Opportunities and challenges for environmental MRIO modelling: Illustrations with the GTAP database

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Abstract

The application of multi-regional input-output (MRIO) modelling to environmental flows is a useful methodology to evaluate global linkages between consumption and production systems. There are many opportunities for environmental MRIO studies ranging across scales from analyzing the environmental impacts of individual products, household consumption, and international climate policy. Initially I discuss several applications of MRIO models, particularly in relation to global environmental problems and pollution embodied in trade. I discuss how many of the widely used IO techniques can be implemented for global systems. Despite the promise of environmental MRIO studies, there are still several challenges. An initial problem is consistent and transparent data with enough detail for policy relevant investigations. I discuss many of the challenges for MRIO modelling encountered when implementing the GTAP database to an MRIO model (covering 57 sectors in 87 world regions). The discussion is focussed on highlighting important issues and research required for future database construction.

Keywords:

Multi-region input-output analysis; MRIO; IOA; emissions embodied in trade; GTAP; EXIOPOL;

1 Introduction

International trade provides a mechanism to geographically separate consumption and the environmental impacts in production. Through international trade, polluting and low value-added production can be relocated to distant lands, while the domestic economy increases high value-added and cleaner production (Peters and Hertwich, 2007). Researchers are placing increasing attention on the role of international trade in displacing environmental problems. Active areas of research include material flow analysis (Müller et al., 2006), ecological footprints (Wackernagel and Rees., 1996), virtual water flows (Guan and Hubacek, 2007), and embodied flows of various air pollutants (Wiedmann et al., 2007). Arguably, international trade plays a critical role in competitiveness, participation and effectiveness concerns of global climate policy (Peters and Hertwich, 2006d, 2007). Despite the importance of international trade in displacing environmental impacts it has received little attention in policy, which may be a consequence of the political system boundary covering the domestic consumption system, but not the global production system (Peters and Hertwich, 2007).

Understanding flows of pollutants and materials through international trade provides challenges and opportunities for both policy and research. In terms of policy, the geographic separation between consumption and production requires that policy operates outside of standard geo-political regions since regions with low cost mitigation options may lie outside the region of consumption (Peters and Hertwich, 2006e). Developing an understanding of the political structures necessary to deal with the interface of trade and the environment is an area that needs active research, but is beyond the scope of this paper. The main focus of this paper is to describe and discuss the opportunities and challenges for quantitative modelling of the global connections between consumption and production systems.

Most studies investigating the separation of consumption and production systems through international trade apply multi-regional input-output (MRIO) analysis (Wiedmann et al., 2007), particularly when supply chain environment impacts are important. Data availability for global studies has been a significant obstacle to implementation. One currently available option for implementation at a global level is the GTAP database database (Global Trade Analysis Project, `https://www.gtap.agecon.purdue.edu/`, Dimaranan and McDougall, Forthcoming, 2006). Many of the methodological challenges discussed in this article relate to experiences with implementing the GTAP database for MRIO studies (Peters and Hertwich, 2006f, 2007). In the following section I briefly discuss the theoretical foundation of MRIO analysis. Following this I discuss opportunities for MRIO modelling in research and policy applications. The bulk of the paper is concerned with theoretical and empirical challenges to implementing MRIO models. This builds upon experiences in implementing the GTAP database in a MRIO model and is particularly relevant for future database projects such as the EU funded EXIOPOL project ("A New Environmental Accounting Framework Using Externality Data and Input-Output Tools for Policy Analysis").

2 MRIO Theory

MRIO theory has now been developed and discussed by several authors (Miller and Blair, 1985; Ahmad and Wyckoff, 2003; Lenzen et al., 2004; Peters and Hertwich, 2004; Turner et al., Forthcoming; Peters and Hertwich, 2006a) and I do not wish to repeat the details here. Although, I present the main MRIO theory relevant for the following discussions, in particular I set a framework to show different definitions of emissions embodied in trade (EET).

In the standard IOA framework (Leontief, 1970) the economic output is first determined,

$$x_r = A_r x_r + y_r \tag{1}$$

and from this the environmental impacts are calculated,

$$f_r = F_r x_r = F_r \left(I - A_r\right)^{-1} y_r \tag{2}$$

where y is a vector with the each element representing the final demand in each industry sector, A is a matrix where the columns represent the input from each industry to produce one unit of output for each industry, I is the identity matrix, F is a row vector with each element representing the environmental impact per unit industry output, and r indexes the region of interest. The data can be constructed in physical, monetary, or mixed units (Weisz and Duchin, 2006).

To explicitly model the emissions embodied in imports (EEI) or emissions embodied in exports (EEE) requires a decomposition of the standard IO model into the final use of domestically produced and imported products (Peters and Hertwich, 2004, 2006a). Domestic consumption can be decomposed into the products produced domestically and imports, $y_r = y_{rr} + \sum_s e_{sr}$. The exports, $e_r = \sum_s e_{rs}$, and imports, $m_r = \sum_s e_{sr}$, can be constructed from bilateral trade data from region r to region s, e_{rs}. The interindustry requirements can be decomposed as $A_r = A_{rr} + \sum_s A_{sr}$ where A_{rr} represents the industry input of domestically produced products and A_{sr} represents the industry input of products from region s to region r. With these definitions it is possible to rewrite (1) as

$$x_r = A_{rr}x_r + y_{rr} + \sum_s e_{rs} \tag{3}$$

and (2) becomes

$$f_r = F_r x_r = F_r \left(I - A_{rr}\right)^{-1} \left(y_{rr} + \sum_s e_{rs}\right) \tag{4}$$

From this point it is possible to have different approaches to modelling the emissions embodied in trade depending on whether total trade or arbitrary consumption activities are of interest.

