

Chapter prepared for inclusion in Suh, S. (Ed.) (2005):
“Handbook of Input-Output Economics in Industrial Ecology”

Modelling global resource use: material flows, land use and input-output models

Stefan Giljum^{a*}, Friedrich Hinterberger^a,
Christian Lutz^b, Bernd Meyer^b

^a *Sustainable Europe Research Institute (SERI),
Garnisongasse 7/27, 1090 Vienna, Austria*

^b *Institute for Economic Structures Research (GWS),
Weissenburger Straße 4, 49076 Osnabrück, Germany*

* *corresponding author: T +43 1 9690728 19, F +43 1 9690728 17
E stefan.giljum@seri.at*

1 Introduction

Monitoring the transition of modern societies towards a path of sustainable development requires comprehensive and consistent information on the relations between socio-economic activities and resulting environmental consequences. In the past 15 years, several approaches have been developed providing this information in biophysical terms (see, for example, Daniels and Moore, 2002 for an overview). These methods of physical accounting are applied to quantify “societal metabolism” (Fischer-Kowalski, 1998) and to measure the use of “environmental space” (Opschoor, 1995) by human activities. Within the system of physical accounts on the national level (for a classification see the “Integrated System of Environmental and Economic Accounts” developed by the United Nations, 2003), material flow accounting and analysis (MFA) and land use accounting are regarded as appropriate tools to provide a comprehensive picture of environmental pressures induced by and inter-linked with the production and consumption of a country.

In the European Union (EU), a large number of policy documents address high levels of resource use and production of huge amounts of waste and emissions as one major obstacle for the realisation of an environmentally sustainable development in industrialised countries. The sustainable management of natural resources, in order to keep anthropogenic environmental pressures within the limits of Earth’s carrying capacity, is highlighted as one central

objective for the implementation of a sustainability strategy within Europe (for example, European Commission, 2001a). De-coupling (or de-linking) economic growth from the use of natural resources and environmental degradation is defined as the core strategy to achieve sustainable levels of resource use; raising the resource productivity of production and consumption activities should help producing the same or even more products with less resource input and less waste (European Commission, 2003).

In 2001, the European Council at Gothenburg agreed on a “European Strategy for Sustainable Development”. In the European Commissions’ (2001b) background document for the EU sustainability strategy, it is emphasised that production and consumption activities within EU borders would have environmental impacts in other world regions and would increase the pressure on the environment (particularly in developing countries). Thus the links between trade and environment would have to be taken into account in order to guarantee that the goal of achieving sustainability within Europe fosters sustainability on a global scale at the same time.

This becomes particularly relevant, as the externalisation of environmental burden through international trade might be an effective strategy for industrialised countries to maintain high environmental quality within their own borders, while externalising the negative environmental consequences of their production and consumption processes to other parts of the world (Giljum and Eisenmenger, 2004; Muradian and Martinez-Alier, 2001).

An evaluation of the economic activities of one country or world region within the context of the urgently due transformation of societies towards sustainability on the global level, can therefore only be carried out by extending the domestic physical accounts and including so-called indirect resource requirements (or “ecological rucksacks”) associated to imports and exports. The declining material use per unit of GDP (“relative dematerialisation”) in countries of the western hemisphere (see for example Adriaanse et al., 1997) does not automatically lead to lower overall consumption of material-intensive goods, but results to some extent from higher imports of these products from other world regions (Muradian and Martinez-Alier, 2001; Schütz et al., 2004). Physical accounting studies, which comprehensively integrate international trade aspects, can clarify whether relative dematerialisation in the North is going along with a de-intensification of trade flows or is linked to increased physical inputs of natural resources from the global South.

While input-output (IO) models have been used for assessments of economy-environment relationships since the late 1960s, the integration of physical accounts with monetary IO models is a relatively young, but rapidly developing research field. With regard

to integrated sustainability scenario simulation and policy evaluation, these models are regarded as powerful tools, in particular for applications on the international level.

This chapter has three main objectives: it aims (a) at providing the methodological foundations for performing parallel analysis of material flows and land appropriation of economic activities within a framework of monetary input-output models, (b) at describing necessary properties and the state of the art of global sustainability models and most important data sources for their construction and (c) at presenting policy applications of such an integrated modelling approach with regard to sustainability assessments on the global level.

Section 2 introduces the basic concept of material flow accounting and analysis (MFA) and land use accounting. Methodological foundations for linking resource input accounts to monetary IO models are presented in section 3. In section 4 we review the state of the art with regard to global simulation models and summarise necessary properties of a global sustainability model and most important data sources. Section 5 describes the main areas of applications of this approach for world-wide sustainability policy-oriented assessments. Section 6 contains the conclusions.

