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SURVEY

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

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ABSTRACT

This paper offers a detailed review of recently described single- and multi-region input–output models used to assess environmental impacts of internationally traded goods and services. It is the second part of a two-part contribution. In Part 1 [Turner, K., Lenzen, M., Wiedmann, T. and Barrett, J. in press. Examining the Global Environmental Impact of Regional Consumption Activities — Part 1: A Technical Note on Combining Input–Output and Ecological Footprint Analysis; Ecological Economics.] we describe how to enumerate the resource and pollution content of inter-regional and inter-national trade flows with the aim to illustrate an ideal accounting and modelling framework for the estimation of Ecological Footprints.

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 has been 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 reviewed studies 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 with global coverage and detailed sector disaggregation. Only then reliable figures for indicators of impacts embodied in trade, such as the Ecological Footprint, can be derived.

1. Introduction

In the 'Oslo Declaration on Sustainable Consumption'[1] more than 200 scientists call for an intensification of efforts from policy-makers and researchers to help implement more

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[1] http://www.oslodeclaration.org; see also (Hertwich et al., 2005) and (Tukker et al., 2006).

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sustainable modes of consumption, as outlined in the plan of implementation for a ten-year framework of programmes on sustainable consumption and production (SCP).[2] The Declaration proposes to launch a comprehensive research effort on the subject of sustainable consumption. Amongst the numerous knowledge gaps identified are those that aim at an increased "understanding of the consumption-environment connection", including "the environmental impacts of consumption in developed countries upon trading partners in developing nations" (Tukker et al., 2006, page 12). The assumption behind this is that increasing demand in the developed world for imported goods and services leads to a rise in pollution and greenhouse gas emissions from the production in other countries.

Similarly, in the context of greenhouse gas accounting, discussions have taken place in the literature on how to allocate responsibility for emissions (Eder and Narodoslawsky, 1999; Munksgaard and Pedersen, 2001; Muradian et al., 2002; Ferng, 2003; Bastianoni et al., 2004; Mongelli et al., 2006; Hoekstra and Janssen, 2006; Munksgaard et al., in press). In contrast to the method of accounting for the territorial emissions of a nation in the Kyoto Protocol (also called 'producer responsibility'), other concepts have been proposed that hold the consumer of goods and services responsible for the emissions that are caused during their production ('consumer responsibility', see e.g. Munksgaard and Pedersen, 2001; Munksgaard et al., 2005a, in press)[3].

The Ecological Footprint is one of those indicators that try to capture a broad picture of humanity's demand on natural resources, following the principle of consumer responsibility (Wackernagel et al., 1999). In Part 1 of this paper however, we argue that the Footprint concept captures the embodied impacts of trade only in a rudimentary way (Turner et al., in press). We come to the conclusion that the analytical method by which national Ecological Footprints should ideally be estimated in an international framework should be based on a global multi-region input–output (MRIO) model. We argue that this is the most appropriate and accurate method to allocate total pollution and resource use embodiments of traded commodities, whichever principle of responsibility is chosen.

There have been a number of attempts to develop a more comprehensive approach of measuring resource use and/or pollution generation embodied in trade flows, including contributions that use input–output based accounting and modelling techniques. In this part of the paper we provide a comprehensive literature review of methodological and empirical developments in this field. In recent years more sophisticated models have been described based on detailed trade statistics and multi-region input–output (MRIO) modelling.

The review is presented in the next section, starting with single-region models (2.1), followed by multi-region models (2.2), feedback loop analysis (2.3), and simulation models (2.4). A discussion of the review is provided in Section 3. Section 4 concludes.

2. Review of input–output models for the assessment of environmental impacts embodied in trade

2.1. *Single-region input–output models*

An early study attempting to quantify the 'environmental loading' of traded products is presented by Walter (1973), examining the pollution content of American trade. Even though the author uses input–output coefficients to allocate environmental control costs to industries, the analysis falls short of all but first-round effects, since no matrix inversion is carried out. The first author to use the Leontief inverse in order to investigate factor embodiments of trade was Fieleke (1975), who determined the US trade deficit in embodied energy. Shortly after that, Bourque (1981) estimated the trade balances of embodied energy between Washington State and the rest of the United States.

