Chapter 38
The Application of Multi-regional Input-Output Analysis to Industrial Ecology
Evaluating Trans-Boundary Environmental Impacts

Glen P. Peters and Edgar G. Hertwich

Introduction

Consumption causes environmental impacts in two different ways. Direct environmental impacts result from consumption when consumers directly burn fossil fuels; for instance, from the petrol used for personal transportation or wood used for space heating. Significant environmental impacts also occur indirectly in the production of consumable goods. When production occurs in the same country as consumption, then government policy can be used to regulate environmental impacts. However, increasing competition from imported products has led to a large share of production occurring in a different country to consumption. Regulating the resulting pollution embodied in trade is becoming critical to stem global pollution levels. Due to increased globalization of production networks, there is increasing interest in the effects of trade on the environment (Jayadevappa and Chhatre 2000; Copeland and Taylor 2003).

With the increased interest in trade and the environment research activity is focusing on methods of accurately calculating the pollution embodied in traded products. Early studies in this area assumed that imports were produced with the same technology as the domestic economy (e.g. Wyckoff and Roop 1994; Lenzen 1998; Kondo et al. 1998; Battjes et al. 1998; Machado et al. 2001), however, using this assumption large errors may result when the countries have diverging technology and energy mixes (Lenzen et al. 2004; Peters and Hertwich 2006a, c).[1] This stimulated research in the use of multi-regional input-output (MRIO) models.

G.P. Peters
Center for International Climate and Environmental Research – Oslo (CICERO), Norway

E.G. Hertwich (✉)
Norwegian University of Science and Technology, Trondheim, Norway
e-mail: edgar.hertwich@ntnu.no

[1] Similar conclusions are found in the economic literature on factors (labor and capital) embodied in trade (Hakura 2001).

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While MRIO models have been applied to regional economics since the 1950s (Miller and Blair 1985), applications to environmental problems has only recently emerged (Chung and Rhee 2001; Ahmad and Wyckoff 2003; Lenzen et al. 2004; Nijdam et al. 2005; Peters and Hertwich 2006a, b; Guan and Hubacek 2007). These studies are finding large portions of pollution embodied in trade. For instance, Ahmad and Wyckoff, 2003 found that the emissions embodied in trade was on average 14% in OECD countries and over 50% in some OECD countries; they included data covering 80% of global emissions and use "conservative" assumptions to obtain a lower bound. Further, Ahmad and Wyckoff, 2003 found that "emissions embodied in international trade are important, growing, and likely to continue to grow".

In this article we discuss the theory behind MRIO models for applications in industrial ecology (IE; section "Multi-regional Input-Output Analysis [MRIO]") and discuss common modeling assumptions (section "Common Assumptions in MRIO"). Most MRIO models require a considerable amount of data and we discuss many of the practical data issues that are encountered in MRIO modeling (section "Practical Issues"). In section "Applications and Policy Implications for MRIO in IE" we briefly review the main applications of MRIO in the field of IE and finally we discuss the potential for increased use of MRIO models in IE (section "Future Applications of MRIO in IE").

Multi-regional Input-Output Analysis (MRIO)

Using IOA the total output of the domestic economy is given by

$$x = Ax + y \tag{38.1}$$

where A is the total interindustry requirements and y is the total net demand on the economy,

$$y = y^d + y^{ex} - m \tag{38.2}$$

where y^d are the products produced and consumed domestically, y^{ex} are the products produced domestically, but consumed in foreign regions (exports), and m are the products consumed domestically for both final and intermediate consumption, but produced in foreign regions (total imports). In this form, (38.1) is not suitable for applying arbitrary demands since imports are embedded in both A and y (Dietzenbacher et al. 2005).

It is possible to separate the domestic and imported components in A and y to obtain

$$x = (A^d + A^{im})x + y^d + y^{ex} + y^{im} - m \tag{38.3}$$

where A^d is the industry requirements of domestically produced products per unit output, A^{im} is the industry requirements of imported products per unit output, and y^{im} is the final demand of imports (United Nations 1999). A balance must hold for the total imports,

$$m = A^{im}x + y^{im} \tag{38.4}$$

and thus (38.1) can be reduced to domestic activity only,

$$x = A^d x + y^d + y^{ex} = A^d x + y^t \tag{38.5}$$

Using the linearity assumption of IOA, it follows that the output of the domestic economy for an arbitrary demand is

$$x^* = (I - A^d)^{-1} y^* \tag{38.6}$$

where y^* could represent household demand, government demand, a unit demand on a particular sector, and so on. Given the domestic output, the requirement of imports by industry to produce y^* are given by $A^{im} x^*$. This import may instigate a series of feedbacks through trade flows and is discussed further below.