2 MFA & land use accounting

Material flow accounting and analysis (MFA)

The basic concept underlying the MFA approach is a simple model of the interrelation between the economy and the environment, in which the economy is an embedded subsystem of the environment and – similar to living beings – dependent on a constant throughput of materials and energy. Raw materials, water, and air are extracted from the natural system as inputs, transformed into products and finally re-transferred to the natural system as outputs (waste and emissions). To highlight the similarity to natural metabolic processes, the terms “industrial” (Ayres, 1989) or “societal” (Fischer-Kowalski, 1998) metabolism have been introduced. Since the beginning of the 1990s, MFA has been a rapidly growing field of scientific interest and major efforts have been undertaken to harmonise the different methodological approaches developed by different research teams (Bringezu et al., 1997; Kleijn et al., 1999), resulting in the publication of a standardised methodological guidebook for economy-wide material flow accounting by the European Statistical Office (EUROSTAT, 2001).

The main purposes of economy-wide material flow accounts are to provide insights into structure and change over time of the physical metabolism (resource throughput) of national economies, to derive a set of aggregated indicators for the material basis and resource productivity of production and consumption patterns, and to permit analytical uses, including as-

assessments of resource flows induced by international trade as well as decomposition analyses separating technological, structural and final demand changes (see the chapter by Stocker in this handbook). Today, MFA is recognised as a key tool for evaluating resource use and eco-efficiency policies, for example by the European Union (European Commission, 2003) and the OECD (2004).

A large number of national MFA studies have been carried out for developed countries (for example, Adriaanse et al., 1997; EUROSTAT, 2002; Matthews et al., 2000) and transition economies (Hammer and Hubacek, 2002; Mündl et al., 1999; Scasny et al., 2003). Concerning countries in the global South, economy-wide MFAs have been presented for Brazil and Venezuela (Amann et al., 2002), for Chile (Giljum, 2004) and for China (Chen and Qiao, 2001). A first estimation of the material basis of the global economy was presented by Schandl and Eisenmenger (2004) for the year 1999. A time series for resource extraction of all countries of the world from 1980-2002 was recently compiled by Giljum et al. (2004). The availability of detailed material input accounts is necessary for building global economic-environmental simulation tools (see section 4 below).

Land use accounting

Together with energy and material flows, land use is the third important natural resource input category of economic activities (see for example, Spangenberg and Bonnoit, 1998). Changes in land use and land cover are among the issues central to the study on environmental and socio-economic impacts of global environmental change (for example, Fischer et al., 2002).

The most influential physical accounting method focusing on land appropriation is the ecological footprint (EF) (Wackernagel and Rees, 1996). The EF method is a tool to perform natural capital assessments on the national level and provide indicators for overall land (and water) appropriation related to production and consumption patterns in different world regions. EFs are available for all countries of the world (see WWF et al., 2004 for the latest global data set). The calculation method of the EF is in general not based on actual land use data, but starts from the resource consumption of a specific population in terms of mass units and transforms this mass into land appropriation in a second step. The largest share of the EF is made up by “hypothetical land areas” required to absorb the CO₂ emitted from the combustion of fossil energy carriers (or to produce an energy carrier of the same energy content from renewable resources).

A number of critical points concerning the calculation procedure of EFs have been raised (Ecological Economics, 2000; McDonald and Patterson, 2004), such as the aggregation

of actual appropriated land areas with hypothetical land areas to the total EF, the assumption that current practices of land use (e.g. in agriculture) are sustainable, the focus on those (bi-otic) products, for which conversion of mass units into land areas is feasible and the inability to relate EFs directly to other economic and social indicators derived from the System of National Accounts.

For all those reasons, in our opinion, a more suitable approach for including land use aspects in physical accounting is to use land use data, available from land use statistics or from Geographical Information Systems (GIS) (for example, EEA 2000). In some European countries (for example, in Germany), land use accounts are compiled according to classifications of economic use (such as transport, housing, agriculture, industrial production, etc., see Statistisches Bundesamt, 2002), making them directly connectable to economic accounts and models. By using real land use data and keeping it separate from the material accounts, problems related to the conversion of different categories is avoided, which significantly increases scientific transparency and credibility of the approach (Spangenberg et al. 1999).

3 Extending IO models with physical accounts

IO models and MFA

First studies calculating resource productivities of different sectors disaggregated in monetary input-output tables and estimating overall (direct and indirect) material inputs to satisfy final demand were presented by Behrensmeier and Bringezu (1995) and Femia (1996), using the example of the German economy¹. Since then, the method to apply IO analysis of material flows was further improved in several steps and applied in various studies using the German case (Bringezu et al., 1998; Hinterberger et al., 1999; Hinterberger et al., 1998; Moll et al., 2004; Moll et al., 2002).

