 2005) can only provide a rough estimate of land appropriation associated with the trading of goods. Using FAOSTAT data (FAO, 2005) on domestic production, imports, exports and yields for a number of primary and secondary products from agriculture, forestry and fisheries, the accounts estimate the apparent net consumption of a nation and the associated appropriation of land. The national energy Footprint is calculated via CO₂ emissions data from IEA². For the trade balance of manufactured products, embodied energy data from disparate sources are used to convert their quantities into energy equivalents. These values are then assigned CO₂ equivalents and subsequently energy Footprints.

¹ This principle is in contrast to the producer responsibility principle, which is the basis of the Kyoto Protocol. Here, only territorial greenhouse gas emissions of a nation are accounted for; the emission embodiments of trade are not taken into account (Task Force on National Greenhouse Gas Inventories, 1996). Accordingly, many national greenhouse gas policies are aimed at reducing domestic greenhouse gas emissions and, in the Kyoto Protocol, national reduction goals based on a previous level of domestic emissions are used as a benchmark for success and compliance. But the consumption of imported goods and services, in some countries amplified by the relocation of domestic production abroad and subsequent import substitution, gives rise to environmental impacts in other places around the world and this calls for the consideration of greenhouse gas embodiments in international trade flows and their correct accounting.

² International Energy Agency, Paris, France

While the NFA method is a practical way of computing the apparent resource consumption of 150 countries in the world, there are still fundamental shortcomings in the methodology³. The main issues with respect to international trade are:

- For domestically produced bio-products national conversion efficiency factors are used to calculate the Footprint, whereas average global conversion efficiency factors are used for imports. The Footprint of exported products from biological resources is weighted in proportion to the amount of products imported and produced domestically and their respective conversion factors.
- Manufactured products have the same embodied energy regardless of the country of manufacture, i.e. the same energy intensities for imports and exports are used and they are the same for each country. For the conversion into energy Footprints via embodied CO₂ emissions, world average carbon dioxide intensity is used for all imports, whereas for exports of manufactured products the average carbon dioxide intensity of the exporting economy is used, reflecting the national fuel mix for energy production.
- Imports and exports of services are not included in the NFA analysis. This means that any direct and indirect resource use and/or pollution embodied in trade flows of services are not accounted for.

More generally, since only the total imports and exports from and to the rest of the world are listed for each country and thus no trade supply chains are identified, no distinction can be made as to where or how the imported products are produced. Hence, no account is taken for differences in production technology in trading partners, or, specifically, the direct and indirect Footprint intensity of trade flows of goods and services (with trade in the latter, and associated Footprints, neglected all together).

Given that the focus of the Ecological Footprint is to capture the total (direct plus indirect) resource use embodied in final consumption in an economy, input-output based models would seem to be the ideal accounting framework. Input-output analysis is based around a set of sectorally disaggregated economic accounts, where inputs to each industrial sector, and the subsequent uses of the output of those sectors, are separately identified. The primary function of input-output analysis is to quantify the interdependence of different activities within the economy. It uses straightforward mathematical routines to track all direct, indirect and, where appropriate, induced, resource use embodied within consumption (Leontief, 1970, Miller and Blair, 1985).

The question of how to allocate greenhouse gas emissions and environmental impacts of production to consumption anywhere in the world has been heavily debated in the literature (Eder and Narodoslowsky, 1999; Munksgaard and Pedersen, 2001; Muradian et al., 2002; Ferng, 2003; Bastianoni et al., 2004; Hoekstra and Janssen, 2006; Munksgaard et al., 2007; Mongelli et al., 2006). As a consequence of and in parallel to this discussion there has been a tremendous development of input-output based models that are able to account for pollution embodied in trade. Recently, a range of multi-region input-output models has been described in the literature (Wiedmann et al., 2006a; Wiedmann et al., 2007).

The purpose of this paper is

³ Other shortcomings, outside the scope of this paper, include the omission of biodiversity and ecosystem health issues (Lenzen et al., 2007) and inconsistencies in the unit conversion from local to global hectares (Wiedmann and Lenzen, 2007).

- to provide examples from recent studies described in the scientific literature where multi-region input-output models have been applied to calculate environmental impacts embedded in international trade flows (Section 2),
- to describe the suitability and adaptation of MRIO modelling to Ecological Footprint analyses (Section 3), and
- to discuss advantages and limitations of an integrated EF-MRIO approach (Section 4).

2. Review of MRIO models for the assessment of environmental impacts embodied in trade

In a recently published, comprehensive literature review we identify a number of models based on multi-region input-output analysis used to estimate the environmental loads associated with international trade flows (Wiedmann et al., 2007; Table 1).

> *Table 1 (see Appendix)*<

Ahmad and Wyckoff (Ahmad, 2003; Ahmad and Wyckoff, 2003) present a framework for estimating CO₂ emissions embodied in internationally traded goods based on input-output and trade modelling. The calculations for 24 countries (responsible for 80% of global CO₂ emissions) are based on national input-output tables on a 17 sector level, bilateral trade data for 41 countries/regions and IEA⁴ data for CO₂ emissions from fossil fuel combustion. For the importing country under investigation separate import matrices for each country or region that exports to this country are established, distinguishing between imports for intermediate and for final demand. For the embodied emissions of services only tentative estimates are included in the analysis.

Following this approach under conservative assumptions shows that estimates of CO₂ emissions generated to satisfy domestic consumption in OECD countries in 1995 were 5% or over 0.5 Gt CO₂ higher than emissions related to production. Based on volume, the United States alone account for nearly half of the total global CO₂ emissions embodied in imported goods. The largest net outflow of emissions embodied in exports bound for OECD countries in 1995 came from China and to a lesser extent Russia.

Nijdam and colleagues (Nijdam et al., 2005) present an analysis of a range of household environmental impacts based on a global input-output model, that differentiates production technology and emissions in the Netherlands and three different world regions. The technological matrices for the three world regions were constructed using input-output tables of countries and sub-regions from the international economic Global Trade Analysis Project (GTAP) database⁵. Three import matrices describing the requirements of imports per region for Dutch production are derived from import statistics.

⁴ International Energy Agency, Paris, France

⁵ GTAP (Global Trade Analysis Project) is a global network of researchers and policy makers conducting quantitative analysis of international policy issues (<http://www.gtap.agecon.purdue.edu>). Products from GTAP include data, models, and utilities for

The results from this study (Nijdam et al., 2005) show that most of the impacts take place abroad, except of greenhouse gases and road traffic noise for which 49% and 9% of the total impact takes place abroad, respectively. A substantial fraction of the impacts is due to imports from non-OECD countries. Most land use was found to take place in developing countries, whereas most emissions occur in industrialised countries.

Similar to Lenzen et al. (2004, see below), Peters and Hertwich (2004) develop a consistent theoretical framework for a closed MRIO model to calculate pollution embodied in trade for arbitrary demands in the receiving economy. The authors discuss a number of simplifications that lead to reductions in data requirements, without the introduction of large errors (Peters and Hertwich, 2004; Peters and Hertwich, 2007).