Gale (1995) investigates the effect of Mexico's participation in the NAFTA agreement on CO_2 emissions, by estimating changes in Mexican imports, exports and import-competing goods, and subsequently inserting adjusted figures into an augmented input–output model. Gale's results show that even though tariff elimination gives rise to an overall 12% increase in Mexican CO_2 emissions, half of this increase is compensated by shifts in the production structure away from pollution intensive sectors.

In a study of international trade flows, Wyckoff and Roop (1994) estimate the amount of CO_2 emissions in imports of 21 different groups of manufactured goods to six of the largest OECD countries. The model is based on individual input–output tables for these countries and bi-lateral trade matrices. Their findings suggest that about 13% of these countries' total CO_2 emissions are embodied in imported manufactured products and they conclude that measures of greenhouse gas abatement policies will be less effective, if they solely rely on domestic emissions.

Wyckoff and Roop (1994) also test their model in terms of variability towards sector aggregation. The results of the 33-sector model are compared to a 6-sector model. This test reveals that the CO_2 emissions embodied in manufactured imports to Canada, France, Germany, Japan and the UK from the USA are about 30% less when calculated using the more aggregated 6-sector model.

The problem of 'territorial' or 'attributable' emissions (Proops et al., 1993) is also addressed by Kondo et al. (1996) and Munksgaard and Pedersen (2001), who demonstrate the differences between CO_2 accounts assuming producer and consumer responsibility. The latter authors highlight the significant changes that Denmark's CO_2 trade balance underwent between 1966 and 1994. Eder and Narodoslawsky (1999) examine several criteria for inter-regional consumer and producer responsibility in their augmented input–output-based case study of a small Austrian region. Energy and/or CO_2 emissions embodied in imports have also been estimated by Common and Salma (1992), Schaeffer and Leal de Sá (1996) and Frickmann Young (2000).

[2] World Summit on Sustainable Development in Johannesburg, 2002; see http://www.un.org/esa/sustdev/documents/WSSD_POI_PD/English/POIChapter3.htm.

[3] Full producer and full consumer responsibility are two extreme accounting principles. Suggestions have been made to quantify 'shared responsibility', i.e. to allocate the environmental impact of producing (and consuming) a certain commodity to all agents of a supply chain (see e.g. Gallego and Lenzen, 2005; Rodrigues et al., 2006).

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The effect of imports and foreign emissions on the life-cycle CO_2 emissions of German production was examined by Wenzel (1999). This author carries out a life-cycle analysis of the CO_2 requirements of passenger cars, computers and food items, involving input–output analysis. Wenzel finds that, in spite of long distances, CO_2 emissions from transport form a relatively minor part of total emissions (1–2% for cars and computers, and around 6% for food items). If, however, foreign energy production is explicitly taken into account, CO_2 requirements change significantly (9% for cars and computers; food is not examined). Wenzel concludes that differences in (foreign) production structures have higher effects on embodied CO_2 emissions than transport requirements.

Using structural decomposition analysis in a single-region input–output model, Munksgaard et al. (2000) analyse the factors affecting the development in CO_2 emissions from private consumption in Denmark over the period 1966 to 1992, distinguishing between direct and indirect as well as domestic and imported CO_2 emissions. The study finds that indirect emissions accounted for a major part of growth in total emissions from households, although CO_2 emissions from direct consumption have exceeded emissions from indirect consumption during the whole period. CO_2 emissions from non-energy commodities increased by 15%, mainly due to overall growth in private consumption.

Using a single-region input–output model, Jacobsen (2000) examines the relation between trade patterns and the energy consumption in Danish manufacturing industries. His results show that manufacturing sectors, such as chemicals or paper production, can be affected in opposite directions as a result of changes in trade patterns. Another interesting aspect of his analysis is the dependence of the results on the aggregation level of input–output data. Results from a 27-sector model differ significantly from those obtained from a 117-sector model. This dependence is due to the aggregation of sectors with very different trade developments and energy intensities.