IO analysis of material flows within a dynamic IO model was performed in the project “Work and Ecology”, carried out by three research institutions in Germany (Hans-Böckler-Stiftung, 2000). In this project, a dynamic input-output model for Germany (“Panta Rhei”, see Meyer et al., 1998) was extended by material input data, in order to simulate and evaluate different sustainability scenarios for Germany (Hinterberger et al., 2002; Spangenberg et al., 2002). Earlier, a similar approach was used by Lange (1998), who integrated natural resource accounts in a 30-sector, dynamic input-output model for Indonesia in order to assess possible

¹ Earlier, the integration of material accounts in physical units into economic input-output models was already explored by Leontief et al. (1982), in order to forecast trends in the use of non-fuel minerals in the US.

environmental implications of policy goals stated in Indonesia's national development plan. Bailey and colleagues (2004) perform an analysis of material flows within an ecological input-output framework to analyse material flow paths and cycles in the industrial system of selected production branches (such as the aluminium industry). The first application of IO analysis of material flows using an international IO model system is being realised in the EU-funded project *MOSUS*².

The starting point for an explanation of the basic calculation procedure, which follows the standard procedure for the extension of monetary-input output tables by an additional input vector (see Miller and Blair, 1985), is a monetary input-output table (MIOT).

Table 1: Simplified monetary input-output table (MIOT) extended by a material input vector in physical units

Supply \ Use	Sectors ($1, \dots, n$)	Final demand (y)		Total output
		Domestic	Exports	
Sectors ($1, \dots, n$)	Z	d	e	x
Value Added	v'			
Imports	m'			
Total input	x'			
Material input (physical units)	r'			

From the monetary flow table, we derive the general equation for the static input-output model:

$$(1) \quad x = (I - A)^{-1} y$$

with x : Total output,

$(I - A)^{-1}$: Leontief inverse matrix,

y : Total final demand.

Adding material input data (r') (consisting of domestic material extraction and foreign material requirements necessary to produce imported intermediate products³) to this input-

² Modelling opportunities and limits for restructuring Europe towards sustainability. MOSUS is funded by the 5th Framework Programme of the EU (see www.mosus.net for more information on this project).

³ Domestic material extraction can either only include used domestic extraction, or used plus unused (e.g. overburden from mining) domestic extraction. Foreign material requirements can either comprise only imports in physical units, or direct imports plus up-stream indirect material requirements. In the German studies cited above, all 4 categories were considered in the IO calculation.

output model requires that the inputs in physical units (in the case of materials: tons) are expressed as vector of direct inputs attributed to each production sector. Dividing the physical resource input appropriated by each sector (R_j) by the total (monetary) output of each sector (X_j) leads to a vector of sectoral input coefficients (C_i). The extended Leontief inverse matrix or multiplier matrix weighted by material input coefficients (M_w) is finally calculated by post-multiplying the diagonal vector of sectoral material input coefficients (\hat{c}) with the Leontief inverse matrix.

$$(2) \quad M_w = \hat{c} (I - A)^{-1}$$

with M_w : Weighted multiplier matrix,
 \hat{c} : Diagonal vector of material input coefficients.

The element ij of this weighted multiplier matrix illustrates the amount of material input of sector i needed to produce one additional unit of output of sector j . In order to calculate direct and indirect material input required to satisfy the different categories of final demand in different economic sectors, the weighted multiplier is multiplied with final (domestic⁴ and foreign) demand.

$$(3) \quad r^d = M_w * d \text{ and } r^e = M_w * e$$

with r^d : Vector of direct and indirect material input for domestic consumption
 r^e : Vectors of direct and indirect material input for export production
 d : (Monetary) vector of domestic consumption
 e : (Monetary) vector of exports
and $r^d + r^e = r$

A more disaggregated calculation procedure is presented in Moll et al. (2004; 2002). This approach on the one hand distinguishes domestic material extraction for intermediate use from domestic material extraction, which directly enters final demand. On the other hand, imports are divided into imports for intermediate use and imports for final demand, respectively.

Material input accounts are generally compiled in a disaggregated way, distinguishing a large number of material flow categories within the three major groups of biomass extraction, extraction of minerals and ores, and extraction of fossil fuels. This detailed information can be

⁴ Domestic final demand can be further disaggregated into private consumption, investment, government expenditures, etc., in order to calculate material input requirements for more specific categories.

used to split up the aggregated material input vector and perform IO analysis for specific material flows (for example, fossil fuels or heavy metals), which are more specifically related to different environmental problems (e.g. climate change; toxic pollutants, etc.) than aggregated material flow-based indicators (for a methodological description see Moll et al., 2004).

IO models and land use accounting

In the past few years, several studies relating input-output analysis to land use accounting were presented (Bicknell et al., 1998; Eder and Narodoslowsky, 1999; Ferng, 2001; Hubacek and Giljum, 2003; Hubacek and Sun, 2001). These approaches proved to be useful for the calculation of directly and indirectly appropriated land areas of production and consumption processes and are discussed as possible further development of ecological footprint calculations (McDonald and Patterson, 2004).

The basic calculation procedure is analogous to the one described for material flows, with the difference that the vector of resource input (l) is expressed in hectares of sectoral land appropriation.⁵ Consequently, the land input coefficient, calculated by dividing total land appropriation in each sector by total monetary output, illustrates the appropriated land area necessary to deliver one unit of (monetary) output. Post-multiplying the diagonal vector of land input coefficients with the monetary multiplier delivers the multiplier weighted by land inputs. The element ij of this weighted multiplier matrix illustrates the amount of land input of sector i needed to produce one additional unit of output of sector j .