2.1 Total emissions embodied in trade (EET)

A key assumption employed in IOA is that the production technology is based on fixed proportions. This allows (4) to be decomposed into components for domestic demand on domestic production in region r

$$f_{rr} = F_r \left(I - A_{rr}\right)^{-1} y_{rr} \tag{5}$$

and the EET from region r to region s

$$f_{rs} = F_r \left(I - A_{rr}\right)^{-1} e_{rs} \tag{6}$$

Adding these gives the total emissions occurring in the country

$$f_r = f_{rr} + \sum_s f_{rs} \tag{7}$$

The direct household emissions can be included in f_{rr}. The total EEE from region r to all other regions can be determined by summation,

$$f_r^e = \sum_s f_{rs} \tag{8}$$

The total EEI is obtained by reversing the summation,

$$f_r^m = \sum_s f_{sr} \tag{9}$$

The EET method considers the total trade to or from a country regardless of whether the trade goes to final demand or industry. This greatly reduces the data requirements and makes the EEE and EEI consistent with national trade data. However, to determine the global environmental impacts of an arbitrary demand requires a different methodology.

2.2 Emissions embodied in consumption (EEC)

While the EET methodology is conceptually sound it is not applicable for arbitrary final demands since a method is needed to determine the share of imports required for an arbitrary demand. For instance, if calculating the emissions embodied in the production of a car only the share of imports required for the production of that car are required. Further, intermediate inputs may also "pass through" an economy. For instance, to produce a car in country A may require imports from B, but to produce the imports country B may require imports from countries A and C. This section discusses the MRIO model for dealing with arbitrary demands, but it also challenges us to reassess the definition of EET.

To introduce the methodology for calculating emissions embodied in consumption (EEC) it is necessary to distinguish between exports to final demand and exports to industry. The exports from region r to region s go to either final demand or interindustry demand,

$$e_{rs} = e_{rs}^{ii} + y_{rs} \tag{10}$$

The exports to industry can be expressed as

$$e_{rs}^{ii} = A_{rs} x_s \tag{11}$$

where x_s represents the output for an arbitrary demand in region s. By substitution of the decomposed exports into (3) the standard MRIO model results (Peters and Hertwich, 2006c)

$$x_r = A_{rr} x_r + y_{rr} + \sum_{s \neq r} A_{rs} x_s + \sum_{s \neq r} y_{rs} \tag{12}$$

or in matrix form

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_m \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & A_{13} & \dots & A_{1m} \\ A_{21} & A_{22} & A_{23} & \dots & A_{2m} \\ A_{31} & A_{32} & A_{33} & \dots & A_{3m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_{m1} & A_{m2} & A_{m3} & \dots & A_{mm} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_m \end{pmatrix} + \begin{pmatrix} \sum_r y_{1r} \\ \sum_r y_{2r} \\ \sum_r y_{3r} \\ \vdots \\ \sum_r y_{mr} \end{pmatrix} \tag{13}$$

Due to data availability the off-diagonal terms, A_{ij}, are estimated using trade statistics (Lenzen et al., 2004; Peters and Hertwich, 2006a),

$$A_{rs} = \hat{s_{rs}} \left(A_r - A_{rr} \right) \tag{14}$$

where

$$\{s_{rs}\}_k = \frac{\{e_{rs}\}_k}{\{\sum_i e_{rs}\}_k} \tag{15}$$

The implications of this assumption are discussed later. The emissions are calculated using regional outputs and emission intensities,

$$f = F_1 x_1 + F_2 x_2 + \ldots + F_m x_m \tag{16}$$

In the EEC formulation the final demand on the right hand side of (13) represents final demand only (not trade directly to industry). Essentially, the EET and EEC models differ due to the trade which may "pass through" the economy without going to final demand (imports required to produce exports). This can be demonstrated by constructing national consumption by scaling up household final demand. Suppose that $h_r^{(n)}$ represents the total consumption (including imports) of household n in region r. We further assume that capital and government expenditure have been distributed across households (so the only national level final demand are households and exports). Summing over all households produces the total final demand consumed in region r, $y_r^{EEC} = \sum_n h_r^{(n)}$. In other words, y_r^{EEC} is the domestic plus imported *final demand*. It is important to note here that not all imports serve final demand in the domestic economy, but some imports go to industry to produce exports (which ultimately serve final demand in a different region). If y_r^{EEC} is used in the EEC model then the global emissions for region r, f_r^{EEC}, will differ from the EET framework which calculates $f_r^{EET} = f_{rr} + \sum_s f_{sr}$. The difference is due to allocation. The EEC formulation only considers the imports to final demand in region r, y_r^{EEC}, and endogenously calculates any imports and exports required to produce that final demand (which may occur in multiple regions). The EET framework considers all imports together regardless of whether they go to final demand or industry. Ultimately, all imports eventually serve final demand in some country, so if we aggregate the EEC for all regions together the EET results can be obtained. I will refer to the difference between the EET and EEC models as the emissions that "pass through" the economy (the imports required to produce exports).