A paper by Sánchez-Chóliz and Duarte (2004) describes the sectoral impacts that Spanish international trade has on levels of atmospheric pollution using a single-region input–output model. The 18-sector model uses a domestic and imports technical coefficient matrix and distinguishes direct and indirect CO_2 emissions of domestic production, imports, exports and imports that are re-exported. The emission coefficients however are identical in all cases, assuming that traded goods were produced with the same technology as in Spain. The sectors food, construction, transportation materials (vehicles) and other services are identified as main contributors to overall CO_2 emissions. Exports of embodied CO_2 emissions are mainly concentrated in the basic sectors of the Spanish economy – mining and energy, non-metallic industries, chemicals, and metals – which are also responsible for the greatest amount of territorial emissions.

Using CO_2 emission factors derived from the Economic Input Output–Life Cycle Assessment (EIO-LCA)[4] software, Shui and Harriss (2006) estimate the amount of CO_2 embodied in US exports to China. For Chinese exports to the US, the CO_2 factors have been corrected for differences in the fuel mix of the manufacturing sector in China and the US. The study finds that, due to the high use of coal and less efficient manufacturing technologies in China's industrial sector, US–China trade has increased global CO_2 emissions by an estimated 720 million metric tons during 1997 to 2003.

Recently, more studies based on national input–output analysis have been presented. Guan and Hubacek (in press) assess virtual water flows via regional trade patterns in both North and South China. They point out that the use of a natural resource such as water has to be considered as a factor of production. Tunç et al. (2007) estimate the CO_2 content of imports to the Turkish economy by industrial sector and Limmeechokchai and Suksuntornsiri (2007) calculate energy and greenhouse gas embodiments of final consumption in Thailand for a number of years, taking into account the import of electricity.

The impact of different assumptions concerning the emissions embodied in imports in the case of Finland was tested by Mäenpää and Siikavirta (2007). Using domestic emission intensities and data from the OECD study by Ahmad and Wyckoff (2003, see below) in a 139-sector single-region input–output model, the authors found relatively small differences: in the analysis for 1999 the net export of CO_2 from fossil fuel combustion changed from 4.2 to 3.6 Mt. Results for 1990–2003 show that Finland has increasingly been a net exporter of GHG emissions.

Most authors listed above carry out an input–output analysis of a closed economy, and subsequently apply multipliers obtained from this model to exports and imports. In this approximation, the imports structure does not enter the direct requirements matrix, and is hence not reflected in the multipliers. In contrast, Proops et al. (1993), Lenzen (1998), Kondo and Moriguchi (1998) and Machado et al. (2001) incorporate the imports matrix into the input–output framework. Their analyses show Australia, Brazil, Germany and the UK as CO_2 exporters, whereas Japan is a net CO_2 importer. Kondo and Moriguchi (1998) compare in detail sectoral CO_2 intensities calculated in the open-and closed-economy approaches. Machado et al. (2001) suggest that Brazil's international trade policy should incorporate environmental concerns in order to harmonise the country's trade targets with its environmental priorities. Similarly, De Haan (2002) examines the Dutch trade balance in terms of emissions of carbon dioxide, acidifying and nutrifying substances as well as solid waste, using the domestic requirements and the imports matrix. Export surpluses are reported for all indicators.

In general, imports to one country come from a number of different countries and world regions with different production technologies. Each of these regions also places import demands on foreign economies. Thus, embodied production factors may continue far upstream in an international supply chain in the same way that inter-industry demands continue far upstream on the domestic level. These differences in production and supply paths cannot be modelled with a single-region model. The mathematical formulation to analyze this problem comprehensively becomes more complex. As described in Part 1 of this paper (Turner et al., in press) a truly multi-region input–output (MRIO) model is needed

[4] Developed by Green Design Initiative at Carnegie Mellon University, EIO-LCA is based on a single-region input–output model of the US economy (see http://www.eiolca.net).

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where inter-regional trade flows are internalised within the intermediate demand.

Single-region models are also not able to capture feedback effects, which are changes in production in one region that result from changes in intermediate demand in another region, which are in turn brought about by demand changes in the first region (see Miller, 1969, page 41). The error associated with this assumption can also be overcome by employing multi-region input–output models. The use of feedback loop analysis is described in Section 2.3.