Direct and indirect land inputs necessary to satisfy final demand in the categories of domestic consumption and exports are finally calculated by multiplying the weighted multiplier with the different final demand categories:

$$(4) \quad l^d = M_w * d \quad \text{and} \quad l^e = M_w * e$$

with l^d : Vector of direct and indirect land input for domestic consumption

l^e : Vectors of direct and indirect land input for export production

d : (Monetary) vector of domestic consumption

e : (Monetary) vector of exports

and $l^d + l^e = l$

⁵ In analogy to material inputs, the vector of land requirements should include both domestic land appropriation by economic sectors and land appropriation necessary abroad for producing imports to the national economy. However, few data on embodied land inputs of traded products are available so far (Hubacek and Giljum, 2003).

In parallel to the category of material flows, the sectoral land input vector should be disaggregated in order to separately reflect different types of land categories (e.g. land for infrastructure, for transport purposes, etc.) appropriated by the respective economic sectors.

Parallel analysis of material flows and land use

Material flows (including energy carriers) together with land use are widely regarded as the most important categories of resource inputs for economic activities. In the literature on material flow accounting on the economy-wide level, spatial aspects are in general not addressed. To our knowledge, no empirical study has been published so far addressing questions of the spatial distribution of material flows and the implications of changes in the metabolic profile of countries or regions for land use changes.

On the product (micro) level, the definition of an indicator, which relates the intensity of land use to the service provided, was presented by Schmidt-Bleek (1994). This procedure was intended to follow the “MIPS” (material intensity per service unit) approach developed for the category of material use. However, this approach was not further developed or applied for empirical studies.

The integration of environmental data in physical units (from physical accounts) into monetary IO models allows the parallel analysis of these two categories within a consistent and comprehensive framework. Thereby, parallel analyses of resource intensities and land intensities of different economic sectors can be performed, clarifying correlations and possible trade-offs between material intensity and land intensity can be identified. Finally, land intensity could be one possible criterion to evaluate different types of material flows with regard to negative environmental impacts.

Another possible extension of this analysis is to establish links between resource and land-related indicators to other indicators that can be attributed to the economic sectors under investigation, in order to allow for comprehensive sustainability analyses. These indicators can comprise labour (in terms of employed people as well as working time; see Hinterberger et al. 2002) as well the use of capital.⁶

⁶ In economic terms, capital use would be measured in economic terms of official SNA statistics. Related to sustainable development, the term can also be broadened to include natural, social, and human capital (see Spangenberg et al., 2002).

4 Global economic environmental models

The increasing availability of multi-national economic models opens up new possibilities for performing integrated economic environmental assessments of globalisation processes. This allows analysing economic and environmental implications of, for example, international structural change and increasing liberalisation of trade on the global level.

Required model properties

There are five requirements, which global economic environmental models should fulfill (see Meyer et al., 2003):

1. They have to be *multi-country* global models. The multi-country approach is needed as policy decisions are made in countries and for countries and in general not for whole world regions. Therefore, all countries important from an economic and environmental point of view have to be described explicitly. The model must include a region “Rest of the World” to close the system and to ensure global coverage.
2. *Multi-sector* models are needed. The interrelations between the economy and the environment with its complex structures for the different resources and emissions can only be depicted in a deep sector disaggregation of the economy.
3. From 1 and 2 follows that also *international trade* has to be analysed in a *multi-sector/multi-country* approach. This means that for every product group, which is important to describe the economic-environmental interdependencies, international trade between all important countries has to be depicted bilaterally.
4. The models have to provide an *endogenous explanation of socio-economic development and its linkage with the environment*. This follows from the integrative approach of sustainability.
5. The models must be able to describe concrete and realistic policy alternatives. How will the future be in the business-as-usual case? How can this path be influenced by currently debated policy instruments? A *forecast* model is needed, which is able to reproduce the historical development because of the *statistical significance of its parameters*.

State of the art

Uno (2002b) found and summarised not less than 34 global simulation models in the literature - most of them focussing on energy issues - that were developed since 1993. In 27 of these models, economic development is *exogenous*. Since we are interested in the interde-

dependencies of socio-economic and environmental development from the integrative perspective of sustainability, this is not a promising approach. Another five models endogenise the economy, but do not fulfil other requirements, since they are not deeply disaggregated with regard to countries/world regions and industrial branches.

The fundamental qualities - global coverage, endogenous economy and a deep sector and regional disaggregation - are accomplished by the models GTAP (Hertel, 1997), COMPASS (Meyer and Uno, 1999; Uno, 2002a) and GINFORS (Meyer et al., 2004). GTAP distinguishes 57 sectors/commodities and 67 countries and regions, COMPASS distinguishes 36 sectors and 53 countries and regions, GINFORS has 41 sectors and 43 countries and two regions. The core of all three models is a multi-sector bilateral trade model.