An example may help explain the difference between the EEC and EET models. In the EEC model the total domestic consumption (final demand) in region r can be expressed as

$$y_r = \begin{pmatrix} y_{1r} \\ y_{2r} \\ y_{3r} \\ \vdots \\ y_{mr} \end{pmatrix} \tag{17}$$

The induced activity of imported interindustry purchases required to produce this demand are calculated endogenously in the EEC model and the emissions are allocated to the region that produces the necessary products. To see this, consider the output, x_r, obtained from y_r. The vector x_{rr} not only includes the output to produce y_{rr} but also includes the output to produce the indirect imports required by region s to produce y_{sr}. Extending this further, x_{rr} also includes the imports required by s to produce the imports required by q to produce y_{qr}, and so on. Similar arguments follow for x_{rs}. Thus the block elements in (13) behave in an identical way to the coefficients in standard IOA; instead of considering spill-overs between sectors, we now consider spill-overs between regions (and sectors). By calculating the emissions for the final demands in all regions and adding we still get the correct output and emissions in each country (that is, balance with EET).

While the two different approaches may cause confusion, they do serve different purposes. The EET approach is relevant for considering the environmental impacts of aggregated exports and imports, while the EEC approach is relevant for considering only the exports and imports which serve a particular final demand. Ultimately, the calculated emissions from each approach agree at an aggregated level. Below I discuss some examples using the EET and EEC approaches. Overall I would argue that both approaches are needed as they are suited to different policy questions. EET is more relevant for global climate policy, while EEC is more relevant for environmental assessment of different final demands.

3 Opportunities

In this section I discuss the various opportunities for performing MRIO studies for both research and policy applications. A practical way to structure this section is to consider the different scales that the calculations can be performed—product, household, national, and global (Munksgaard et al., 2005). Another important distinction is the necessary methodology, EEC or EET. For sub-national studies the EEC methodology is required while at the national level it is more straight-forward to use EET.

3.1 Sub-national level

To date most MRIO studies have been performed to address policy issues at a national level (Wiedmann et al., 2007), but there are many possibilities to apply MRIO at the sub-national level. The most obvious applications are to extend hybrid-LCA to include global environmental impacts or to consider segments of the economy such as households.

MRIO can be used as an extension of hybrid-LCA (Suh et al., 2004) to consider global emissions. Typically, LCA is focused on individual products or processes, but the production system may still be global. There is an argument that LCA should apply marginal technology (Weidema et al., 1999), but in some situations regional specific impacts may be of interest. Either way, MRIO may play an important role. In terms of marginal technology, MRIO models can construct the marginal technology at a global level for the background economic system. If regional specific impacts are of interest, then MRIO provides a method of allocating impacts to regions, albeit in an averaged sense (discussed later). For the necessary detail in the foreground system it is possible to apply the MRIO framework to describe the supply-chain acting across regions (Norman et al., 2007). I am not aware of any product or process level LCA studies that have incorporated an MRIO model.

At the next level of detail MRIO can be applied to sectors of the economy such as households (Nijdam et al., 2005; Peters and Hertwich, 2006b; Weber and Matthews, 2007a) or government, capital, exports, and so on (Peters and Hertwich, 2006e). In many countries imports are an important part of household consumption and hence household environmental impacts (HEI). In the case of Norway 50% of household CO_2 emissions occurred outside of Norway despite imports representing 22% of imports by value (Peters and Hertwich, 2006b). Similar numbers were found for The Netherlands and the USA, but covering a wider range of pollutants (Nijdam et al., 2005; Weber and Matthews, 2007b). These MRIO studies found that the HEI originating in developing countries formed a significant share of the HEI. For instance, Peters and Hertwich (2006b) found increased importance of textiles and clothing largely due to pollution intensive production of chemicals and electricity in developing countries. For individual households, Weber and Matthews (2007b) and Peters et al. (2006) have used MRIO models to calculate the HEI of individual households for use in econometric studies. This allows a clearer indication of which households may have load displacement in their HEI. Overall, the MRIO models give a much clearer understanding of HEI and the geographic separation of household consumption and environmental impacts.

Peters and Hertwich (2006e) applied an MRIO model to each of the final demand categories in the Norwegian economy to show how imports play a different role in different parts of the economy. Government activities generally have low imports and hence most of the emissions occur domestically. On the other hand, there are significant imports for investment (often pollution intensive) and for household consumption. Depending on the method of analysis it is possible to place focus on the consumption activities, the production activities, or the consumption-production linkages causing environmental impacts through structural path analysis (Peters and Hertwich, 2006e). Based on the production approach the load-displacement of Norway to developing countries dominates despite the small value of imports originating in developing countries. This suggests that Norwegian environmental policy should encourage or perform mitigation in developing countries.

The role that governments should play in mitigating pollution when domestic consumption causes emissions in foreign regions is likely to be a highly contentious issue. On the one hand, governments may claim they do not have the jurisdiction to act in foreign regions. On the other hand, governments do play a role in shaping domestic consumption activities, which cause pollution in foreign regions. An understanding of these issues is clearly needed. One potential approach is to develop indicators which weights consumption and production impacts (Gallego and Lenzen, 2005; Rodrigues et al., 2006; Lenzen et al., 2007). Development of a transparent and politically relevant methodology, whether a combination of production and consumption or presentation of both as individual indicators, is an important area of research.

3.2 National and global level

As discussed earlier, at the national level it is possible to apply two methodologies. The EEC approach is based on scaling up individual (arbitrary) consumption to arrive at the final demand of consumers. The other approach, EET, is based on considering the total trade into a country regardless of whether it is consumed by industry or final demand. While EEC enjoys consistency through scaling from different levels of consumption, at the national level EET is more consistent with national trade balances. Further, EET has less methodological concerns as a method is not required to split final demand and industry from trade flows. Consequently, at a national level I suggest that the EET approach should be employed. These issues are discussed further below.