Using the direct multiplier for environmental impacts[2] per unit output, F, the environmental impacts embodied in domestic consumption are,

$$f^* = F(I - A^d)^{-1} y^* \tag{38.7}$$

This equation does not include the environmental impacts that may occur in foreign regions due to imports.

Particularly for environmental impacts with global implications, such as global warming, it is important to calculate the global environmental impacts for production and consumption. Imports are generally produced in countries with different production technologies and energy mixes compared to the domestic economy. This suggests that a multi-regional model is required to correctly evaluate the pollution embodied in traded products. When trade is allowed between two or more countries trade feedbacks may occur so that production in one country, may require some of its own production via feedback loops (see Fig. 38.1a). This type of interaction can be analyzed using MRIO.

An MRIO model extends the standard IO matrix to a larger system where each industry in each country has a separate row and column. If there are m regions then the extended IO matrix becomes[3]

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_m \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & A_{13} & \dots & A_{1m} \\ A_{21} & A_{22} & A_{23} & \dots & A_{2m} \\ A_{31} & A_{32} & A_{33} & \dots & A_{3m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_{m1} & A_{m2} & A_{m3} & \dots & A_{mm} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_m \end{pmatrix} + \begin{pmatrix} y_{11} + y_1^{ex} \\ y_{21} \\ y_{31} \\ \vdots \\ y_{m1} \end{pmatrix} \tag{38.8}$$

[2] The same equation applies for the standard economic factors of production such as labor and capital.

[3] Peters and Hertwich (2004) build the MRIO equations from a two-region system and is useful for those that may require a more detailed description of how the equations are derived.

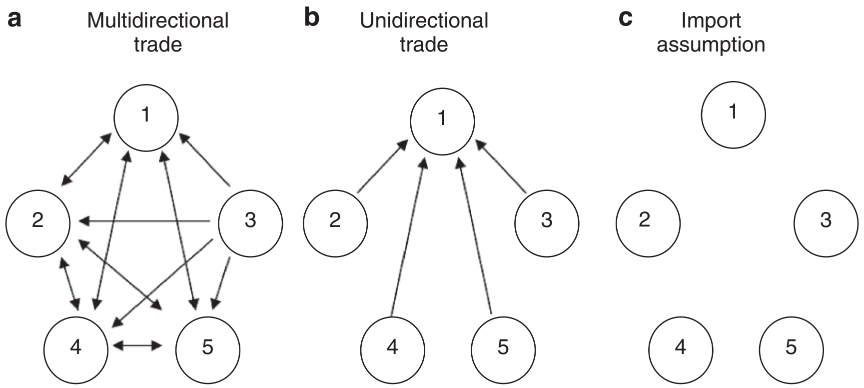

Fig. 38.1 A Schematic Representation of the Three Trade Scenarios for a Five Region Model (Lenzen et al. [2004])

Table 38.1 The Notation Used for the MRIO Model

Name	Description
x_i	Output of region i
y_{ii}	Final demand for goods produced and consumed in i
y_{ij}	Final demand from region i to region j
$y_i^{ex} = \sum_{j=1,j\neq i}^{m} y_{ij}$	Total final demand exports from region i
A_{ii}	Interindustry requirements on domestic production in region i
A_{ij}	Interindustry requirements from region i to j
$A_i = \sum_j A_{ij}$	Total interindustry requirements in region i
$m_{ij} = A_{ij}x_j + y_{ij}$	Total trade from region i to region j
F_i	Direct factor requirements in region i

The notation is described in Table 38.1. We have simplified the system by centering the model on the domestic economy, $i = 1$. Due to symmetry, any region can be considered as the domestic economy by re-labeling it as region 1. The block matrices of the extended IO table represent the global technology. The diagonal block matrices represent domestic interindustry requirements and the off-diagonal elements represent the interindustry requirements of traded products.