GTAP is a neoclassical CGE model, whereas COMPASS and GINFORS follow the INFORUM philosophy (Almon, 1991), which combines the traditional input-output- analysis with the econometric modelling approach. Based on the assumption of a long run general competitive equilibrium, the elasticities of the GTAP model are obtained from the literature and all other parameters are calibrated by one data point. The INFORUM approach allows bounded rationality of the agents, which are acting on imperfect markets. The parameters of COMPASS and GINFORS are estimated econometrically based on time series data, so information about the statistical significance of the parameters is included.

Global resource use models should consistently link monetary flows in a bilateral trade model to country or regional models on a sector level. In COMPASS and GINFORS, the country models consist of an IO model, a macroeconomic model including the System of National Accounts (SNA) and additional resource modules for energy, material flows, and land use. The trade model is based on trade matrices describing bilateral trade flows at the commodity level. It obtains from each of the countries export prices and import volumes and delivers export volumes and import prices to the country models. The IO models describe the production technology in the countries as reflected in the input structures. It delivers components of primary inputs to the SNA system, where sector information is aggregated. The SNA system describes the redistribution of income between corporations, households, government and the rest of the world. Resource use is linked to production on the sector level in every country or world region represented in the model. The whole system is consistently linked and simultaneously solved on a global level. Behavioural parameters are estimated by econometric techniques to catch country and sector specifics.

The calculation of indirect resource requirements (ecological rucksacks in terms of materials, energy and land use) of all goods – whether imported or domestically produced – and

the attribution of primary resource use to final demand of all economic sectors in all countries is then carried out by the model system according to the monetary structure of interindustry relations and international trade flows. This allows a consistent (double counting is obviated) and comprehensive (total world-wide resource extraction and land use is considered) assessment of the overall resource use of final demand for each sector in each of the countries/regions specified in the model.

Data requirements and data sources

Data requirements for constructing a global economy environment model according to the requirements presented above are enormous. Interindustry relations of monetary IO tables should be available for countries or regions with a global coverage. IO tables are especially important for those countries with different production stages and large shares in final demand. For countries exporting large shares of domestically extracted or harvested raw materials or slightly processed products (such as many OPEC countries), IO tables are not a necessary precondition, as resource use is mainly transmitted via international trade to final consumption in other countries.

International trade flows for all the countries or regions have to be available in the same or a compatible sector classification. Monetary IO tables are produced by national and international statistical offices. As national IO tables often differ in format – commodity-by-commodity versus industry-by-industry -, sector and time coverage, and classifications, they have to be harmonised for application in an international framework. Additionally, macroeconomic data has to be integrated, as monetary production and consumption are main drivers for resource use and changes of international trade patterns. If available, (already harmonised) international data sources should be used to provide high transparency of the model.

Box 1 summarises most important data sources for the building of global economic environmental models.

Box 1: Data sources for global economic environmental models

(a) Economic models

For the building of the economic models, the following components are needed: macroeconomic and monetary data, national accounts data, input-output data and data on international trade flows.

International data are provided by UN annual trade yearbooks and OECD trade statistics, IMF and World Bank provide basic macroeconomic and monetary data for almost all countries in the world, and OECD publishes more detailed national account data. Input-output tables are available from several sources. Table 1 summarises the availability of input-output tables for European countries and non-European OECD countries.

Table 1: Available input-output data for European and OECD countries

Country	EUROSTAT pp/ii 1995/2000	National pp/ii 1995 ff.	OECD pp 1990	OECD ii 1995/1997	GTAP ii
<u><i>EU OECD</i></u>					
Austria	*	*			1983
Belgium/Lux	*	*			1995
Denmark	*		*	*	1992
Finland	*			*	1995
France			*	*	1992
Germany	*	*	*	*	1995
Greece	*			*	
Ireland					1990
Italy	*		*	*	1992
Netherlands	*		*	*	1995
Portugal		*			1993
Spain	*			*	1984
Sweden	*			*	1995
United Kingdom	*	*	*	*	1990
Czech Republic		*		*	
Hungary	1998	*		*	1991/96
Poland	*	*		*	1997
Slovak Republic		*			
<u><i>EU non-OECD</i></u>					
Cyprus					
Estonia	1997				
Latvia					
Lithuania					
Malta					
Slovenia	1996				
<u><i>non-EU OECD</i></u>					
Turkey					1990
Iceland					
Norway				*	
Switzerland					1990
Canada			*	*	1990
Mexico					1995
United States		*	*	*	1992
Japan			*	*	1995
Korea				*	1995
Australia			*	*	1993/94
New Zealand				*	1992/93
<u><i>non-EU non-OECD</i></u>					
Bulgaria		*			
Romania					

* ... Input-output data available

pp ... Product-by-Product tables

ii ... Industry-by-Industry tables

Note: a year indicates the availability for a certain base year different from the other tables

The GTAP database is compiled from several different sources providing IO tables for different base years. The new GTAP 6 database that will be released at the end of the year 2004 and will contain input-output tables for 57 countries or regions, although most statistical offices have not yet published or even produced input-output tables for this year. The procedure of ad-hoc data harmonisation is therefore intransparent. The most reliable and largest harmonised data set on monetary input-output tables is published by the OECD for 14 countries on an industry by industry format for 42 harmonised sectors. Industry classification makes use of NACE, Rev 1. Time coverage ranges from 1995 up to 1998.