Several MRIO studies have been used to evaluate the global footprint of a countries consumption (Ahmad and Wyckoff, 2003; Lenzen et al., 2004; Peters and Hertwich, 2006c; Weber and Matthews, 2007a). These studies give an indication of the role of exports and imports in shaping a countries environmental profile, generally from the perspectives of either the consumer or the producer (Kondo et al., 1998; Munksgaard and Pedersen, 2001). The importance of including regional technologies is clearly demonstrated in many studies and the impacts may vary by more than a factor of two, depending on the pollutant (Lenzen et al., 2004; Peters and Hertwich, 2006c; Weber and Matthews, 2007a). Several studies have performed analysis covering a many countries; 24 (Ahmad and Wyckoff, 2003) and 87 (Peters and Hertwich, 2006f, 2007). These studies have found considerable embodied emission flows through international trade, Figure 1. The figure indicates that there is considerable variation in EEE and EEI between countries and this can be related to various regional characteristics such as geographic location, population, GDP, area, resource endowments and so on. This indicates that obtaining a better understanding of EEE and EEI may help develop global climate policies that a more sensitive to politically relevant issues such as competitiveness concerns and effectiveness due to low participation (Peters and Hertwich, 2006f,d, 2007).

Using international comparisons of EET it is possible to trace global trade patterns, either at a national or sectoral level, evaluate the extent of carbon leakage, understand regional specific characteristics, and establish the geographic separation of consumption and production systems. At the most aggregated level using MRIO it is possible to map the flow of EEE and EEI between countries. Table 1 shows the origin of EEI to the USA and the EU. The table demonstrates that geography is important in shaping a countries EEI. For the EU, 38% of the EEI originates countries within the EU, while for the USA 24% of the EEI originates in China. The USA has a greater share of EEI from all regions except those close to the EU—Eastern Europe, Russian Federation, Africa. An important point is that the USA is geographically close to China which has a pollution intensive economy and this will play an important role in shaping the environmental profile of the USA relative to the EU. Similar results can also be presented for EEE, or at the more detailed level it is possible to trace the production systems at the sector level (results not shown) using techniques such as Structural Path Analysis (Peters and Hertwich, 2006e). By disaggregating the origin of imports in the EEI it is also possible to evaluate the extent of carbon leakage (Wyckoff and Roop, 1994) between countries, see Figure 2. This figure also shows the importance of geography since the share of non-Annex I emissions in the total EEI (carbon leakage) is lower for countries within the EU compared to the USA, Japan, or India (Peters and Hertwich, 2007). This is since the USA,

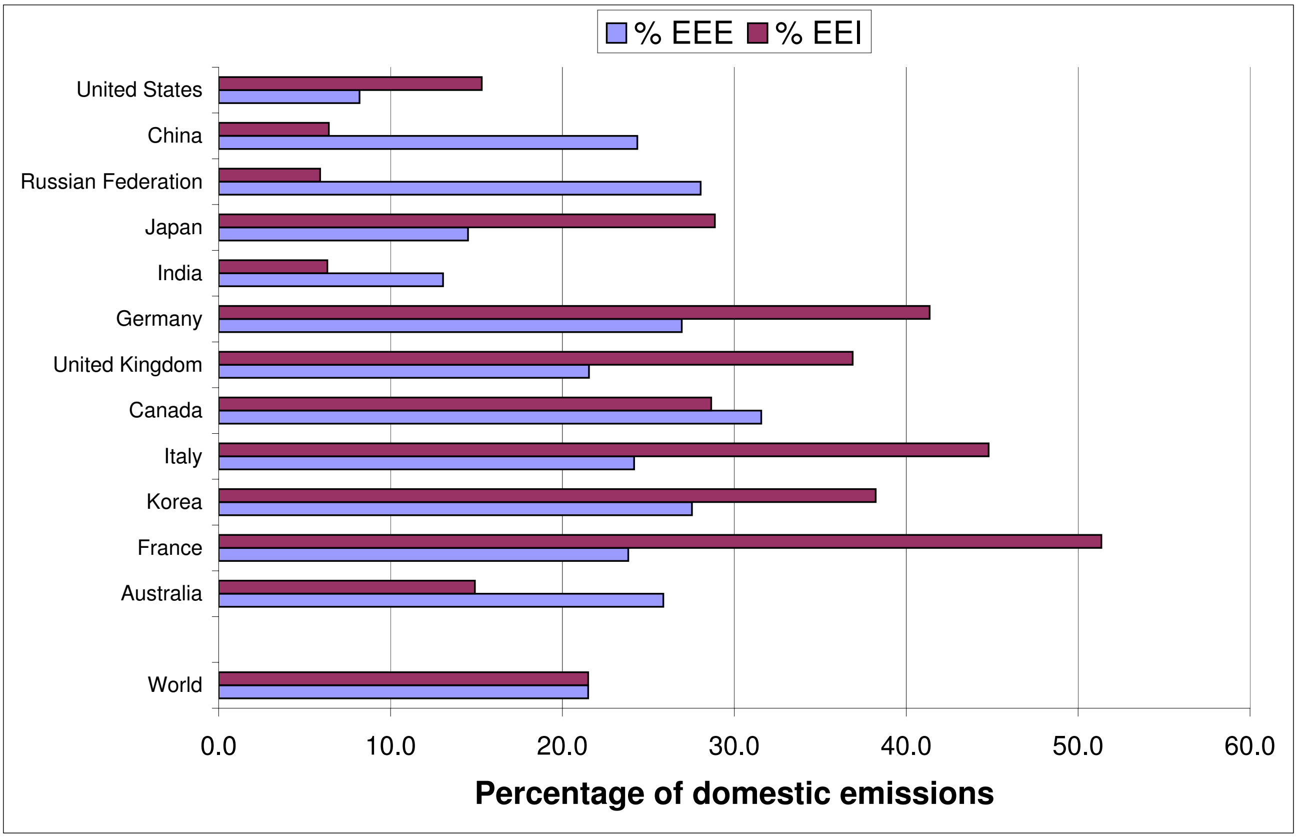

Figure 1: The percentage EEE and EEI compared to total domestic emissions for selected countries (based on Peters and Hertwich, 2006f, 2007).