There are several applications of the model. Peters and Hertwich (2006a) find that, in 2000, CO₂ emissions embodied in imports are 67% of Norway's domestic emissions with around a half of this embodied pollution originating in developing countries. Exports account for 69% of Norway's domestic emissions. The study also shows that assuming imports were produced with Norwegian technology would lead to an underestimation of total embodied emissions by a factor of 2.5. In Peters and Hertwich (2006b) the authors use their MRIO model for a structural path analysis (SPA) across borders, thus enabling the investigation of international supply chains (on an aggregation level of 49 sectors). Embodied impacts in household and government consumption and exports are quantified, identifying high ranking impacts from imports, for example the household purchase of clothing from developing countries in the case of CO₂. Furthermore, the authors use SPA in a consumption and a production perspective, offering complementary insights, both in terms of analysis and policy. Another application focuses on household consumption and impacts of imports to Norway (Peters and Hertwich, 2006c; Peters and Hertwich, 2007). The study finds that household environmental impacts occurring in foreign regions represent 61% of indirect CO₂ emissions, 87% for SO₂, and 34% for NO_x, whereas imports represent only 22% of household expenditure in Norway. All studies by Peters and Hertwich confirm the importance of considering regional technology differences in a multi-region model when calculating pollution embodied in trade.

A detailed multi-region input-output model featuring feedback loop analysis is described by Lenzen et al. (2004). In order to calculate CO₂ multipliers for multi-directional trade between Denmark, Germany, Norway, Sweden and the rest of the world the authors construct a consistent MRIO system which, as a central element, features domestic make and use matrices as well as use matrices for traded goods and services between all trading partners, resulting in total, region-specific multipliers of intermediate demand, trade, energy consumption and CO₂ emissions. With this closed model it is possible to include feedback loops and capture direct, indirect, and induced effects of trade.

Lenzen et al. (2004) can demonstrate the differences in results when either domestic or foreign production recipes are used for traded commodities. In the case of Denmark, 18.9 Mt of CO₂ emissions embodied in imports resulting from a single-region model (assuming that Danish imports are produced with Danish technology) turn into 38.4 Mt of imported CO₂ emissions when multi-directional trade with specific production recipes for the country/region of origin is considered (see also Munksgaard et al., 2005, 2007). Lenzen et al. (2004) also describe in detail the practical challenges of their five-region compound model and provide pragmatic assumptions and solutions for issues such as re-classification, currency conversion, valuation and estimation of trade flows. They show that the level of sector aggregation has a

multi-region, applied general equilibrium analysis of global economic issues. The GTAP project is coordinated by the Center for Global Trade Analysis, Purdue University, USA.

significant impact on the results and argue that therefore the most possible detail of disaggregation should be used.

The econometric input-model GINFORS (Global INterindustry FORecasting System) described by Lutz et al., 2005 (see also Meyer et al., 2003a, 2003b as well as Giljum et al., 2007) is not primarily used to calculate pollution embodiments of trade, but contains all essential elements to do so in the form of linked economy, energy and environment models with global coverage. A bilateral world trade model, closed on the global level, links national models for 25 commodity groups and one service aggregate, using bilateral trade share matrices. All EU-25 countries, all OECD countries and their major trading partners are explicitly modelled and time series from 1980 to 2002 are provided. The economic part consists of macro models for all countries and input-output models where data is available, which is the case for 25 countries, mostly European.

GINFORS has been used as part of the European MOSUS project⁶ to simulate sustainability scenarios for Europe's development until 2020. The MOSUS project has linked total resource use (comprising material flows and land use) to socio-economic indicators, e.g. growth and employment, in a global (multi-national and multi-sectoral) view (Giljum et al., 2007). As a follow-up it is intended to set up a global multi-country input-output model in order to quantify embodied natural resource requirements and to calculate comprehensive material flow indicators such as Total Material Consumption (TMC) (Giljum, 2005).

Another simulation model with global coverage has been developed by the Global Trade Analysis Project (GTAP)⁷ (Hertel and McDougall, 2003). The GTAP model is a static multi-region, multi-sector applied general equilibrium model. GTAP distinguishes 57 sectors and 87 countries/regions and is thus able to capture some detail of interactions between domestic sectors as well as international trading partners. Chung (2005) couples Ahmad and Wyckoff's approach (Ahmad and Wyckoff, 2003) with the global trade CGE model developed by GTAP and with the GTAP-E dataset⁸ to calculate CO₂ emissions embodied in international trade for nine regions of the world. Chung's baseline calculations suggest that the countries/regions with the highest Balance of CO₂ Emissions Embodied in International Trade (BEET) deficit are Japan and the EU, with 7.3% and 3.9% of their domestic emissions, respectively. In other words, Japan and the EU import more embodied emissions than they export and thus carry some responsibility for emissions outside of their territory (compare Chung and Rhee, 2001).

A new European Integrated Project (IP) funded under the Seventh Research Framework Programme (FP7) of the EU is EXIOPOL – a new environmental accounting framework using externality data and input-output tools for policy analysis⁹. EXIOPOL aims to develop estimates of external costs of a broad set of economic activities for Europe and to set up a detailed environmentally extended input-output framework including these estimates, in order to apply the results of this analysis to address policy questions in fields, such as Integrated Product Policy or Sustainable Consumption and Production. One work area of the new project

⁶ "Is Europe sustainable? MOdelling opportunities and limits for restructuring Europe towards SUstainability", see <http://www.mosus.net>.

⁷ Center for Global Trade Analysis, Purdue University, USA (<http://www.gtap.agecon.purdue.edu>).

⁸ GTAP-E is an extension of the standard GTAP model that adds a module for the substitution effects towards more energy efficient capital and a module of CO₂ emissions resulting from the use of emission generating commodities in the production process (see Truong, 1999 and Burniaux and Truong, 2002). A comparison of the GTAP-E model with other CGE models can be found in Kremers et al. (2002).

⁹ <http://www.feem.it/Feem/Pub/Programmes/Sustainability+Indicators+and+Environmental+Valuation/Activities/200703-EXIOPOL.htm>

which was kick-started in April 2007 is the creation of a detailed input-output framework for the EU 25 which is extended with environmental information and will enable the creation of MRIO models in the future. The Ecological Footprint is one of the environmental indicators meant to be used in EXIOPOL (Tukker, 2006).

3. Applying environmentally extended input-output models to Ecological Footprint analysis

3.1. Ecological Footprint studies using input-output analysis

In recent years there have been a number of contributions to the literature attempting to use input-output techniques to calculate Ecological Footprints (Bicknell et al., 1998; Ferng, 2001 and 2002; Lenzen and Murray, 2001; McDonald and Patterson, 2003 and 2004; Lenzen et al., 2005; Wiedmann et al., 2006b) or similar indicators (Eder and Narodoslowsky, 1999; Proops et al., 1999; Hubacek and Giljum, 2003; Sánchez-Chóliz and Duarte, 2004).

Applying the input-output method to an Ecological Footprint basically involves populating the matrix Ω of resource use coefficients with a set of Ecological Footprint coefficients (see Turner et al., 2007). That is, a $K \times N$ matrix of direct Footprint coefficients $\Omega = \mathbf{f}^x \cdot \hat{\mathbf{x}}^{-1}$ is established with elements $\omega_{ki} = f_{ki} / x_i$ for each economic sector i , for example by disaggregating an existing Ecological Footprint account for the production in a country. Then an input-output calculation is used to estimate what types of final consumption directly or indirectly give rise to the pre-existing Footprint estimate. Such an approach is described in Wiedmann et al (2006b) who reconcile the National Footprint Account of the UK – in terms of demand for bioproductivity – with the UK economic National Accounts. Their method has been applied empirically to calculate the Ecological Footprint of local authorities, regions and devolved countries in the UK (Barrett et al., 2005; WWF-UK, 2006) as well as of UK socio-economic groups (Birch et al., 2004).