(b) Material input models

Concerning material input models, a number of internationally available statistics are used to compile material flow accounts in the different categories. In general, about 200 renewable and non-renewable natural resources are distinguished. Most common data sources are:

- Data on extraction of fossil fuels published by the International Energy Agency (IEA), the Industrial Commodity Statistics of the UN and the US Energy Information Administration (US EIA), which provides free download of world-wide energy tables (www.eia.doe.gov).
- Data on extraction of metal ores and industrial and construction minerals published in statistics by the British Geological Survey (BGS), in the Industrial Commodity Statistics of the UN and in freely available country and mineral reports from United States Geological Survey (USGS) (www.usgs.gov).
- Biomass extraction data published by the Food and Agricultural Organisation of the United Nations (FAO), which provides an online database for agricultural, forestry and fishery production on the national level (www.fao.org).

(c) Land use models

In addition to a number of national studies and statistics on land cover and land use, the online database of the FAO reports data on land used for different purposes (e.g. agricultural areas disaggregated into arable land, permanent crop and permanent pasture areas, forest and

wood lands and all other land). Concerning forestry areas, also more detailed studies are available, such as the “Temperate and Boreal Forest Resource Assessment (TBFRA)” reporting country data for 81 countries in North America, Europe, Asia and Oceania. TBFRA data can be downloaded from the website of the UN timber committee (www.unece.org/trade/timber/fra). Data can also be obtained from a large number of studies using a GIS (Geographical Information System) approach (see the internet page www.geo.ed.ac.uk/home/giswww for a comprehensive collection of related information sources).

5 Global resource use and policy scenario modelling

Assessing total resource use of final demand

Global multi-country and multi-sector models allow for calculating indirect material flows and land appropriation (ecological rucksacks in material and land units) and thereby provide a comprehensive assessment of *all* direct and indirect material flows (domestically extracted or imported) related to production and consumption activities. The concept behind is to use the monetary proportions as proxies for the complex physical relations behind indirect resource uses. Information concerning resource use for traded products in physical units is not necessary, as the model uses its inherent bilateral monetary trade flows for allocating physical inputs along international product chains. Resource extraction in a country is thus linked to the final demand of goods and services either in the extracting country or in any other part of the world. Obviously, the sector dimension should be the same in both the monetary IO tables and the international trade models to transmit the resource use correctly from one country to another. The system has to be closed on the world level for consistent modelling.

This procedure for assessing total resource use based on input-output modelling is a promising alternative to the life-cycle assessment (LCA)-oriented approach for calculating ecological rucksacks, which has been applied in most MFA studies published so far (for a description of this method, see Schmidt-Bleek et al., 1998). The LCA-oriented approach is mainly suitable for the calculation of resource requirements associated to biotic and abiotic raw materials and products with a low level of processing. Applying this method to calculate resource use for semi-manufactured and finished products, in particular, if several countries are part of the international production chain, requires the compilation of an enormous amount of material (and land) input data at each stage of production. This is a cost- and time-intensive undertaking and makes the definition of exact system boundaries a difficult task (see

also Joshi, 2000). One major advantage of the IO approach is therefore that it avoids imprecise definitions of system boundaries, as the entire global economic system is the scope for the analysis. Furthermore, it allows estimating total resource inputs for all types of products with less effort than the LCA-based method, as only material inputs of those economic sectors have to be assessed, which are extracting primary materials (mainly agriculture, forestry and fisheries for biotic materials, and mining and construction for abiotic materials).

Resource availability in global scenario simulations

In standard IO models, all production activities are assumed to be demand driven and supply is assumed to be perfectly elastic in all sectors. Applying this assumption to the categories of natural resource use would imply that whatever changes in production and consumption levels would be simulated in future scenarios, resource availability would never be a restricting factor. With regard to this issue, a distinction between the categories of material flows on the one hand and land use on the other hand has to be made concerning the future availability of natural resources.

If running models up to the year 2020 or 2030, it can be assumed that there will be no major resource constraints concerning material inputs for economic activities. This assumption is backed by a number of studies and policy documents, which illustrate that at least within the next 20 years, natural resources will in general not become scarce, in particular with regard to non-renewable resources (extraction of minerals and ores), as known reserves for many raw materials are growing faster than production (see, for example, European Commission, 2003). However, if growth in worldwide demand outpaces opening of new resource extraction sites (e.g. oil drillings or mines of metal ores), significant increases in prices for raw materials and fossil energy carriers can be the consequence (as currently being observed due to rapidly growing demand for natural resources in particular in China). Furthermore, for some renewable resources (such as marine fish and timber), scarcity will be an increasingly serious problem to be addressed by policy makers already in the next few decades (for example, EEA, 2003).