2.2. *Multi-region input–output models*

Two types of multi-region input–output models can be distinguished, linked single-region models and true multi-region models. In the first case, national input–output tables are exogenously linked with bilateral trade data for different countries or regions and embodied emissions are calculated for each national economy separately[5]. This approach only captures the last stage of an international supply chain of imports. True multi-region models, on the other hand, endogenously combine domestic technical coefficient matrices with import matrices from multiple countries or regions into one large coefficient matrix, thus capturing trade supply chains between all trading partners as well as feedback loops[6].

After Isard's (1951) introduction of input–output analysis into regional science, multi-region approaches were first applied to regions in Italy by Chenery (1953, as cited by Polenske, 1989) and in the USA by Moses (1955, as cited by Polenske, 1989). Polenske (1976, 1980) examines the economic interactions and repercussions between the coal mining, freight transport and electricity generation sectors in nine regions of the USA.

A multi-sector, multi-region approach is described by Imura and Tiwaree (1994) who adapt an input–output model extended with energy statistics in order to attribute CO_2 emissions to trade activities in ten countries in the Asia-Pacific region. The region is treated as if it is a closed economy and trade with the rest of the world is neglected. The model features 20 economic sectors and three types of fossil energy sources.

Imura and Moriguchi (1995) use an international trade matrix in monetary values as an input–output table, assuming that each country or region is represented by one economic sector; only Japanese industries are modelled in sectoral detail. Thus they can derive flows of embodied energy and CO_2 emissions between twelve countries and regions, albeit without sectoral breakdown. They show that international trade tends to increase the disparity between North and South in terms of energy consumption and CO_2 emissions.

Proops et al. (1999) construct an analytical multi-region input–output framework in order to derive a weak sustainability criterion for both a closed and an open economy approach. However, each of the national economies is only represented by one sector and the analysis for the global economy, broken down into 12 regions, assumes identical resource intensities for both domestically produced and imported goods. The authors demonstrate that for countries with resource-intensive imports, such as the USA and many European nations, the sustainability index decreases when the economies are assessed in a multi-region framework. Similarly, Battjes et al. (1998) test the assumption of identical domestic and foreign factor intensities by examining the differences between energy intensities from a multi-region input–output system and the corresponding single-region systems. Using the consolidated input–output tables of a number of European-Union countries compiled by van der Linden and Oosterhaven (1995), they show that single-and multi-region energy intensities for Germany are equal, but that single-region energy intensities are lower for the Netherlands and higher for Ireland than multi-region energy intensities.

Hayami et al. (1999) assess the bilateral trade in greenhouse gases between Japan and Canada. An interesting finding in their study is that almost all CO_2 embodied in Japanese exports is itself induced by imports, while emissions from Canada's exports were generated by the respective exporting industries. In their bi-regional analysis of energy and air pollutants in Japan and China, Hayami and Kiji (1997) examine fuel, CO_2, and SO_x intensities and research whether energy-and pollution-intensive industries are also strongly interlinked within the economy. Murata et al. (1998) use a combined Japan–US–EC–Asia input–output table from 1985 and show that for energy consumption, and for emissions of CO_2, SO_x, and NO_x, Japan causes a higher environmental impact due to imports from East Asian countries than vice versa, both in intensity and embodiment terms. Giljum and Hubacek (Giljum and Hubacek, 2001; Hubacek and Giljum, 2003) describe a calculation of land appropriation through international trade using a physical input–output model of the EU-15 countries. As no physical tables are available for all countries, they construct a preliminary PIOT by combining data from published national studies with material flow data for the rest of the EU-15.

Suh and Huppes (2001) outline a multi-region generalised input–output approach for compiling life-cycle inventories for the industrialised world. Atkinson and Hamilton (2002) examine natural resource flows (in value terms) between nine main world regions, and report a net 'ecological deficit' for the OECD, with surpluses in most developing regions. They concede however that the high degree of aggregation in their global model is likely to underestimate real resource flows.

The Directorate for Science, Technology and Industry of the OECD develop further the approach described by Wyckoff and Roop (1994). Ahmad and Wyckoff (Ahmad, 2003; Ahmad and Wyckoff, 2003) present a framework for estimating CO_2 emissions embodied in internationally traded goods based on input–output and trade modelling. The calculations for 24 countries (responsible for 80% of global CO_2 emissions) are based on national input–output tables on a 17-sector level, bilateral trade data for 41 countries/regions and IEA[7] data for CO_2 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

[5] See for example Wyckoff and Roop (1994).