Other studies attempt to calculate the Ecological Footprint using other metrics: Bicknell et al (1998) were the first to present an application of input-output analysis to estimate an Ecological Footprint for New Zealand, where Ω is a matrix of land-use coefficients. The main critique of their work (see for example Lenzen and Murray, 2001, McGregor et al, 2004a) is that Bicknell et al (1998) use a closed-economy framework where imports are exogenously given and the direct and indirect land-use coefficients of these imports are assumed to be identical to those in New Zealand.

In closed-economy input-output studies on CO₂ and other quantities (c.f. Wiedmann et al, 2007) this assumption is usually implemented by adding the imports coefficients matrix \mathbf{A}^m to the domestic direct requirements matrix, which we now distinguish as \mathbf{A}^d , so that the modified total requirements coefficients are

$$[1] \quad \Omega [\mathbf{I} - (\mathbf{A}^m + \mathbf{A}^d)]^{-1}$$

where Ω is the same for all trading nations that directly or indirectly produce the goods and services that are imported to the country studied. Whether domestic multipliers are under- or overestimated through this assumption depends on whether land inputs per unit of output are

higher or lower in the trading partners' territories. As some of the examples in the literature review show, resource use and pollution intensities per industrial sector can vary substantially between different countries (see also Wiedmann et al., 2007). One extreme example quoted by Peters and Hertwich (2006a) is that CO₂ emission intensity for electricity production in China (generated mainly by coal power plants) is 231 times higher than for Norway (generated mainly by hydro power).

Similarly, in the case of direct resource-use and pollution intensities, Turner (2006) demonstrates the potential information loss when proxy measures of Ω are used. In the case of standard economic multiplier analysis, with respect to the importance of region- and/or country-specific A-matrices, a number of studies have been conducted in the regional literature (c.f. Turner et al., 2007) focusing on how economic input-output relationships differ across even small regional economies within the same national economy.

The Bicknell et al. (1998) approach of assuming New Zealand production structure applies in the rest of the world would seem particularly unrealistic: if a proxy must be used it would seem more valid to use information from an economy that is large relative to the rest of the world (the US, for example). However, Bicknell et al. (1998) are not alone in making this type of assumption: for example, in a review of alternative methods the Office for National Statistics in the UK (2002) recommend, albeit with caution, a similar approach in the case of greenhouse gas emissions embodied in imports to the UK (see McGregor et al., 2004a and 2004b).

In another modification of the metric, Lenzen and Murray (2001) employ an input-output framework in terms of land disturbance, where land use coefficients are weighted by land condition, or impact on land. These authors model the open economy by internalising current as well as capital imports into intermediate demand. The multipliers of domestically produced commodities and imports are still identical. The same imports assumption is applied in a comparative bioproductivity-based Footprint study of the Australian State of Victoria (Lenzen et al., 2005), which aimed at reconciling differences between the manual accounting practices of the Global Footprint Network, and input-output accounting.

Ferng (2001) identifies another shortcoming in Bicknell et al.'s (1998) estimation procedure and suggests corrections in the methodology. Instead of a land multiplier vector, Ferng uses a land multiplier composition matrix, distinguishing land types by sectors and demonstrates that significantly different results are obtained by the two methods. Ferng (2002) also improves the methodology for the energy component of the Footprint by using a standard input-output approach for the calculation of embodied energy. In this framework imports to intermediate and final demand are considered separately but still with the assumption that the exporting countries have the same producing technology as the domestic economy. Also, no distinction is made for the origins of the intermediate inputs used by the producing sectors in those exporting countries (Ferng, 2002).

Bicknell et al.'s methodology has been developed further by McDonald and Patterson (2003 and 2004) in a sub-national input-output framework that explicitly models the land appropriation of 16 regions in New Zealand, including the embodied Footprints of regional imports and exports. Another application based on input-output analysis is described in a recent study by McDonald et al. (2006) that quantifies patterns of resource use and waste generation ('ecofootprints') of different age groups in New Zealand. In both cases however, the same single-region assumption as in the approach of Bicknell et al. (1998) is adopted, i.e. it is assumed that products imported from overseas have exactly the same embodied impact-per-\$ ratio as products made in New Zealand.

The single-region assumption, albeit an improvement compared to the NFA method, needs to be challenged for setting up an accurate Footprint account for consumption, because the inclusion of land use and emissions associated with imports from all over the world exceeds the national boundaries of input-output tables.

A methodologically sound respond to this challenge is to extend the basic multi-sectoral single region input-output framework to the inter-regional case and to employ a multi-region input-output (MRIO) model ideally covering all trading partners of the country under investigation. A few studies comparing single versus multi-region input-output models of energy and CO₂ (e.g. Proops et al, 1999; Lenzen et al, 2004) have already demonstrated that multipliers and embodiments can differ substantially, thus warranting the extension to many regions. The MRIO model is discussed in the next section.

3.2. Theory of a multi-region input-output method for the Ecological Footprint

Given their widespread application (Wiedmann et al., 2007), MRIO models would constitute obvious improvements of the Footprint method. In this section we provide an exposition of the extension of the basic single-region framework to the multi-region case, and to explicitly identify the key practical problems that are likely to arise and what the most appropriate solutions may be.

For the purpose of simplicity, the following exposition (derived from McGregor et al., 2004a and Miller and Blair, 1985) is given in terms of a 2-region world. However, it is straightforward to extend to the multiple region case (see Allan et al, 2004).

From the basic input-output equation (Leontief, 1970; Miller and Blair, 1985)

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

we can derive that in a 2-region model the outputs \mathbf{x} to support demand domestically (\mathbf{x}_{11} or \mathbf{x}_{22}) or in the other region (\mathbf{x}_{12} and \mathbf{x}_{21}) is

$$[3] \quad \begin{pmatrix} \mathbf{x}_{11} & \mathbf{x}_{12} \\ \mathbf{x}_{21} & \mathbf{x}_{22} \end{pmatrix} = \begin{pmatrix} \mathbf{I} - \mathbf{A}_{11} & -\mathbf{A}_{12} \\ -\mathbf{A}_{21} & \mathbf{I} - \mathbf{A}_{22} \end{pmatrix}^{-1} \begin{pmatrix} \mathbf{y}_{11} & \mathbf{y}_{12} \\ \mathbf{y}_{21} & \mathbf{y}_{22} \end{pmatrix}$$

where elements a_{ij}^{rs} of the $N \times J$ submatrices \mathbf{A}_{rs} show the transactions between sector i in producing region r and using sector j in consuming region s , per unit of output of sector j in region s . Final demand \mathbf{y} is separated into local final demand in region 1 of commodities produced in region 1 (\mathbf{y}_{11}) and export demand in region 2 for region 1 commodities (\mathbf{y}_{12}). Similarly for region 2, final demand for region 2 commodities is split into export demand in region 1 (\mathbf{y}_{21}) and local demand in region 2 (\mathbf{y}_{22}). The partitioned matrix $(\mathbf{I} - \mathbf{A})^{-1}$ is the inter-regional Leontief inverse, breaking down the gross output multiplier for each sector in each region into gross outputs that are induced by domestic and by foreign final demand. In other words, by having partitioned the \mathbf{A} -matrix for each region into local and imported intermediate consumption, and the \mathbf{y} vector for each region into domestic and traded final demand, we can determine the level of inter-regional spillovers in terms of how activity in one region drives activity in the other.