Land availability obviously is a limiting factor for future global development (see Wackernagel and Rees, 1996), even within a relatively short time horizon such as up to 2020. Clearly, it cannot be assumed that certain sectors will expand or shrink their land requirements in proportion to changes in demand and output, due to restriction of land availability or land use regulations. Unmodified land multipliers used in the different country models could thus deliver unrealistic results. A much more appropriate assumption is that land use will actually restrict future economic activities. Consequently, land use models used in global econ-

omy environment models have to be adapted in order to include supply restrictions, which could be even completely inelastic for some of the economic sectors. Increase in demand will then have to be met by increased output in non-restricted sectors or by imports from other countries. These restrictions are important factors for the evaluation of future scenarios of land use (see Hubacek and Sun, 2001 for a land-related IO simulation study on China).

Policy scenarios toward a sustainable use of natural resources

Global integrated sustainability models allow a comprehensive quantification of the use of natural resources (scale) in terms of material flows and land appropriation, including “ecological rucksacks” induced by international trade flows in other regions of the world. Time series of this analysis reveals, whether or not a tendency towards re-location of resource intensive production from rich countries towards the global South can be observed. Thus it can be analysed, whether the process of relative dematerialisation, which can be observed in industrialised countries, is going along with a dematerialisation of imported products or whether Northern dematerialisation is connected to a “re-materialisation” in other world regions, as some empirical studies suggest (Fischer-Kowalski and Amann, 2001; Giljum, 2004; Schütz et al., 2004). By doing so, comprehensive indicators on resource use can be provided, which extend and update existing indicators of resource use (as published for example for the European Union, Bringezu and Schütz, 2001) and add the dimension of land use, for which no comprehensive indicators (including “embodied” land appropriation of traded goods) have been calculated so far.

Second, this research allows accounting for and analysis of the economic sectors (industries) and world regions/countries by which these resource flows are activated. Thus, inter-linkage indicators, such as resource productivities and labour intensity of resource use of sectors of economies and their changes over time can be calculated. Furthermore, the role of domestic and total material inputs for growth potentials and job creation can be analysed and economic policy strategies identified, which could facilitate a reduction of resource use in an economically efficient way. Recent studies (see Fischer et al., 2004 for a simulation study with an integrated IO model for Germany) revealed that there exist high potentials for economically profitable resource savings even under current policy regulations and at prevailing price levels.

Third, global resource use models can be applied for analysing different questions regarding the interrelations of technological change, consumption behaviour (lifestyles) and international production and trade patterns. Changing final demand components in a country or a group of countries can help calculating the global resource elasticity of a specific compo-

ment of final demand. For example, a 10% increase in private car expenditures in the USA has various impacts on the resource extraction in the USA and worldwide. Relations may change over time due to changes in life-style (consumer demand shifts to low weight cars), due to changes in the production process (steel may be substituted by plastics) as relative prices change, due to changes in import shares either in intermediate inputs (steel from Germany instead of Korea) or final demand (Japanese cars instead of US cars) and due to changes in other countries in resource extraction or production of intermediate inputs (adapting US production technologies and reduce resource use). All these possible changes may be driven by technical change, changing consumption patterns or policy measures. These three drivers of potential resource use decrease can be included into global resource use models: Technology transfer may take place between countries due to spill-over effects. Technology transfers can be modelled via changing input structures in an economy that may shift towards the input structures in the technologically leading economies. Changes in consumption patterns may also be influenced by experiences in other countries, which may be a target for policy measures. Changes of relative prices due to policy measures in some or a group of countries may also change trade flows. Of course, leakage effects (such as an increasing substitution of domestic production in polluting sectors by imports) are possible, that could countervail decreasing resource use in a country. Therefore, different policy options have to be tested.

Finally, and most importantly from the policy perspective, global resource use models can be used to simulate and evaluate sustainability scenarios. These scenarios can illustrate potential impacts of key environmental policy measures (e.g. ecological tax reform, reform of the subsidy system, flexible mechanisms within the Kyoto Protocol) for socio-economic indicators as well as for the use of natural resources in different world regions. Scenario evaluation can explore opportunities as well as barriers and limits for restructuring economies towards a more sustainable development path, giving special emphasis on potentials for technological changes for supporting these restructuring processes. In particular, possibilities for decoupling economic growth from environmental pressures can be identified on a country and sector-specific level. Based on scenario evaluation covering the economic, environmental and social dimension, policy strategies and actions capable for reconciling long-term economic development and competitiveness with social cohesion and environmental protection requirements can be elaborated, in order to suggest formulated and tested best policy tools to realise the implementation of sustainability strategies.