For some it may be easier to understand the MRIO model with separate equations. The output in the domestic economy is

$$x_1 = A_{11}x_1 + y_{11} + \underbrace{\sum_{j\neq 1}\left(A_{1j}x_j + y_{1j}\right)}_{\text{exports}} \quad \text{for } i = 1 \tag{38.9}$$

where the export terms are all exports from region 1 to interindustry and final demand in all other regions. The outputs in the other regions are,

$$x_i = A_{ii} x_i + \underbrace{\sum_{j \neq i} A_{ij} x_j + y_{i1}}_{\text{exports}} \quad \text{for all } i \neq 1 \tag{38.10}$$

Since region 1 is treated as the domestic economy, the final demands y_{i1} are imports to region 1.

For a given consumption bundle, y_{i1}, in region 1 the environmental impacts occurring in each region to produce y_{i1} are given by $F_i x_i$ and the global environmental impact are,

$$f = \sum_i F_i x_i \tag{38.11}$$

where F_i are the direct pollution intensities in region i.

Common Assumptions in MRIO

To perform an MRIO study requires a considerable amount of data, much of which is not directly available. Consequently, most current applications of environmental MRIO have applied some approximations to (38.8). In this section we discuss various approximations and simplifications that have been used in environmental MRIO. The following is largely based on Ahmad and Wyckoff (2003), Lenzen et al. (2004), Peters and Hertwich (2004), Nijdam et al. (2005), and Peters and Hertwich (2006a, b). Practical issues associated with data availability and handling are discussed in section "Practical Issues".

Uni-directional Trade

If it is assumed that the domestic economy trades with all regions, but the other regions do not trade amongst each other (see Fig. 38.1b), then the data requirements are greatly reduced without introducing large errors. Lenzen et al. (2004) found these effects to be around 1–4% (see their Table 7) and these terms are often assumed to be negligible in other regional models (Round 2001).

Mathematically, the uni-directional trade assumption reduces (38.8) to,

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_m \end{pmatrix} = \begin{pmatrix} A_{11} & 0 & 0 & \dots & 0 \\ A_{21} & A_{22} & 0 & \dots & 0 \\ A_{31} & 0 & A_{33} & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_{m1} & 0 & 0 & \dots & A_{mm} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_m \end{pmatrix} + \begin{pmatrix} y_{11} + y_1^{ex} \\ y_{21} \\ y_{31} \\ \vdots \\ y_{m1} \end{pmatrix} \tag{38.12}$$

Since this assumption reduces many of the feedback loops, the equation can be solved directly to obtain,

$$x_1 = (I - A_{11})^{-1}\left(y_{11} + y_1^{ex}\right) \tag{38.13}$$

for the domestic economy and the output in the other regions are

$$x_i = (I - A_{ii})^{-1} M_i \qquad \text{for} \quad i > 1 \tag{38.14}$$

where

$$M_i = A_{i1} x_1 + y_{i1} \tag{38.15}$$

The exports term y_1^{ex} now includes both exports to final demand and exports to industry. This approach has been applied by Nijdam et al. (2005), and Peters and Hertwich (2006a, b).

If only analyzing the total final demand on an economy, the uni-directional trade assumption does not require A_{ij}. If the total final demand is used, then (38.15) gives the total imports into the domestic economy and so M_i can be obtained directly from IO or trade data.

The assumption of uni-directional trade gives two options for the diagonal terms of the foreign regions. If $A_{ii}, i > 1$ is placed on the diagonal, then multi-directional trade is totally neglected. Alternatively, if $A_i, i > 1$ is placed on the diagonal, then multi-directional trade is included, but with the assumption that imports are produced with domestic technology (see section "Import Assumption"). However, the country that is allocated the emissions for the production of the imports will be incorrect. Due to data availability, countries may only supply A_i in which case it is implicitly assumed that multi-directional trade is included using domestic technology.

Import Assumption

A common assumption is that imports are produced with domestic production technology (Fig. 38.1c). The import assumption has also been called "autonomous regions" by Lenzen et al. (2004) and "mirrored economy" by Strømman and Gauteplass (2004). The assumption greatly reduces data requirements, but may lead to large errors. Lenzen et al. (2004) found the error between the import assumption and multi-directional trade for Danish CO_2 emissions to be 20–50% depending on the final demand. Peters and Hertwich (2006a) found the difference between the import assumption and uni-directional trade for Norwegian household consumption to be a factor of 2.7 for CO_2, 9.7 for SO_2, and 1.5 for NO_x. Most IO studies of environmental issues apply the import assumption and so it is likely that many of these studies incorrectly calculate the emissions associated with the production of imports.