Of course, the activity we are interested in here is resource use. We therefore introduce a $(K \times N)$ matrix of coefficients Ω^x , showing the direct resource-use intensity of output in each production sector i for each region:

$$[4] \quad \begin{pmatrix} \mathbf{f}_{11}^y & \mathbf{f}_{12}^y \\ \mathbf{f}_{21}^y & \mathbf{f}_{22}^y \end{pmatrix} = \begin{pmatrix} \Omega^x_1 & \mathbf{0} \\ \mathbf{0} & \Omega^x_2 \end{pmatrix} \begin{pmatrix} \mathbf{I} - \mathbf{A}_{11} & -\mathbf{A}_{12} \\ -\mathbf{A}_{21} & \mathbf{I} - \mathbf{A}_{22} \end{pmatrix}^{-1} \begin{pmatrix} \mathbf{y}_{11} & \mathbf{y}_{12} \\ \mathbf{y}_{21} & \mathbf{y}_{22} \end{pmatrix} \\ = \begin{pmatrix} \Omega^x_1 \mathbf{L}_{11} \mathbf{y}_{11} + \Omega^x_1 \mathbf{L}_{12} \mathbf{y}_{21} & \Omega^x_1 \mathbf{L}_{11} \mathbf{y}_{12} + \Omega^x_1 \mathbf{L}_{12} \mathbf{y}_{22} \\ \Omega^x_2 \mathbf{L}_{21} \mathbf{y}_{11} + \Omega^x_2 \mathbf{L}_{22} \mathbf{y}_{21} & \Omega^x_2 \mathbf{L}_{21} \mathbf{y}_{12} + \Omega^x_2 \mathbf{L}_{22} \mathbf{y}_{22} \end{pmatrix}$$

where \mathbf{f}_{11}^y is a $K \times 1$ vector of the amount of resources that are used in production activities in region 1 to support region 1 final demand, while \mathbf{f}_{21}^y is the amount of resources used in region 2 production to support region 1 final demand. The sum of these, in a 2-region world, will give us the Ecological Footprint for region 1 final demand:¹⁰

$$[5] \quad \mathbf{f}_1^y = \mathbf{f}_{11}^y + \mathbf{f}_{21}^y$$

And the Ecological Footprint of region 2 is equal to

$$[6] \quad \mathbf{f}_2^y = \mathbf{f}_{22}^y + \mathbf{f}_{12}^y$$

Similarly if we extend to the N -region case, this will simply involve summing down a column with an additional $N-2$ entries for each additional region. For example \mathbf{f}_1^y would become

$$[7] \quad \mathbf{f}_1^y = \mathbf{f}_{11}^y + \mathbf{f}_{21}^y + \dots + \mathbf{f}_{n1}^y$$

3.3. Practical issues for the application of a MRIO framework for Ecological Footprint analysis

In order to estimate the MRIO system in Eq. [4] information is required on

- the direct imports to final consumption in the local economy/country, s , broken down by commodity and country of origin (to derive the elements of $\mathbf{y}_{r,s}$ for each external region, r , from which imports are drawn)
- the imports used as intermediate inputs for each local industry in economy/country s , broken down by commodity and country of origin, r (to derive the elements of \mathbf{A}_{rs})
- an input-output table for each country from which imports are drawn (to determine the elements of the inter-regional trade component, $-\mathbf{A}_{rs}$, of the partitioned inter-regional

¹⁰ The direct resource use by final consumers is omitted here for simplicity.

Leontief inverse, $[\mathbf{I} - \mathbf{A}]^{-1}$, in order to determine multiplier effects in the exporting country, r).

The input-output tables from each of the exporting countries, r , would themselves need to have the following characteristics:

- a sector mapping (i.e. a matrix that maps, or re-classifies sector i in the exporting country, r , into sectors i in each of the importing nations, s)
- a comparable set of input-output coefficients for resource use (i.e. for each sector i there must be a coefficient ϖ_{ki} within the matrix $\mathbf{\Omega}$ showing the average direct resource intensity for resource k of producing one unit of output)
- equivalent input-output data to track direct and indirect imports from all other countries that the exporting country, r , trades with.

There are three basic problems that have so far prevented the application of a full inter-regional framework of the type described above. The first is data availability, mainly in terms of flows of traded commodities between sectors in different countries. The second is reconciliation of data from different sources in different countries. The third is computability, particularly in terms of balancing conflicting data. Full discussions of these issues of the challenges involved in applying multi-region input-output frameworks can be found in Lenzen et al (2004) (see also Peters and Hertwich, 2006b).

4. Discussion

Economic-environment models based on input-output analysis are able to capture indirect environmental impacts caused by upstream production – be it domestic or foreign – and this makes them suitable for the estimation of Ecological Footprints, embodied emissions, virtual water consumption and other indicators.

However, it is important to allow for the inclusion of foreign technology coefficients if a distinction between Footprint intensities of production processes in trading countries is to be made. If, as frequently done, a closed economy single-region model is employed to calculate the direct requirements matrix, the resulting multipliers only represent the production structure of the domestic economy. This is a far reaching limitation which does not permit analysis and assessment of foreign production efficiencies. There would be no difference, for example, in the embodied Ecological Footprint of iron and steel produced in the UK or produced in China. Such an evaluation however needs to be an intrinsic part of modelling factor embodiments. In policy analyses and scenarios for example, one might want to explore the environmental implications of trade with different countries or the consequences that the relocation of a particular industry to foreign countries has on emissions.

The National Footprint Accounts compiled by the Global Footprint Network is one method of estimating the Ecological Footprint of nations (Wackernagel et al., 2005)¹¹. Trade embodiments are calculated by multiplying the reported weights of product flows between nations by Footprint intensities in global hectares per tonne to arrive at an estimate of total global hectares imported or exported (Monfreda et al., 2004). These intensities are derived from ecosystem yields, with energy intensities usually drawn from disparate LCA product

¹¹ An alternative approach is presented by Venetoulis and Talberth (2007).

analyses. Because of the data disparity and a lack of standardized boundary setting principles among process-flow LCA studies, the process-based Footprint estimates for trade may be subject to over and under-counting.¹² Furthermore, the current omission of trade in services has the potential to bias upward the Footprint of service exporting nations, such as those with large telecommunications sectors, research and development, or knowledge-based industries. These issues are currently being discussed in the Footprint community and suggestions for research have been made (Kitzes and et al., 2007).

The methodologically sound respond to this challenge is to employ a multi-region input-output (MRIO) model ideally covering all trading partners of the country under investigation. The more economic sectors such a model can identify the stronger the analysis will be as more interdependencies between sectors that are distinct in their production technology (such as resource use and pollution intensities) can be quantified. Studies comparing single versus multi-region input-output analyses of energy and CO₂ (Proops et al, 1999; Haukland, 2004; Lenzen et al, 2004; Peters and Hartwich, 2006a) have demonstrated that multipliers and embodiments can differ substantially, thus warranting the extension to many regions.