Japan, and India are geographically far from most Annex I countries. Linking studies of carbon leakage over time gives a method of evaluating the extent to which production is being increasingly displaced from consumption. In summary, by using different levels of aggregation a detailed understanding of the global consumption and production systems can be established.

	Share (%) of EEI to:	
Imports From	**US**	**EU**
Oceania	1.5	1.1
China	23.8	9.0
Japan	5.1	1.9
Korea	2.3	1.1
Taiwan	2.5	0.8
India	2.7	2.0
Rest of Asia	6.5	4.2
Canada	13.3	1.3
United States	0.0	8.5
Mexico	5.8	0.4
South and Central America	5.9	3.0
Western Europe	12.2	38.1
Eastern Europe	2.5	9.8
Russian Federation	5.1	8.6
Middle East	6.5	5.2
Africa	4.4	5.1

Table 1: The distribution of EEI in the USA and EU from different regions (based on Peters and Hertwich, 2007).

Understanding the interplay between international trade and the environment is arguably a key requirement to understanding global climate policy (Peters and Hertwich, 2006d). Peters and Hertwich (2007) argue that the EEE have implication for participation in climate policy through its affect on competitiveness, while the EEI has implications for effectiveness if participation remains relatively low. Further, with limited participation issues such as carbon leakage may undermine any mitigation efforts. Some have argued that adjusting a countries emissions inventory for the emissions embodied in trade will lead to improvements in the effectiveness of climate policy (Kondo et al., 1998; Munksgaard and Pedersen, 2001; Peters and Hertwich, 2006d). This again introduces a possible

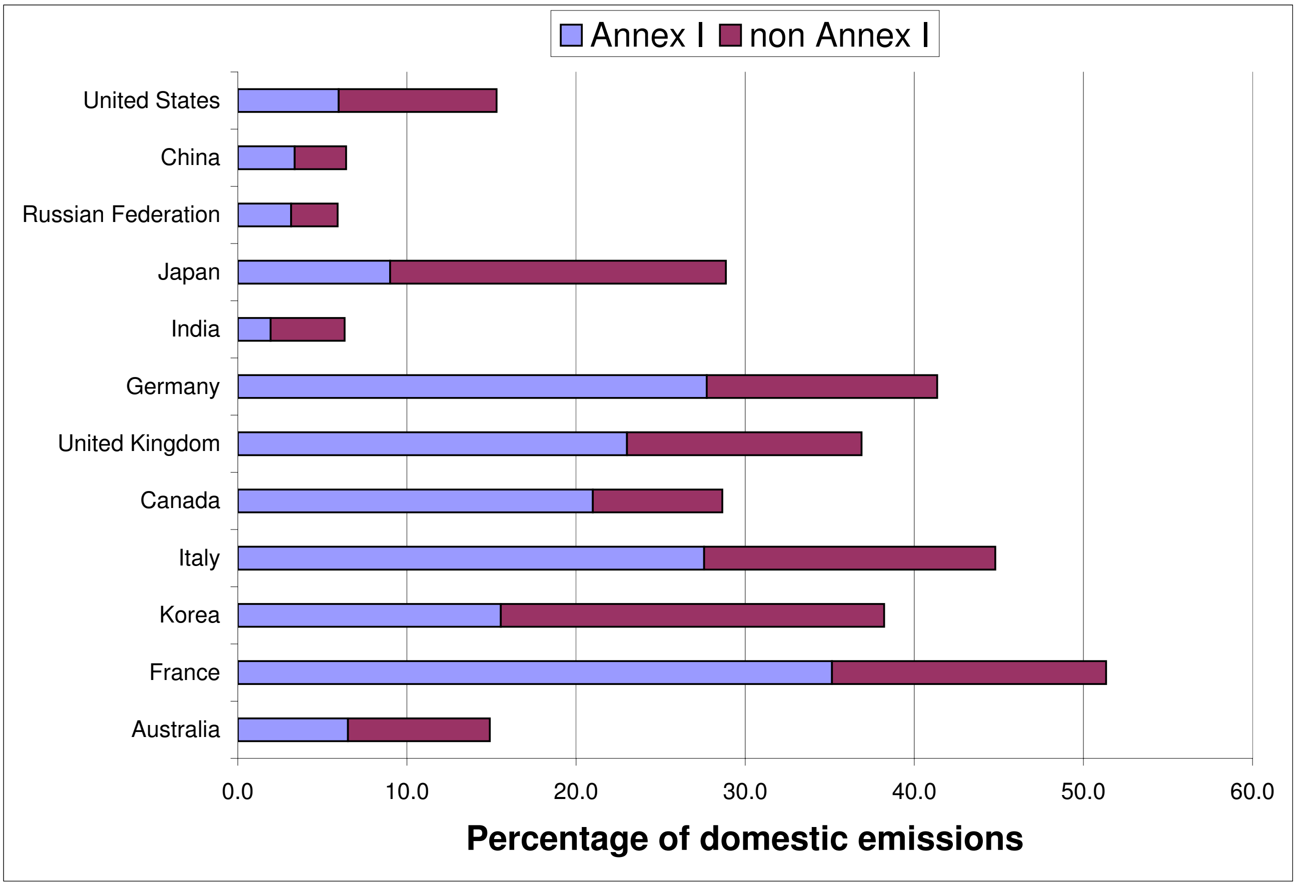

Figure 2: The EEI of selected Annex I countries showing the EEI from Annex I countries and non-Annex I countries (carbon leakage). Relative to total EEI, EU countries have a larger share of EEI originating in Annex I countries since EU countries are surrounded by other Annex I countries (based on Peters and Hertwich, 2006f, 2007).

productive interface between MRIO research and policy.