One way to apply the import assumption is to assume $A_{ii} = A_{11}$, $A_{ij} = A_{i1}$, and $F_i = F_1$ and then substitute into (38.8). Simplification then results in,

$$x_i = (I - A_1)^{-1} y_i \tag{38.16}$$

where y_i is the final demand placed on each region (Peters and Hertwich, 2004). This equation gives the emissions in each region, including imports to industry, but it assumes they have the same production technology as the domestic economy and allocates the embodied emissions to the domestic economy. The correct allocation can be obtained by using (38.8), but with substitution of $A_{ii} = A_{11}$ and $A_{ij} = A_{i1}$.

Others

Some approaches have been slightly different to what is outlined above. Ahmad and Wyckoff (2003) do not use the matrix based approach we have described above, but use an iterative procedure which approximates the matrix solution. Lenzen et al. (2004) replace each of the block matrices with a make and use block which displays additional structure, but applies an industry-technology assumption on solution. Methods not using IOA to estimate pollution embodied in trade often neglect indirect emissions in the production chain and are consequently not considered in this article.

Practical Issues

A significant amount of data from a variety of sources is required to perform an MRIO study. As a consequence several practical issues arise in the data manipulation phase. This section briefly discusses the main areas of concern. Lenzen et al. (2004) also give a detailed discussion of some of these issues.

General Data Availability

To perform a detailed MRIO study IO data is essentially required for every country. This data is generally available for most OECD countries, but for relatively few non-OECD countries. Most EU countries submit data to Eurostat in a consistent format. The USA, Canada, and Australia regularly compile IO data but using different classifications. The data availability in non-OECD countries is sparse and often for major non-OECD countries only. Some data projects have attempted to build large IO databases for global models. The Global Trade, Assistance, and Production project (GTAP; version 6) provides data for 87 world regions in 57 sector detail (Dimaranan and McDougall 2006).[4]

Emissions data is often available for countries that supply IO data, but in many cases the data needs separate construction. Energy data can be used to construct some air emissions data (e.g., Ahmad and Wyckoff 2003; Dimaranan and McDougall 2006) alternatively, additional data work may be required (e.g., Suh 2005; Guan and Hubacek 2007). Care needs to be taken with energy and environmental data from some sources as they may have a different system boundary to the IO data (Gravgård Pedersen and de Haan 2006; Peters and Hertwich 2006c). Energy and emissions data are often constructed according to "national territory", while IO data are constructed according to "resident institutional units". Resident institutional units may operate and pollute outside national territory, but are still a part of the domestic economy. The main differences between the two definitions are for international transportation and tourist activities. For Denmark in 2001 the differences between the two definitions were 23% for CO_2, 93% for SO_2 and 72% for NO_x (Gravgård Pedersen and de Haan 2006). For Norway in 2000 the difference was 25% for CO_2 (Peters and Hertwich 2006c).

Trade data is available from several sources, but generally trade data has missing data and mismatches. This requires addition processing and cross-checking for consistency (e.g., Dimaranan and McDougall 2006). Import and export data often do not match due to different pricing conventions and errors in reporting. If traded goods between two countries go through a third country then allocation problems often arise.

Grouping of Like Regions

Two approaches have been used in the past to fill in for missing IO data. A first approach is to allocate the countries without IO data the IO data of a "representative" country. Ahmad and Wyckoff (2003) used the United States of America and Lenzen et al. (2004) used Australia as the representative country. Another approach is to collect IO data for the most significant trading partners and then allocate the minor trading partners to one of the major trading partners to make larger aggregated regions with fixed technology. This approach was applied by Peters and Hertwich (2006a, b) and the allocation was performed based on energy use per capita, CO_2 emissions per capita, and gross domestic product per capita. If the major trading partners represent a diverse range of economies, then the second approach is likely to give a better approximation. In both approaches, it is also possible to adjust emission coefficients if the data is available; for example, when allocating

[4] While the GTAP database is extensive, it must be noted that it is not always the most up to date and accurate data available. The data for individual regions is usually submitted by users of the data and consequently data is sometimes not updated with new versions of the database. The database also has a strong emphasis on food and agriculture.

emissions data between countries Ahmad and Wyckoff (2003) adjusted the emission coefficient for electricity production based on other reliable data sources (also see Battjes et al. 1998).