As demonstrated in this literature review, a number of models employing input-output analysis have been described but only in the last few years models have emerged that use a more sophisticated multi-region, multi-sector input-output framework. A decade ago, models of this type were not practical due to the lack of consistent data. Improvements in data availability and quality have changed the situation in the last few years and more sophisticated models have been described recently. We identify six major models that employ multi-sector, multi-region input-output analysis in order to calculate environmental impacts embodied in international trade (see Table 1).

The data requirements for a full scale MRIO model are substantial. Input-output tables are available for many developed and some developing countries and can be estimated or approximated for minor trading regions or where national tables are not available. Although the sector aggregation varies from country to country, the principal economic accounting framework is a standardised process (United Nations, 1999, 2003) and some data sources provide input-output tables in a consistent format for a number of countries (Ahmad, 2002; Hertel and McDougall, 2003; Ahmad et al., 2006; Wixted et al., 2006; Yamano and Ahmad, 2006). However, detailed inter-regional trade data are also required for any model that deals with impacts embodied in traded commodities. Naturally, the more countries and regions are featured in the model, the higher are the data requirements. In the case of the Ecological Footprint, direct (or 'on-site') land use data for the different land area types as well as CO₂ emissions or energy use data are required per economic sector for all countries/regions. This type of data is available from environmental accounts for many developed countries, but might be difficult to obtain for others.

Data availability has become better in the last few years and more comprehensive due to improvements in input-output databases (Dimaranan and McDougall, 2005; Yamano and Ahmad, 2006) and trade data and models (Eurostat, 2003; Pain et al., 2005) and environmental accounts (United Nations, 2003). Therefore, it can be expected that more

¹² Interestingly, many newer LCA databases derive their estimates using input-output frameworks, leading to increasing convergence between these two methods (Hendrickson et al., 1998; Joshi, 1999; Treloar et al., 2000; Lenzen, 2002; Suh and Huppel, 2001 and 2002; Hertwich, 2005; Nijdam et al., 2005; Weidema et al., 2005; Heijungs et al., 2006; Tukker et al., 2006; Wiedmann et al., 2006b)

comprehensive and robust techniques for estimating Ecological Footprints will be developed in the near future.

In any case, constructing a database for a MRIO model requires a sophisticated method of data handling and entails considerable specific challenges as described in Turner et al. (2007). Compiling the required data, estimating missing data and balancing conflicting data in the right way is the most crucial part of a MRIO framework.

With a complete closed MRIO model it is also possible to include feedback loops and capture direct, indirect, and induced effects of trade. Another advantage of input-output based approaches is that they allow the quantification of responsibility according to different principles. Not only, can full producer and consumer responsibility accounts be calculated (Munksgaard et al., 2007) but also any share of responsibility can be quantified with such a framework (Gallego and Lenzen, 2005).

5. Conclusions

Over the last decade in particular there has been a tremendous increase in applications of analytical, and indeed forecasting, models based on environmentally extended input-output techniques. Besides being scientifically well described and established, the crucial advantage of input-output based analyses is that it is possible to attribute environmental impacts to virtually *any consumption activity*, such as consumption of regions, nations, governments, cities, socio-economic groups or individuals, whether domestically or abroad (imports/exports); to virtually *any production activity* of organisations, companies, businesses, product manufacturing, service provision etc and to virtually *any associated economic activity in between* such as supply chains, trade flows or recycling.

It is an old truism that there is no 'best' model as such, but only a 'best' model for a specific purpose. Input-output models are very detailed in their description of commodities produced in economies. They can provide detailed static *ex-post* accounting tools for monetary and non-monetary (physical) quantities. However they are not well suited to describe change in a predictive (*ex-ante*) way, because they usually do not contain any realistic description of agent behaviour (e.g. producer and consumer demand). Input-output coefficients (the Leontief production function) provide an indication of average factor use, but should not be assumed to give information on marginal factor use, as a function of price or other determinants. The latter may better be reflected by Constant Elasticity of Substitution (CES) or similar production functions usually incorporated in General Equilibrium models. However, this is ultimately an empirical question.

As a consequence, which type of model is most suitable for usage in Ecological Footprint (EF) analysis depends on the research question and the purpose of the particular application. At present, the main purposes of Footprint accounts are 1) to give an *ex-post* static comparative snapshot of the use of biologically productive land and sea area, and 2) to identify and communicate potential sources of unsustainability to the general public and to political and corporate decision-makers. Furthermore, given that EF accounts already operate at comparatively high commodity detail, single- or multi-region input-output models appear as the most suitable approach. Based on the results of a comprehensive literature review we argue that multi-region input-output (MRIO) models seem to be particularly appropriate to estimate the Ecological Footprints of production, consumption, imports and exports with the possibility to track their origin via inter-industry linkages, international supply chains and

multi-national trade flows. The latter features are not possible with the current method used to compile the National Footprint Accounts (Wackernagel et al., 2005).

Employing a MRIO model for Ecological Footprint accounting in an international context would provide the following advantages:

- A MRIO framework is consistent with existing UN Accounting Standards (United Nations Statistics Division, 2003) and it is desirable to develop it in parallel with the ongoing standardisation of the Footprint methodology. This will underpin and lend credibility to a Footprint accounting standard. Attention will also be paid to retaining commodity classification as disaggregated and relevant for the Footprint as possible.
- Using a model with a high sector disaggregation also allows the tracking of international supply chains. An entirely novel development is the use of Structural Path Analysis (SPA) in a multi-region framework: MRIO-SPA is an extension of applications in single-region input-output frameworks (Treloar 1997; Lenzen 2002 and 2007; Peters and Hertwich, 2006b). Applying SPA to an MRIO system is far from trivial, mostly because of the larger size and nested hierarchy of the MRIO system, compared to a single-region system. However, once developed, MRIO-SPA is ideally suited to extract and prioritise international commodity chains and to link locations of consumption with hot spots of environmental impacts. MRIO-SPA can also be used to prioritise targets for action for corporate or government decision-makers (Wood and Lenzen, 2003).
- Furthermore, comprehensive economic-environmental IO model systems are in particular suited to perform scenario simulation of the environmental and socio-economic effects of the implementation of environmental policy measures. Thus, policy strategies and instruments can be tested and elaborated, which are capable of best reconciling competing policy goals in economic, social and environmental policies.
- Implementing an MRIO would overcome uncertainties in energy or emissions intensities of imported goods and services, since all international trade links – direct and indirect – are potentially included. It would thus add accuracy and comprehensiveness to Ecological Footprint accounts of trade.
- MRIO is also the only comprehensive method for assessing the activities of multinational corporations, since these essentially represent a production network spanning multiple sectors in multiple countries.

6. Acknowledgements

Barrett and Wiedmann acknowledge the support of the UK Department for Environment, Food and Rural Affairs as part of the Sustainable Consumption and Production science programme. Turner acknowledges the support of the UK EPSRC (Grant Reference Res-342-25-0002) as part of the Supergen Marine Consortium.