3.3 Comparing the EEC and EET approaches

As discussed earlier, there are two approaches to determine the EEE and EEI. Generally, the EEC approach would be used for sub-national studies (arbitrary final demands), while the EET approach would be used at a national level to study total trade flows. If starting from total domestic consumption (final demand) at a national level then the EEC results will differ from the EET results. The main part of this difference is due to "through trade" (imports required to produce exports). As an example, in the USA the EET formulation gives the EEI as 15.3% of domestic emissions, whilst if the EEC formulation is used then the EEI is 18.1% (based on Peters and Hertwich, 2006f, 2007). Interesting in this case the EEC value is higher and the reason behind this is best demonstrated with an example. In the EEC formulation if the US imports a car from Canada and Canada imports material from China to produce the car, then the EEC model calculates the EEI for the trade from Canada to the USA and from China to Canada. Thus, the EEC model can determine the instigated imports from China to Canada to meet a final demand in the USA. Clearly, this extra detail may be of particular interest for research and policy. The EET framework cannot calculate trade flows at this level of detail, but only determines the total aggregated EEI into the USA (disaggregated by country), the total aggregated EEI into Canada, and so on. In each case the flow between countries can be determined, but not the flows particular for a given product or final demand. As another example, for China the EEI using the EET model is 6.4%, while using the EEC model the EEI is 5.9% indicating that the intermediate imports can shift EEI either upwards or downwards. It is possible to elaborate on these issues further and to include examples with EEE. However, it suffices to say that consistency between the EEC and EET models can be achieved by reallocation and summation. In practice, studies based on arbitrary demands will use EEC while those starting from national demands will use EET. Clear communication of the definition and methodology is required.

4 Challenges

Despite the significant opportunities for informative and policy relevant studies using MRIO techniques there are significant challenges. These challenges cover various methodological, theoretical, and modelling issues, much of which is an indirect result of data availability. This section builds upon previous work, (Lenzen et al., 2004; Peters and Hertwich, 2006a), but does not seek to reproduce that work. Rather, this work is heavily based on experiences with the GTAP database (Peters and Hertwich, 2006d, 2007). Much of the discussion is relevant for future database projects such as EXIOPOL.

4.1 Theoretical and modelling issues

A key assumption in IOA is linearity (Miller and Blair, 1985) and this assumption is compounded in MRIO models based on the EEC framework. The distribution of imports from origin to destination sector is usually derived from trade statistics, (14). Thus the linearity assumption is spread across global production chains. For instance, if a country imports steel from China for construction and steel from Canada for automobiles then the MRIO model assumes that the construction and automobile sectors use a mix of the imported steel (weighted average of the Chinese and Canadian steel). While this averaging process happens in standard IOA, it is arguably worse in an MRIO setting since the overall effect is amplified by variable emission factors. In our example, the automobile sector might use "clean" steel from Canada, but its emissions are affected by the import of "dirty" steel from China which is only used in construction. This makes the automobile sector seem dirtier than it actually is. While this is arguably a data issue I classify it as theoretical as it is unlikely that trade statistics will map both from region r to region s in addition to sector i to sector j (the data forces us to estimate A_{rs} using (14)). This averaging issue does not arise in the EET formulation as A_{rs} is not required.

In most likelihood the IO data available for each country will be the domestic requirements A_{rr} and the total import requirements $\sum_s A_{sr}$. If aggregating data together than care is needed that inter-regional imports are allocated correctly. For instance, consider if data for Portugal, Spain and France are being aggregated together. Before aggregation a portion of the imports, to Spain say, came from Portugal and France. These imports will now be a part of the domestic activity of the aggregated Portugal/Spain/France region. Thus, if the domestic and imported requirements are simply added separately then there will be a systematic underestimation of domestic activity and an overestimation of imported activity. In regional blocks like the EU, this may be significant. To avoid this allocation issue the full MRIO model must first be constructed, as in (13). Then a concordance matrix must be used to map regions 1, 2, and 3 (Portugal, Spain, France) together. This step allocates the $A_{sr}, r = 1, 2, 3$ import requirements to domestic production in the new aggregated region.

A common assumption in MRIO models is that uni-directional trade dominates (Lenzen et al., 2004; Peters and Hertwich, 2006a). Uni-directional trade makes the MRIO model specific to one country only, but also greatly reduces the data requirement. In the uni-directional model only the diagonal and one column (for the country of interest) are needed in (13). The magnitude of the difference between the multi-directional and uni-directional models will depend on the choice of final demand. To give an indication, if the total final demand is considered in each country then the uni-directional assumption differs from the multi-directional model by 1-20% depending on the country. Generally, smaller countries with high EEI have a 5-15% difference (such as most EU countries), while bigger countries have 1-5% difference such as China and the USA (based on Peters and Hertwich, 2006f, 2007). Choosing between a uni-directional or multi-directional model will be a trade-off between data requirements and accuracy, though if a country has smaller EEI then the uni-directional trade assumption becomes more accurate. Overall, it is best to aim for a full multi-directional model as it is not only more accurate, but makes the model applicable to a wider number of regions. Again, it can be argued whether this is a theoretical issue or an empirical issue. The data is available for a multi-directional analysis, but the data issues are significantly reduced for a uni-directional analysis. For a detailed study using the EEC approach, the multi-directional model is desirable.