Using Trade Shares to Estimate A_{ij}

Data on A_{ij} and y_{ij} is generally not directly available; however, many countries construct $A_i^{im} = \sum_{j \neq i} A_{ij}$ and $y_i^{im} = \sum_{j \neq i} y_{ij}$. Using A_i^{im} together with trade flow data it is possible to estimate the share of trade flows to final demand and industry in each region using

$$A_{ij} = \hat{s}_{ij} A_i^{im} \tag{38.17}$$

and

$$y_{ij} = \hat{s}_{ij} y_i^{im} \tag{38.18}$$

where

$$\{s_{ij}\}_k = \frac{\{m_{ij}\}_k}{\{\sum_i m_{ij}\}_k} \tag{38.19}$$

where $\{m_{ij}\}_k$ is the total imports of product k from region i to j. It is important to consider the trade shares in individual sectors and not the average of all sectors. More details on using trade shares to estimate A_{ij} can be found in Lenzen et al. (2004).

Exchange Rates

In an MRIO model, exchange rates are needed to link the data from different regions to a common currency. There has been considerable debate in the climate change literature about the use of Purchasing Power Parities (PPP) or Market Exchange Rates (MER) in currency conversation (Castles and Henderson 2003; Grübler et al. 2004; Nordhaus 2006). The MER is calculated based on traded products, while the PPP is calculated based on a bundle of consumed products; both traded and non-traded. The PPP rates give a better measure of income levels across different countries. Much of the debate about PPP and MER has been based on the comparison of income levels and not a comparison of traded products. Since MRIO models focus on traded products we suggest the use of MERs to obtain a common currency. It is possible to avoid the exchange rate problems by using physical units for key sectors; however, data in physical units requires additional data issues, particularly availability.

Inflation

The data covering a variety of regions is likely to come from various time periods. Adjustments for inflation are required to make the data consistent for a given base year. The easiest approach is to use the Consumer Price Index (CPI) in each country to adjust for inflation. However, the CPI is likely to introduce other errors. The CPI is an aggregated index, while price changes are likely to be different in each of the IO sectors. Further, the CPI also varies depending on the base year used and the method of indexing applied. These issues are difficult to resolve and the errors will be greater for a large CPI and when there is a big difference in base years.

Product or Industry Classifications

It is possible to perform IOA using a product classification or an industry classification. Through the make and use system it is possible to transfer between the two using the make matrix. The emissions data is usually in an industry classification and the final demand, depending on the application, will be either an industry or product classification. Consequently, for some studies there will be a need to map between the industry and product classifications. Given that the emissions data is always in an industry classification and IO tables are often only supplied in an industry classification we suggest using industry classifications as this requires less data manipulations. This would imply mapping the final demands in a product classification into the industry classification using the make matrix.

Re-classifying Data

The IO data from different regions is often in different classification systems. To perform the analysis requires mapping the data, at some stage, to a consistent classification. For some classifications it is possible to obtain correspondence tables, otherwise, the correspondence tables need to be constructed by referring to the different classification descriptions. Often, the classification systems do not have a direct correspondence between sectors and while the classification definitions can be used as a guide, re-classification will nearly always introduce errors of unknown size.

Another issue is that some data is collected based on entirely different conceptual framework. For example, IO data in an industry classification is based on industries being the smallest unit, while consumer expenditure survey data is collected on the basis of products and functions being the smallest unit (the classification of individual consumption by purpose [COICOP] is a good example). Mapping between products or functions and industries is difficult implying that several assumption and approximations are required. In some cases checks can be applied. For example, when mapping consumer expenditure data to an industry classification, it is possible to ensure that a rough balance is obtained at the sector level between the mapped expenditure data and the household expenditure from the IO tables.

Aggregation

In the MRIO setting, Lenzen et al. (2004) show the importance of aggregation errors with the broad conclusion that the data should be in the highest detail available. Thus, a global MRIO with ten-sector aggregation, for example, may produce unreliable results.