7. References

Ahmad, N. and Wyckoff, A.W., 2003. Carbon dioxide emissions embodied in international trade of goods. STI Working Paper DSTI/DOC(2003)15, Organisation for Economic Co-operation and Development (OECD), Paris, France

- Ahmad, N., 2002. The OECD Input-Output Database. DSTI/EAS/IND/SWP(2001)14 [14th International Conference on IO Techniques - Montreal October 10-15, 2002.]. Organisation for Economic Co-operation and Development (OECD), Science, Technology and Industry Directorate
- Ahmad, N., 2003. A framework for estimating carbon dioxide emissions embodied in international trade of goods. STI Working Paper STI/SD/WAF(2003)20, Organisation for Economic Co-operation and Development (OECD), Paris, France
- Ahmad, N., Yamano, N., and OECD, 2006. The OECD's Input-Output Database: 2006 Edition. 29th General Conference of The International Association for Research in Income and Wealth, August 20-26, 2006, Joensuu, Finland.
- Allan, G., McGregor, P.G., Swales, J.K, and Turner, K.R. (2004), 'Construction of a multi-sectoral inter-regional IO and SAM database for the UK', mimeo, Strathclyde Discussion Papers in Economics, No. 04-22.
- Barrett, J., Birch, R., Cherrett, N., Wiedmann, T., 2005. Reducing Wales' Ecological Footprint – Main Report. Stockholm Environment Institute, University of York; published by WWF Cymru, Cardiff, UK; March 2005. <http://www.walesfootprint.org>.
- Bastianoni, S., Pulselli, F.M., and Tiezzi, E., 2004. The problem of assigning responsibility for greenhouse gas emissions. *Ecological Economics*, 49:253-257
- Bicknell, K.B., Ball R.J., Cullen R. and Bigsby H.R., 1998. New methodology for the ecological footprint with an application to the New Zealand economy. *Ecological Economics* 27(2), 149-160.
- Birch, R., Barrett, J., Wiedmann, T., 2004. Exploring the consumption and related environmental impacts of socio-economic groups within the UK. International Workshop on Sustainable Consumption, School of the Environment, University of Leeds; 5/6 March. <http://www.env.leeds.ac.uk/~hubacek/leeds04/call.htm>.
- Burniaux, Jean-Marc and Truong, Truong P., 2002. GTAP-E - An energy-environmental version of the GTAP model. GTAP Technical Papers, No. 16. Center for Global Trade Analysis, Purdue University, West Lafayette, Indiana, USA 47907-1145.
- Chung, H.-S. and Rhee, H.-C., 2001. Carbon Dioxide Emissions of Korea and Japan and its Transmission via International Trade. *International Economic Journal*, 15:117-136.
- Chung, H.-S., 2005. Balance of CO2 Emissions Embodied in International Trade: Can Korean Carbon Tax on its Imported Fossil Fuels Make Any Difference in BEET? EcoMod2005 - International Conference on Policy Modeling, 29 June – 1 July 2005, Istanbul, Turkey.
- Dimaranan, Betina V. and McDougall, Robert A., 2005. Global Trade, Assistance, and Production: The GTAP 6 Data Base. Dimaranan, Betina V. and McDougall, Robert A. Center for Global Trade Analysis, Purdue University.
- Eder, P. and Narodoslawsky M., 1999. What environmental pressures are a region's industries responsible for? A method of analysis with descriptive indices and input-output models. *Ecological Economics* 29, 359-374.
- Eurostat, 2003. 'International trade in services 1992–2001', Compilation Guide, European Commission, Office for Official Publication of the European Communities, Luxembourg.
- FAO, 2005. FAOSTAT. Food and Agriculture Organization, Statistical Databases, Rome. <http://faostat.fao.org>
- Ferng, J.J., 2001. Using composition of land multiplier to estimate Ecological Footprints associated with production activity. *Ecological Economics*, 37:159-172.
- Ferng, J.J., 2002. 'Toward a scenario analysis framework for energy footprints', *Ecological Economics*, vol. 40, pp. 53-69.
- Ferng, J.J., 2003. Allocating the responsibility of CO2 over-emissions from the perspectives of benefit principle and ecological deficit. *Ecological Economics*, 46:121-141
- Gallego, B. and Lenzen, M., 2005. A consistent input-output formulation of shared producer and consumer responsibility. *Economic Systems Research*, 17:365-391

- GFN, 2005. National Footprint Accounts, national summary data sheets. Global Footprint Network. http://www.footprintnetwork.org/gfn_sub.php?content=national_footprints
- Giljum, S., Hinterberger, F., Lutz, C., and Meyer, B., 2007. Modelling global resource use: material flows, land use and input-output models. In: S.Suh (Editor), Handbook on Input-output Economics for Industrial Ecology. Springer, Dordrecht; forthcoming.
- Haukland, E. 2004. Trade and environment: Emissions intensity of Norway's imports and exports. Master's thesis, Norwegian University of Science and Technology (NTNU), Trondheim, Norway.
- Heijungs, R., de Koning, A., Suh, S., and Huppes, G., 2006. Toward an Information Tool for Integrated Product Policy: Requirements for Data and Computation. *Journal of Industrial Ecology*, 10:147-158 pp.
- Hendrickson, C.T., Horvath, A., Joshi, S., and Lave, L.B., 1998. Economic Input-Output Models for Environmental Life-Cycle Assessment. *Environmental Science & Technology*, 32:184A-191A pp.
- Hertel, T. W. and McDougall, Robert A., 2003. GTAP Model Version 6.2. Center for Global Trade Analysis, Purdue University.
- Hertwich, E.G., 2005. Life cycle approaches to sustainable consumption: a critical review. *Environmental Science & Technology*, 39:4673-4684 pp. <http://dx.doi.org/10.1021/es0497375>
- Hoekstra, R. and Janssen, M.A., 2006. Environmental responsibility and policy in a two-country dynamic input-output model. *Economic Systems Research*, 18:61-84.
- Hubacek, K. and Giljum S., 2003. Applying physical input-output analysis to estimate land appropriation (ecological footprints) of international trade activities. *Ecological Economics* 44, 137-151.
- Joshi, S., 1999. Product Environmental Life-Cycle Assessment Using Input-Output Techniques. *Journal of Industrial Ecology*, 3:95-100 pp.
- Kitzes, J. and 27 co-authors, 2007. A Research Agenda for Improving National Ecological Footprint Accounts. Paper prepared for the International Ecological Footprint Conference (Stepping up the Pace: New Developments in Ecological Footprint Methodology, Policy & Practice), Cardiff, 8-10 May 2007
- Kremers, H., Nijkamp, P., Wang, S., 2002. A comparison of computable general equilibrium models for analyzing climate change policies. *Journal of Environmental Systems* 28:41– 65.
- Lenzen, M. and Murray, S.A., 2001. 'A Modified Ecological Footprint Method and its Application to Australia', *Ecological Economics*, Vol.37, pp. 229-255.
- Lenzen, M., 2002. A guide for compiling inventories in hybrid life-cycle assessments: some Australian results. *Journal of Cleaner Production*, 10:545-572 pp.
- Lenzen, M., 2007. Structural path analysis of ecosystem networks. *Ecological Modelling*, 200:334-342 pp.
- Lenzen, M., Hansson, C.B., and Bond, S., 2007. On the bioproductivity and land-disturbance metrics of the Ecological Footprint. *Ecological Economics*, 61:6-10 pp. <http://dx.doi.org/10.1016/j.ecolecon.2006.11.010>
- Lenzen, M., Pade, L.-L., and Munksgaard, J., 2004. CO₂ Multipliers in Multi-region Input-Output Models. *Economic Systems Research*, 16:391-412
- Lenzen, M., Wackernagel, M., Lauck, B., Wermer, P., 2005. The Ecological Footprint of the State of Victoria. University of Sydney, Global Footprint Network and Environment Protection Authority, Victoria. <http://www.epa.vic.gov.au/eco-footprint>.
- Leontief, W., 1970. 'Environmental Repercussions and the Economic Structure: An Input-Output Approach', *Review of Economic Statistics*, vol.52, pp.262-277.
- Lutz, C., Meyer, B., and Wolter, M.I., 2005. GINFORS-Model. Gesellschaft für Wirtschaftliche Strukturforschung mbH (GWS), Osnabrück, Germany. MOSUS Workshop, IIASA Laxenburg; April 14.-15., 2005