[6] See also Lenzen et al. (2004) and Munksgaard et al. (2005a, in press) for a distinction between uni- and multi-directional trade analysis.

[7] International Energy Agency, Paris, France.

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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 CO_2 emissions generated to satisfy domestic consumption in OECD countries in 1995 were 5% or over 0.5 Gt CO_2 higher than emissions related to production. The bulk of these excess emissions can be attributed to a few importing countries, mainly the United States, Japan, Germany, France and Italy. Based on volume, the US alone account for nearly half of the total global CO_2 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. For individual countries, estimated emissions associated with imports or exports are often above 20% and in some cases over 30% of emissions from domestic production (extremes are Finland and Netherlands with over 40%, and Norway and Sweden with over 50%).

Nijdam et al. (2005) present an analysis 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 analysis of Dutch household consumption in the year 2000 determines nine types of direct and indirect environmental impacts for seven consumption domains which in turn are based on 360 expenditure categories. 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) database[8]. Three import matrices describing the requirements of imports per region for Dutch production are derived from import statistics.

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. Their approach is based on symmetric input–output tables and is in fact identical to the model of Lenzen et al. (2004) if the make-use blocks used in the latter one were collapsed into symmetric matrices (see also Miller and Blair, 1985). Peters and Hertwich (2004, in press) discuss a number of simplifications that lead to reductions in data requirements, without the introduction of large errors. Amongst these are the consideration of uni-directional instead of multi-directional trade, using trade shares to estimate import matrices and grouping similar countries into regions with identical technology.

There are several applications of the model. In Peters and Hertwich (2006a) the total embodied flows in and out of Norway are described, and production and consumption related issues are discussed. Matrices with imports to Norway's intermediate and final demand from seven countries or world regions are estimated by using the trade shares for each commodity from Norway's seven major importing partners. The study finds that in 2000 CO_2 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 CO_2. 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). The study finds that household environmental impacts occurring in foreign regions represent 61% of indirect CO_2 emissions, 87% for SO_2, and 34% for NO_x, whereas imports represent only 22% of household expenditure in Norway. Furthermore, a disproportionately large amount of pollution embodied in Norwegian household imports can be traced back to developing countries.

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. The pollution intensity of the electricity sector in China, for example, is 231 times higher for CO_2 and 1078 times higher for SO_2 than in Norway (Peters and Hertwich, 2006c).

2.3. *Multi-region input–output models including feedback loop analysis*

A number of multi-region input–output approaches include an analysis of feedback loops in trade (Round, 1985; Sonis et al., 1993, 1995; Sonis and Hewings, 1998). This concept is based on a decomposition of the Leontief inverse matrix into sub-matrices describing the disjoined interdependence of two sectoral or regional sub-groups in terms of internal and external multipliers, which was introduced by Miyazawa (1966), and then further developed by Cella (1984) and Clements (1990). Reinert and Roland-Holst (2001) utilise a social accounting matrix to examine industrial pollution feedbacks between NAFTA member countries. Their analysis treats air pollutants such as CO, SO_2, NO_2 and volatile organic compounds, but not CO_2.

Miller (1969) examines the deviation of single-and multi-region models in his "experimental" studies of Kalamazoo

[8] 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 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.

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County and the USA, and of the USA and India. He concludes that (monetary) feedback effects are very small, typically affecting multipliers to less than 1%. These results were confirmed in other studies, as summarised by Richardson (1985, p. 631). However, in a study by Greytak (1970), interregional feedbacks appear to be significant, although this result seems to be an outlier when compared to others (see Tables 4–6, p. 127 in Miller and Blair, 1985). Gillen and Guccione (1980), and later Miller (1985) show that the magnitude of feedbacks depends critically on the norm of the technical coefficient matrices (reflecting the interconnectedness of industries in the respective regional economies), on the level of aggregation and on the proportion of interregional trade in intermediate demand (i.e. the self-sufficiency of the economies). Round (2001) reviews the literature on feedback measures and upper feedback bounds, and also presents a decomposition of a multi-region Leontief inverse into feedback, spill-over and "Leontief" effects. There are no studies examining feedback effects in a generalised input–output framework incorporating factors such as labour, energy, or pollutants.