Valuation

IO data is often available in three levels of valuation; basic, producer, or purchaser (retail) prices. The different valuations differ in the trade and transport margins, and taxes and subsidies; producer = basic + taxes – subsidies, purchaser = producer + margins. Typically margins and taxes are applied at different rates in different sectors and on different products. Even across the same product, margins and taxes can differ for a variety of reasons such as, different mark-ups, different modes of transport, different levels of taxation, bulk discounts, different recording principles, and so on (United Nations, 1999). For these reasons it is more homogenous to work in basic prices as they are more representative of the production value of a product compared to the market value.

Unfortunately, not all IO data is available in basic prices. Estimation can be used to adjust the IO data to the required valuation, but without the detailed data in each sector, the possibility for introducing large errors is considerable. Due to data availability, it is likely to be easier to convert the final demand to a new valuation compared to the IO data. In practice, if data is not available in the necessary valuation, it may be best to report the valuation of the data and emphasis that it will either under- or over-estimate the environmental impacts depending on the valuation used.

An addition problem arises in the valuation of trade data. Exports are usually presented as free on board (fob) and imports as cost, insurance, freight (cif). For consistency, the imports need to be converted to basic prices. Lenzen et al. 2004 use economy wide fob/cif ratios and then balance the resulting MRIO table using a RAS technique.

Marginal Technology

It can be argued that the regional technology differences are not relevant in some studies. Instead, any expanded production will occur with marginal technology

(Weidema et al. 1999; Ekvall and Weidema 2004). If modeling past flows, then the technology used in production is required. In the modeling of future scenarios it is important to consider the likely technology mix and emissions coefficients in the future; in this case, marginal technologies may be preferred. A possible alternative is to consider the energy embodied in trade as the energy intensities are less dependent on the fuel mix (Peters and Hertwich 2005a).

Errors

Errors can enter into the calculations in many ways. The IO data and factor use intensities always have an error associated with them (e.g., Rypdal and Zhang 2000; Lenzen 2001). Errors also arise in the adjustments for currency conversions, inflation, different sector classifications, aggregation, and so on. The magnitude of these errors is often difficult to estimate, but the errors still need to be considered (Morgan and Henrion 1990). Ideally, some sort of error analysis should be performed or the potential magnitude of uncertainties discussed.

Applications and Policy Implications for MRIO in IE

Generally, there are three scales of interest in consumption related issues; national, regional, and local (Munksgaard et al. 2005). In the context of this article we will consider two scales; total demand (national and global) and arbitrary demand (regional and local). Most applications of MRIO have been to address global issues of pollution embodied in trade. Only recently have MRIO studies considered arbitrary demands. In this section, we outline the main applications of MRIO in the field of IE. We do not consider studies that have modeled similar questions, but using single region models with the import assumption.

Trans-boundary Pollution

The main motivation for the studies by Chung and Rhee (2001), Ahmad and Wyckoff (2003), Lenzen et al. (2004), and Peters and Hertwich (2006c) was to evaluate pollution embodied in trade at the national level and to determine the different environmental impacts of consumption versus production and its implications to global climate change policy (Kondo et al. 1998; Munksgaard and Pedersen 2001; Bastianoni et al. 2004). These studies generally found a large portion of CO_2 emissions embodied in trade. The most comprehensive study, Ahmad and Wyckoff (2003) found that the CO_2 emissions embodied in imports in some OECD countries was over 50% and on average 14% of OECD CO_2 emissions were embodied in imports. However, the authors used conservative assumption such as not including services trade, excluding process emissions, and intentionally making assumptions that led to a lower bound. It is likely that these numbers are larger in reality. Lenzen et al. (2004) found that 66% of Danish domestic CO_2 emissions in 1997 were embodied in imports which is considerably greater than the value of 36% found by Ahmad and Wyckoff (2003). Peters and Hertwich (2006c) found that 67% of Norwegian domestic CO_2 emissions in 2000 were embodied in imports which is similar to the value of 54% found by Ahmad and Wyckoff (2003) for 1997. The reason for the differences are unknown, but may be since Ahmad and Wyckoff (2003) used different assumptions and data set. Chung and Rhee (2001) used an MRIO for trade between Japan and Korea, but they did not consider the pollution embodied in imports from outside of Japan and Korea. Their study has a regional focus for trade between Japan and Korea, but not on the global implications.