- McDonald, G. W., Forgieb, V. E. and MacGregora, C., 2006. Treading lightly: Ecofootprints of New Zealand's ageing population. *Ecological Economics*, 56(3): 424-439 pp.
- McDonald, G.W. and Patterson, M.G., 2003. Ecological Footprints of New Zealand and its Regions, 1997/98. Technical Paper, Environmental Reporting, Ministry for the Environment, Wellington, New Zealand, September 2003. <http://www.mfe.govt.nz/publications/ser/eco-footprint-sep03/html> or via <http://www.environment.govt.nz>.
- McDonald, G.W. and Patterson, M.G., 2004. Ecological Footprints and interdependencies of New Zealand regions. *Ecological Economics*, 50:49-67.
- McGregor, P.G., Swales, J.K. and Turner, K., 2004a. 'The environmental 'trade balance' between Scotland and the rest of the UK: an inter-regional input-output and SAM analysis', mimeo, Strathclyde Discussion Papers in Economics, 04-21.
- McGregor, P.G., Swales, J.K. and Turner, K.R., 2004b. 'An Input-Output Based Alternative to 'Ecological Footprints' for Tracking Pollution Generation in a Small Open Economy', mimeo, Strathclyde Papers in Economics, 04/04.
- Meyer, B., Lutz, C., and Wolter, M.I., 2003a. Global Multisector/Multicountry 3 - E Modelling: From COMPASS to GINFORS. Paper presented at the IHDP Conference on Governance for Industrial Transformation, Berlin, 5.-6. December, 2003
- Meyer, B., Lutz, C., and Wolter, M.I., 2003b. Modeling Sustainable Development for Europe in a Global Framework. Presentation at the OECD Environment and Modeling Workshop. Ottawa, 9.-10. October, 2003
- Miller, R.E. and Blair, P.D., 1985. *Input-Output Analysis: Foundations and Extensions*. Prentice-Hall, Englewood Cliffs, New Jersey, USA.
- Monfreda, C., Wackernagel, M. and Deumling, D., 2004. Establishing national natural capital accounts based on detailed ecological footprint and biological capacity accounts. *Land Use Policy*, 21:231-246.
- Mongelli, I., Tassielli, G., and Notarnicola, B., 2006. Global warming agreements, international trade and energy/carbon embodiments: an input-output approach to the Italian case. *Energy Policy*, 34:88-100 pp.
- Munksgaard, J. and Pedersen, K.A., 2001. CO₂ accounts for open economies: producer or consumer responsibility? *Energy Policy*, 29:327-334
- Munksgaard, J., Minx, J.C., Christofferson, L.B., and Pade, L.-L., 2007. Models for National CO₂ Accounting. In: S.Suh (Editor), *Handbook on Input-output Economics for Industrial Ecology*. Springer, Dordrecht; forthcoming
- Munksgaard, J., Wier, M., Lenzen, M., and Dey, C., 2005. Using Input-Output Analysis to Measure the Environmental Pressure of Consumption at Different Spatial Levels. *Journal of Industrial Ecology*, 9:169-186
- Nijdam, D.S., Wilting, H.C., Goedkoop, M.J., and Madsen, J., 2005. Environmental Load from Dutch Private Consumption: How Much Damage Takes Place Abroad? *Journal of Industrial Ecology*, 9:147-168 pp. <http://mitpress.mit.edu/jie/consumption>
- Office for National Statistics (2002), 'Methodologies for Estimating the Levels of Atmospheric Emissions arising from the Production of Goods Imported into the UK', Report of a project undertaken by the Office for National Statistics, London.
- Pain, N., Mourougane, A., Sédillot, F., and Le Fouler, L., 2005. The New OECD International Trade Model, 2005. ECO/WKP(2005)27, Economics Department Working Papers No.440. 2005. Paris, Organisation for Economic Co-operation and Development (OECD). Economics Department Working Papers.
- Peters, G.P. and Hertwich, E.G., 2006a. Pollution embodied in trade: The Norwegian case. *Global Environmental Change*, 16:379-387 pp.
- Peters, G.P. and Hertwich, E.G., 2006b. Structural analysis of international trade: Environmental impacts of Norway. *Economic Systems Research*, 18:155-181 pp. <http://dx.doi.org/10.1080/09535310600653008>