A detailed multi-region input–output model featuring feedback loop analysis is described by Lenzen et al. (2004). In order to calculate CO_2 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. The latter ones contain the essential information of how industry j in country s uses commodity i produced in country r in the intermediate production process. Using this extensive MRIO model, a compound total requirements matrix with the dimensions 1199×1199 is constructed, resulting in total, region-specific multipliers of intermediate demand, trade, energy consumption and CO_2 emissions. With this closed model it is possible to include feedback loops and capture direct, indirect, and induced effects of trade.

By running different scenarios with this model, Lenzen and colleagues (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 CO_2 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 CO_2 emissions when multi-directional trade with specific production recipes for the country/region of origin is considered (see also Munksgaard et al., 2005a,b, in press). The first model results in an 11 Mt CO_2 trade surplus whereas the second one shows embodied emissions of imports and exports to be similar (0.3 Mt deficit). The study also shows that feedback loops induce changes in multipliers of around +1.5%. The authors come to the conclusion that, in contrast to purely monetary flows, generalised feedback loops can be significant under certain circumstances, because they are often amplified by large physical factor contents (for example for energy usage).

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 reclassification, currency conversion, valuation and estimation of trade flows. They show that the level of sector aggregation has a significant impact on the results and argue that therefore the most possible detail of disaggregation should be used.

2.4. *Simulation models*

Other types of models can be used to calculate environmental impacts embodied in trade, such as global econometric-environmental models. A recent literature review by Uno (2002) identifies 34 simulation models with global coverage that have been developed since 1993, most of them focussing on energy-related questions.

A number of approaches, based on general equilibrium (GE) modelling, attempt to quantify the amount of carbon leakage as a result of restrictive measures in OECD countries (e.g. Perroni and Rutherford, 1991; Oliveira-Martins et al., 1992; Pezzey, 1992). While Perroni and Rutherford (1991) and Oliveira-Martins et al. (1992) determine carbon leakages of not more than 10% and 16% of the initial emission reduction, respectively, Pezzey (1992) finds a 70% leakage offset of the carbon reduced by unilateral OECD action, thus rendering unilateral action largely ineffective in environmental terms. Nevertheless, Pezzey concedes that these differences "no doubt reflect the very different modelling assumptions [...] about world energy markets, as well as different data on energy supply elasticities". This is confirmed by Paltsev (2001) who finds that not regional sector aggregation but "fossil fuel supply elasticities and trade substitution elasticities are the crucial determinants" in his static, multi-regional GE model of the carbon leakage resulting from the Kyoto protocol.

In most of the simulation models identified by Uno (2002) economic development is exogenous. Only seven models endogenise the economy and only two have a sectoral disaggregation deep enough to allow the distinction of different groups of goods and services. These are the GINFORS model (Lutz et al., 2005) and the GTAP model (Hertel, 1997; Dimaranan and McDougall, 2005). The core of both models is a multi-sector bilateral trade model.

The econometric model GINFORS (Global INterindustry FORecasting System) described by Lutz et al., 2005 (see also Meyer et al., 2003a,b as well as Giljum et al., in press) 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 is not a Computable General Equilibrium (CGE) but a macro-economic model ('econometric input–output model') that uses behavioural parameters estimated by econometric techniques to make simulations and forecasts of economic developments and their effects on markets and employment as well as global energy, resource and land consumption ('ecological rucksacks'). To this end, GINFORS

uses additional energy-emission models, material input models and land use models (Lutz et al., 2005).

GINFORS has been used as part of the European MOSUS project[9] 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., in press). 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)[10] (Hertel and McDougall, 2003). In contrast to GINFORS which follows evolutionary theory assuming agents to decide under conditions of bounded rationality in non-perfect markets, 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.