Guan and Hubacek (2007) consider virtual water flows[5] between south and north China using an MRIO model. They found that the water scarce north exports large quantities of virtual water to the relatively water abundant south. Guan and Hubacek (2007) go on to show that this contradicts the standard theory of comparative advantage; often referred to as the "Leontief paradox". This highlights the wider applications of MRIO models to any factor of production embodied in trade (also see Hakura 2001).

Arbitrary Demands

The studies (Nijdam et al. 2005; Peters and Hertwich, 2005b, 2006a) focus on the implication of imports for household environmental impacts (HEI). Both use MRIO models with uni-directional trade only, Nijdam et al. (2005) consider nine environmental indicators for Dutch household consumption, while Peters and Hertwich (2005b; 2006a) consider CO_2, SO_2, and NO_x emissions for different Norwegian final demands. Both studies found that large fractions of HEI are embodied in imports directly to households and imports to domestic industries as inputs to produce domestic household demand. Except for traffic noise (Dutch study) and NO_x (Norwegian study) over 50% of the measured global HEI were embodied in imports; greenhouse gases were around 50% in both cases. In many cases the environmental impacts from developing countries was most significant, particularly considering the smaller share of imports coming from those regions. Both studies reinforced the overall importance of mobility and food in HEI (cf. Hertwich 2005), but found increased importance of consumable items due to imports. The Norwegian study found that for food, business services, clothing, chemicals, furniture, cars, agriculture, textiles, and most manufactured goods the majority of emissions occurred in foreign regions.

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[5] Guan and Hubacek (2007) refer to embedded water content as "virtual water".

The study by Peters and Hertwich (2006b) considered the importance of imports for the global CO_2, SO_2, and NO_x emissions of Norwegian household, government, and exported final demands. The article considered the final demands from a consumption perspective, production perspective, and used structural path analysis to analyze the trade linkages between consumption and production. The main empirical conclusion from this study was that a large portion of CO_2, SO_2, and NO_x emissions of the Norwegian economy can be traced back to electricity production, primarily by coal, and other energy intensive industries in developing countries. Further, the different methods of analysis were found to be relevant for different policy applications. The article highlights, for global pollutants in particular, that policy needs to address the environmental implications of imports.

Future Applications of MRIO in IE

There is significant scope for MRIO models to be applied to many areas in IE.[6] Most recent MRIO studies have focused on global issues or aggregated final demands such as total household consumption. With the current importance of globalization, MRIO models will find application in many other areas in IE. A direct extension of the current MRIO models is to focus on particular products, processes, or consumption. Hybrid Life Cycle Assessment (LCA; Suh et al. 2004) already uses IO data to increase system completeness and it is also possible to extend these models further using MRIO data. Similarly, the MRIO studies of households can be extended to include socioeconomic analysis of import behavior in households. An area that is yet to utilize MRIO models is Material Flow Analysis (MFA) and the study of "hidden flows". An extension in this area is possible given the material use intensity in the relevant economic sectors.

In the future, it is likely that global issues will continually be explored using MRIO analysis. Given the interconnectedness of the global economic system, it is important to analyze environmental problems through the global system. Since MRIO models are based on the IO framework, many IO techniques can be applied to study global production structures (e.g., Lenzen 2003; Peters and Hertwich 2006b). This gives considerable insight into the importance of both domestic and global trade flows for various environmental problems. It is also possible to apply MRIO models to the traditional economic factors of production such as labor and capital (Hakura 2001). Combining these studies allows an analysis of the eco-efficiency along the global production network to compare the environmental impacts to the value added of different products (Clift and Wright 2000). Using these methods it is possible to determine if, for instance, developing countries are faced with high environmental burdens for low value added.

[6] Suh and Kagawa (2005) and Gravgård Pedersen and de Haan (2006) give general overviews of IOA applied in IE.

Currently, the main obstacle to increased use of MRIO models is data availability and consistency. There is potential to use current data sets, such as GTAP or OECD IO data, or to build more refined data for specific regions, such as using the Eurostat IO database for a regional model of the EU. Data on environmental impacts is less wide-spread. However, with a concerted effort, many of the current data obstacles can be negotiated. Given that several international bodies already collect large amounts of the data required for MRIO studies, it makes sense to maintain an MRIO database through one of these agencies. With a maintained database MRIO models can be applied directly by all countries through the interconnectedness of the model, Fig. 38.1a).

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