4.2 Empirical and data issues

There are many empirical issues that need to be addressed when performing an MRIO analysis. Many of these issues have been discussed previously (Lenzen et al., 2004; Peters and Hertwich, 2006a) and the following will not repeat those studies. Rather, this section will have a heavy focus on the implementation of the GTAP database into a MRIO model. The lessons learnt here are useful for future database construction such as in the EXIOPOL project. Unless otherwise stated, the GTAP related references are based on the GTAP manuals, online material, and chat-line (Dimaranan and McDougall, Forthcoming, 2006).

Before beginning, a brief overview of the GTAP database is required. "GTAP (Global Trade Analysis Project) is a global network of researchers and policy makers conducting quantitative analysis of international policy issues. GTAP's goal is to improve the quality of quantitative analysis of global economic issues within an economy-wide framework." Relevant for MRIO modelling is that the GTAP maintains a global IO, energy, and trade database covering 87 regions and 57 sectors which contains all the data necessary for an MRIO model (see Appendix). The GTAP data has been manipulated from country specific classifications and valuations into a uniform classification and valuation. While this substantially reduces the work requirements for MRIO model construction, many of the assumptions and manipulations are hidden. More problematic is that GTAP makes several manipulations to calibrate the data as required by the underlying general equilibrium model. In my opinion, these manipulations are the biggest uncertainty associated with using the GTAP data in MRIO models.

The data underlying GTAP generally comes from voluntary submissions from GTAP users (in return for free access to the data). The problem with this approach is that the data is not the most recent. For instance, most of the EU data in Version 6 (valid for 2001) dates back to 1990-1995 with Sweden back to 1985. Clearly, this is inadequate. For these countries data is generally available for 2001 (GTAP base year) or adjacent years. To avoid similar issues in data projects such as EXIOPOL it is important that an international and independent body keeps the data updated (such as UN or OECD). The OECD already maintains an IO database (Yamano and Ahmad, 2006), but it is not linked directly with trade data.

Even if the IO data is kept up-to-date it is unlikely that all the data will come from the same year. In addition, the data eventually needs to be converted to a common currency. The GTAP solves these problems simultaneously by scaling the IO flow data to 2001 (Version 6) values using GDP data in USD converted with Market Exchange Rates (MERs). The trade data is also converted in MERs. In effect this process accounts for inflation and currency differences. In terms of inflation this process assumes that all sectors have the same inflation rate. Given the immense size of the database, this is probably the most realistic approach. In terms of currency conversion several issues arise. For MRIO modelling there has been some discussion on whether to use Purchasing Power Parity (PPP) or MERs for currency conversions (e.g. Ahmad and Wyckoff, 2003; Peters and Hertwich, 2006a). PPPs are better for cross-country comparisons of GDP and MERs are better for trade data. In MRIO modelling it might be best to use some weighting of the two or use other hybrid techniques to help reflect additional problems due to product and quality differentiation, inflation, and so on. Ideally physical data should be used where possible, such as for electricity flows. Consistent conversion of data from a range of countries to a uniform currency and year (via inflation) is an area that needs further investigation, particularly in regards to the correct use of MERs and PPPs.

The next step to building an international database is to convert the IO and trade data to a consistent product or industry classification system. Since the classification systems in different countries are often quite different it may be necessary to aggregate some tables to allow more consistent mapping between countries. However, aggregation increases uncertainty (Lenzen, 2001), thus it may be more desirable to disaggregate some sectors. Unfortunately, disaggregation of a sector may introduce additional uncertainties. In the GTAP database the agriculture sectors in the IO tables are disaggregated using other data sources. While this may give more detail, it is unknown how this may affect the uncertainty of the individual data points. The trade-off in uncertainty between keeping aggregated sectors and disaggregating important sectors is an area that needs further research. In terms of environmental MRIO analysis GTAP aggregates some sectors with diverging environmental impacts. For instance the sectors "Land transport", "Transport via pipelines", "Supporting and auxiliary transport activities", and "Activities of travel agencies" are aggregated together. This is problematic for the evaluation of environmental impacts, but also conceptually in trade data as land transport requires a land bridge between countries while service based activities may not (it is uncertain whether this error is due to aggregation or manipulations, see later). It is likely that the sector disaggregation will be quite different for environmental studies compared to economic studies. From an environmental perspective it would desirable for GTAP to have higher disaggregation for manufacturing and other environmentally relevant sectors. For the EXIOPOL project there will be great interest in disaggregating environmentally important sectors and research into robust methodologies for this will be needed.