A project sponsored by the US Environment Protection Agency (GTAP/EPA, 2005) uses GTAP data to develop a land-use and greenhouse gas emissions data base for use in the CGE model. The aim is to fill the gap of links between land use changes and net greenhouse gas emissions from agriculture and forestry, and to assess the costs of climate policies and their spill-over effects via international trade and sectoral interaction.

Kainuma et al. (2000) calculate embodied carbon emissions using a GE model, employing the GTAP database and IEA/OECD energy statistics. These authors calculate energy embodiments by computing the GE response in gross output and associated energy requirements to a step increase in final demand. They compare their results with embodiments calculated via input–output analysis for an open and a closed economy (that is, including and excluding factor inputs from foreign economies, respectively). The study shows that changing from a closed to an open economy model increases the emissions responsibility of Japan, USA and the European Community, but decreases the emissions responsibility for Australia, Former Soviet Union and Eastern Europe, China and India. However, their particular input–output- and GE-based embodiments are only comparable within limits, since they address slightly different questions (static and dynamic, average and marginal analysis) (Kainuma, 2003).

Chung (2005) couples Ahmad and Wyckoff's (2003) approach with the global trade CGE model developed by GTAP. CO_2 emissions embodied in international trade for nine regions of the world have been calculated. The measure BEET (Balance of CO_2 Emissions Embodied in International Trade) is used, defined as the difference between CO_2 emissions related to domestic production and those related to total domestic demand. CO_2 emission data by industrial sector rely on the GTAP-E dataset which includes energy balance and greenhouse gas emissions data[11]. The CGE model context also enables the author to simulate how carbon tax on energy use will affect BEET for the nine world regions. Chung's baseline calculations suggest that the countries/regions with the highest 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).

Two other models that have recently been described should be mentioned here as well. Nijkamp et al. (2005) have used the GTAP-E model to simulate the effects of different climate change policies such as carbon taxes, tradable emission permits, joint implementation and clean development mechanisms. However, no results on emissions embodied in international trade have been reported. Duchin (2005) describes a globally closed input–output model for international trade. Her 'World Trade Model' is a linear programming model where the values of endogenous variables – output, exports, imports, factor scarcity rents for each region, and world prices for traded goods – are determined through production assignments for all goods that are made according to comparative advantage. This model has been extended by Strømman and Duchin (2006) to the 'World Trade Model with Bilateral Trade' (WTMBT) which takes into account the geographically dependent freight transportation requirements for goods by means of four modes of marine transportation. In an application of the WTMBT, Strømman et al. (2005) examine the relationship between global CO_2 emissions and factor costs in order to explore how changes in the global division of labour can contribute to reducing carbon emissions, albeit without explicitly addressing CO_2 embodiments of trade.

Hoekstra and Janssen (2006) use a dynamic input–output model of two trading countries to explore the effects of taxes in different scenarios for environmental responsibility. The study is specified in a hypothetical framework and does not use empirical data.

3. 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 resource

[9] "Is Europe sustainable? Modelling opportunities and limits for restructuring Europe towards sustainability", see http://www.mosus.net.

[10] Center for Global Trade Analysis, Purdue University, USA (http://www.gtap.agecon.purdue.edu).

[11] 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 CO_2 emissions resulting from the use of emission generating commodities in the production process (see Truong, 1999; Burniaux and Truong, 2002). A comparison of the GTAP-E model with other CGE models can be found in Kremers et al. (2002).

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efficiencies and emission 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 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 CO_2 (Proops et al., 1999; Haukland, 2004; Lenzen et al., 2004; Peters and Hertwich, 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 seen to be 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 described in Part 1 of this contribution (Turner et al., in press). 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

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 (environmental 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
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

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.

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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 CO_2 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.

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. (in press). 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., in press) but also any share of responsibility can be quantified with such a framework (Gallego and Lenzen, 2005).

4. Conclusions

Results from the reviewed studies 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.

It is an old truism that there is no 'best' model as such, but only a 'best' model for a specific purpose. This work has analysed mainly three types of models: single-region, multi-region and simulation models based on input–output analysis. Each of these models has their virtues and shortcomings. In a nutshell, 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 be better 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 – at least at this time – as the most suitable approach. As we argue in Part 1 of this contribution (Turner et al., in press), multi-region input–output (MRIO) models are 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).

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