- Peters, G.P. and Hertwich, E.G., 2006c. The Importance of Imports for Household Environmental Impacts. *Journal of Industrial Ecology*, 10:89-109 pp.
- Peters, G.P. and Hertwich, E.G., 2007. The Application of Multi-Regional Input-Output Analysis to Industrial Ecology: Evaluating Trans-boundary Environmental Impacts. In: S.Suh (Editor), *Handbook on Input-output Economics for Industrial Ecology*. Springer, Dordrecht, forthcoming.
- Proops, J.L.R., Atkinson, G., Schlotheim, B.F., and Simon, S., 1999. International trade and the sustainability footprint: a practical criterion for its assessment. *Ecological Economics*, 28:75-97
- Sánchez-Chóliz, J. and Duarte, R., 2004. CO2 emissions embodied in international trade: evidence for Spain. *Energy Policy*, 32:1999-2005
- Suh, S. and Huppes G., 2001. Environmental IOA of the industrialised world - a project description. In: Weidema, B.P. and Nielsen, A.M., Eds. *Input/Output analysis - Shortcuts to life cycle data?* Environmental Project No. 581. Miljøstyrelsen, Ministry for Environment and Energy, Copenhagen, Denmark, 69-75.
- Suh, S. and Huppes, G., 2002. Missing Inventory Estimation Tool Using Extended Input-Output Analysis. *International Journal of Life Cycle Assessment*, 7:134-140 pp.
- Task Force on National Greenhouse Gas Inventories, 1996. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories - Reporting Instructions (Volume 1). Institute for Global Environmental Strategies, Intergovernmental Panel on Climate Change - IPCC National Greenhouse Gas Inventories Programme, Report, <http://www.ipcc-nggip.iges.or.jp/public/gl/invs4.htm> (Tokyo, Japan).
- Truong, T.P., 1999. GTAP-E. Incorporating Energy Substitution into GTAP Model, Technical Paper 16, Center for Global Trade Analysis, Purdue University, Purdue.
- Tukker, A., 2006. An Environmentally Extended Input-Output database for the EU25. International Society for Ecological Economics (ISEE) 9th Biennial Conference on Ecological Sustainability and Human Well-Being, 15-18 December 2006, New Delhi, India
- Tukker, A., Eder, P., and Suh, S., 2006. Environmental Impacts of Products: Policy Relevant Information and Data Challenges. *Journal of Industrial Ecology*, 10:183-198 pp.
- Turner, K., 2006. The Additional Precision Provided by Regional-Specific Data: The Identification of Fuel-Use and Pollution Generation Coefficients in the Jersey Economy, *Regional Studies*, 40(4): 347-364.
- Turner, K., Lenzen, M., Wiedmann, T., and Barrett, J., 2007. Examining the Global Environmental Impact of Regional Consumption Activities - Part 1: A Technical Note on Combining Input-Output and Ecological Footprint Analysis. *Ecological Economics*, 62(1):37-44. <http://dx.doi.org/10.1016/j.ecolecon.2006.12.002>
- United Nations, 1999. *Handbook of National Accounting: Handbook of Input-Output Table Compilation and Analysis*. United Nations, Department for Economic and Social Affairs, Statistics Division, New York.
- United Nations, 2003. *Handbook of National Accounting: Integrated Environmental and Economic Accounting 2003*. United Nations; European Commission; International Monetary Fund; Organisation for Economic Co-operation and Development; World Bank.
- Venetoulis, J. and Talberth, J.; 2007 (in print) Refining the Ecological Footprint. *Environment, Development and Sustainability* Published online: 5 January 2007.
- Wackernagel, M. and Rees W., 1996. *Our Ecological Footprint: Reducing Human Impact on the Earth*, New Society Publishers, Canada.
- Wackernagel, M., Monfreda, C., Moran, D., Wermer, P., Goldfinger, S., Deumling, D., Murray, M., 2005. National Footprint and Biocapacity Accounts 2005: The underlying calculation method. Global Footprint Network, Oakland CA, May 25, 2005. <http://www.footprintnetwork.org>.
- Weidema, Bo P., Nielson, Anne Merete, Christiansen, Kim, Norris, Gregory, Notten, Pippa, Suh, Sangwon, and Madsen, Jacob. Prioritisation within the Integrated Product Policy. Environmental Project Nr. 980 2005 Miljøprojekt. 2005. Copenhagen, Danish EPA, Danish Ministry of the Environment.

- Wiedmann, T. and Lenzen, M., 2007. On the conversion between local and global hectares in Ecological Footprint analysis. *Ecological Economics*, 60:673-677 pp.
<http://dx.doi.org/10.1016/j.ecolecon.2006.10.018>
- Wiedmann, T., Lenzen, M., Turner, K., and Barrett, J., 2007. Examining the Global Environmental Impact of Regional Consumption Activities - Part 2: Review of input-output models for the assessment of environmental impacts embodied in trade. *Ecological Economics*, 61:15-26 pp.
<http://dx.doi.org/10.1016/j.ecolecon.2006.12.003>
- Wiedmann, T., Minx, J., Barrett, J., Vanner, R., and Ekins, P., 2006a. Sustainable Consumption and Production - Development of an Evidence Base. Final Report of Project 'Resource Flows' (EV02001), Stockholm Environment Institute, York and Policy Studies Institute, London; Published by the Department for Environment, Food and Rural Affairs, London, UK, August 2006.
http://www2.defra.gov.uk/research/project_data/More.asp?I=EV02001&M=KWS&V=EV02001&SCOPE=0
- Wiedmann, T., Minx, J., Barrett, J., and Wackernagel, M., 2006b. Allocating ecological footprints to final consumption categories with input-output analysis. *Ecological Economics*, 56:28-48 pp.
<http://dx.doi.org/10.1016/j.ecolecon.2005.05.012>
- Wixted, B., Yamano, N., and Webb, C., 2006. Input-Output Analysis in an Increasingly Globalised World: Applications of OECD's Harmonised International Tables. OECD. DSTI/DOC(2006)7 (unclassified), 1-46. Organisation for Economic Co-operation and Development (OECD), STI Working Paper 2006/7
- Wood, R. and Lenzen, M., 2003. An Application of a Modified Ecological Footprint Method and Structural Path Analysis in a Comparative Institutional Study. *Local Environment*, 8:365-386 pp.
- WWF, 2006. Living Planet Report 2006, World-Wide Fund for Nature International (WWF), Zoological Society of London, Global Footprint Network. WWF, Gland, Switzerland.
<http://www.panda.org/livingplanet>.
- WWF-UK, 2006. Counting consumption – CO₂ emissions, material flows and Ecological Footprint of the UK by region and devolved country; SEI - University of York, CURE - University of Manchester and WWF-UK, Godalming, UK; www.ecologicalbudget.org.uk
- Yamano, N. and Ahmad, N., 2006. The OECD's Input-Output Database - 2006 Edition. STI Working Paper 2006/8. Organisation for Economic Co-operation and Development (OECD), Paris, France

8. Tables

Table 1: Overview of recently described multi-sector multi-region input-output models with global coverage used to calculate environmental impacts embodied in international trade

Reference	Years analysed	Considers trade in ...	Number of world regions / countries	Number of economic sectors	Indicators (env. impacts embodied in trade)	Data sources
Ahmad (2003), Ahmad and Wyckoff (2003)	1995-1997 (years of input-output data)	goods (tentative estimates for services)	24 input-output tables, 41 countries/regions for bilateral trade	17	CO ₂	OECD input-output tables, OECD bilateral trade data, IEA energy and CO ₂ data
Chung (2005)	? (information not provided)	goods and services	9	57	CO ₂	GTAP data for trade, energy and CO ₂
Lenzen et al. (2004)	1999-2000	goods and services	5	different for each country/region, ranging from 39 to 229	CO ₂	national input-output tables and CO ₂ data
Lutz et al. (2005)	last year covered 2001	goods and services	40 countries (EU-25, OECD) and 2 world regions (OPEC, ROW); 25 countries with input-output tables	25 commodities + 1 service aggregate; 41 for input-output models	use of energy (carriers), CO ₂ emissions, land use, material consumption ('ecological rucksack')	OECD, IMF, Eurostat, UN COMTRADE data base and IEA energy and CO ₂ data

Reference	Years analysed	Considers trade in ...	Number of world regions / countries	Number of economic sectors	Indicators (env. impacts embodied in trade)	Data sources
Nijdam et al. (2005)	1995, 2000	goods and services	4 (NL + OECD Europe, OECD other, non-OECD)	30 for world regions, 105 for NL	land use, GHG emissions, acidification, eutrophication, summer smog, fish extraction, freshwater use, road traffic noise, pesticide use	disparate data sources, incl. VROM and GTAP
Peters and Hertwich (2004, 2006a,b,c, 2007)	base year 2000 (data ranging from 1995 to 2000)	goods and services	8 (Norway plus 7 aggregated exporting regions, based on the technology of the top 7 exporting countries)	49	CO ₂ , SO ₂ , NO _x	Statistics Norway, Eurostat, OECD, many disparate data sources mostly from governmental statistics

DC = Developing Countries; GTAP = Global Trade Analysis Project; IEA = International Energy Agency; IMF = International Monetary Fund; OECD = Organisation for Economic Co-operation and Development; ROW = Rest of the World; UN = United Nations; VROM = The Netherlands Ministry of Housing, Spatial Planning and the Environment.