Perhaps the biggest uncertainty with the GTAP database are the manipulations required for use in computable general equilibrium (CGE) modelling. For CGE modelling, it is necessary to calibrate the database so that the initial database is in equilibrium. Since the IO, energy, and trade data come from different sources this data is generally unbalanced and has many inconsistencies. The magnitude of the manipulations performed by GTAP is uncertain and is difficult to test systematically without working closely with the GTAP (access to the raw data and manipulation procedures is needed). There are many anomalies in the data that are relatively straight-forward to detect. For instance, there is significant trade in electricity between Canada and the Pacific Islands, amongst the Pacific Islands, France and Thailand, North America and Africa, and so on. Similar data discrepancies are found in many other areas of the database. Arguably, MRIO models are more sensitive to the manipulations then in CGE models. For MRIO modelling, the balancing procedures are not needed and they clearly affect the results. Considerable challenges are required in preparing the trade data. The main problems are services data, transport data, re-exports, and inconsistencies between and within data sets. The necessary issues are discussed in more detail elsewhere (Lenzen et al., 2004; Dimaranan and McDougall, Forthcoming, 2006). For EXIOPOL, inconsistencies between IO trade data and official trade statistics can be resolved by using IO trade data in absolute values and trade statistics as ratios as in (15). The data from the EXIOPOL project may be in demand for CGE modelling in which case there will be demand for balancing. In this case it is important to publish the raw and balanced data to allow comparisons.

Dealing with international transportation is particularly problematic, especially in relation to trade statistics. Several issues arise, such as poor reporting of transport data (Corbett and Koehler, 2003), system boundary issues (Gravgård Pedersen and de Haan, 2006; Peters and Hertwich, 2006d), and poor trade statistics (Dimaranan and McDougall, Forthcoming, 2006). A key problem is that a country, Norway for example, can provide transport services to/from Norway, or between separate countries such as between Australia and Singapore. In the GTAP, the transport to/from Norway is specified in bilateral trade data, while the transport between other countries is not available on a bilateral basis (only the total transport exported from Norway). Thus the GTAP keeps two sets of transport data, one which does not have the bilateral detail for EET and EEC studies (see Appendix). Further development is required to establish methods of allocating international transportation, first, correctly to countries, and second, correctly to products.

A problem that arises in the GTAP energy database is different system boundary used for economic and energy data. The IO data are based on economic activity through resident institutions and the energy data are based on geographic territory (Gravgård Pedersen and de Haan, 2006; Peters and Hertwich, 2006d). These two measures differ mainly by international trade and international tourism. Dealing with this issue is another area that will require active research in the EXIOPOL project.

5 Conclusion

This paper has demonstrated that the EET are considerable and relevant for policy discussions. An accurate determination of the EET gives insight into the separation of domestic consumption and global production, demonstrates how trade may affect global climate policy, illustrates how geographic location may shape a countries environmental profile and so on. At a more detailed level, the MRIO framework can trace individual production chains from the location of consumption through the international trade network and ending at regional specific environmental impacts. Despite the research potential and policy relevance of MRIO modelling there are considerable challenges to implementation. While some of these challenges are of a theoretical nature, most ultimately lead to data issues. Data sets for detailed MRIO studies are currently available, but suffer many short-comings. This paper has identified areas that need particular attention—currency issues, inflation, product differentiation, aggregation, periodic updating, averaging issues, trade statistics, system boundaries, and international transportation. With continued research, such as through the EXIOPOL project, more detailed and reliable MRIO studies will find continued application at the policy level.

A Application using the GTAP database

In this section we describe how the GTAP data can be manipulated for this type of MRIO study. The GTAP data we use for our analysis is shown in Table 2. We have only used variables in domestic market prices as the value of imports are distorted by taxes and international margins. As an example, the GTAP variable VXMD differs from the variable of imports at domestic prices (WIMS) by: VXMS = VXMD + export tax + international transport margins + import tax. Importantly, (3) shows that we can calculate emissions using only domestic quantities.

Table 2: The GTAP data used in this study. All monetary data in GTAP market prices.

	GTAP	*GTAP description*
x_r	Calculated	Output of region r.
h_{rr}	VDPM	Value of Domestic purchases by Private households in region r.
h_{rs}	VIPM	Value of Imports by Private households in region r.
g_{rr}	VDGM	Value of Domestic purchases by Governments in region r.
g_{rs}	VIGM	Value of Imports by Governments in region r.
k_{rr}	CGDS	Domestic purchases of Cross Capital Formation in region r.
k_{rs}	VIGM	Imports of Cross Capital Formation in region r.
t_r	VST	Value of exports of international Transport Services in region r.
e_{rs}	VXMD	Value of eXports from region r to region s
m_r	VIMS	Value of iMports to region r
A_{rr}	VDFM	Value of Domestic inputs to Firms in region r
A_{rs}	VIFM	Value of Imported inputs to Firms region r
F_r^t	EGHG	Emissions of GreenHouse Gases by industry sector in region r
F_r	Calculated	GHG emissions intensity by industry sector in region r

The GTAP CO_2 data is based on the IEA energy statistics and the IPCC tier 1 reference approach (Dimaranan and McDougall, Forthcoming, 2006). Comparisons of the GTAP CO_2 data and other national data sources shows considerable variation. There are several reasons for this. First, as discussed earlier, the system boundary for the energy statistics differs from the economic data. Second, the GTAP performs various manipulations on energy data for consistency in the entire data set. Third, there is a known error in the petroleum refineries sector causing an overestimation of emissions (Dimaranan and McDougall, Forthcoming, 2006). And finally, region specific emission factors and fuel contents are not used. Consequently, when national specific data that was easily available we overwrote the GTAP data (Australia, China, Japan, USA, Austria, Belgium, Denmark, Finland, Germany, United Kingdom, Italy, The Netherlands, Spain, Sweden, and Norway which we assumed to be Rest of EFTA in the GTAP data). This data was constructed using an economic system boundary. By comparison of the refinery sector in the GTAP data and the national sources we found that on average the GTAP data overestimated refinery emissions by a factor of 3.8. We used this factor to scale down the refinery sector in the remainder of the GTAP database.

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