6 Conclusions

This chapter consisted of three main parts. In the first part, the methodological foundations for extending monetary input-output models with physical accounts with regard to material flows and land appropriation were presented. It was illustrated that extended IO analysis provides a powerful and innovative framework for parallel analyses of material flows and land use on the level of economic sectors. This allows calculating total (direct and indirect) resource requirements of final demand and addressing important questions such as trade offs between sustainability goals of material dematerialisation and de-intensification of land use. In the second part, we summarised the state of the art and necessary properties of global resource use models and most important data sources for constructing economic IO models as well as material input and land use models in physical units. We argued that proper modelling requires time series of deeply disaggregated economic data with regard to the number of countries, the different industries, and the international trade flows, in order to allow a proper estimation of resource requirements along international production chains. In the final part we discussed empirical policy applications of this integrated modelling approach with regard to sustainability assessments on the global level. Comprehensive economic-environmental IO model systems are in particular suited to perform scenario simulation of the environmental and socio-economic effects of the implementation of environmental policy measures. Thus, policy strategies and instruments can be tested and elaborated, which are capable of best reconciling competing policy goals in economic, social and environmental policies.

References

- Adriaanse, A., Bringezu, S., Hamond, A., Moriguchi, Y., Rodenburg, E., Rogich, D., Schütz, H. 1997. *Resource Flows: The Material Base of Industrial Economies*. World Resource Institute, Washington.
- Almon, C. 1991. The INFORUM Approach to Interindustry Modelling. *Economic Systems Research* 3 (1), 1-7.
- Amann, C., Bruckner, W., Fischer-Kowalski, M., Grünbühel, C. 2002. *Material flow accounting in Amazonia. A tool for sustainable development*. Working Paper. No. 63. IFF Social Ecology, Vienna.
- Ayres, R. 1989. *Industrial metabolism*. In: Ausubel, J. (Ed.) *Technology and Environment*. National Academy Press, Washington, D.C.
- Bailey, R., Allen, J.K., Bras, B. 2004. Applying Ecological Input-Output Flow Analysis to Material Flows in Industrial Systems. Part I: Tracing Flows. Part II: Flow Metrics. *Journal of Industrial Ecology* 8 (1-2), 45-91.
- Behrensmeier, R., Bringezu, S. 1995. *Zur Methodik der volkswirtschaftlichen Material-Intensitäts-Analyse. Ein quantitativer Vergleich des Umweltverbrauchs der bundesdeutschen Produktions-sektoren*. Wuppertal Paper. No. 34, Wuppertal.

- Bicknell, K.B., Ball, R.J., Cullen, R., Bigsby, H.R. 1998. New methodology for the ecological footprint with an application to the New Zealand economy. *Ecological Economics* 27 (2), 149-160.
- Bringezu, S., Behrensmeier, R., Schütz, H. 1998. Material flow accounts indicating environmental pressure from economic sectors. In: Uno, K., Bartelmus, P. (Eds.) *Environmental Accounting in Theory and Practice*. Kluwer Academic Press, Hingham.
- Bringezu, S., Fischer-Kowalski, M., Klein, R., Palm, V. 1997. *Regional and National Material Flow Accounting: From Paradigm to Practice of Sustainability*. Leiden.
- Bringezu, S., Schütz, H. 2001. Total material requirement of the European Union. Technical Report No. 55. European Environmental Agency, Copenhagen.
- Chen, X., Qiao, L. 2001. A Preliminary Material Input Analysis of China. *Population and Environment* 23 (1), 117-126.
- Daniels, P.L., Moore, S. 2002. Approaches for Quantifying the Metabolism of Physical Economies. Part I: Methodological Overview. *Journal of Industrial Ecology* 5 (4), 69-93.
- Ecological Economics*. 2000. Special Issue: Ecological Footprint. *Ecological Economics* 32.
- Eder, P., Narodoslowsky, M. 1999. What Environmental Pressures are a Region's Industries Responsible for? A Method of Analysis with Descriptive Indices and Input-Output Models. *Ecological Economics* 29 (3), 359-374.
- EEA. 2003. Europe's environment. The third assessment. Environmental assessment report. No. 10. European Environment Agency, Copenhagen.
- European Commission. 2001a. On the sixth environmental action programme of the European Community - Environment 2010 - Our future, our choice. COM (2001) 31 final. European Commission, Brussels.
- European Commission. 2001b. A Sustainable Europe for a Better World: A European Union Strategy for Sustainable Development. The Commission's proposal to the Gothenburg European Council. European Commission, Brussels.
- European Commission. 2003. Towards a thematic strategy for the sustainable use of natural resources. COM(2003) 572 final. DG Environment, Brussels.
- EUROSTAT. 2001. Economy-wide material flow accounts and derived indicators. A methodological guide. Statistical Office of the European Union, Luxembourg.
- EUROSTAT. 2002. Material use in the European Union 1980-2000: indicators and analysis. Statistical Office of the European Union, Luxembourg.
- Femia, A. 1996. Input-output analysis of material flows: an application to the German economic system for the year 1990. *Quaderni di ricerca*. No. 82. Università di Ancona, Ancona.
- Ferng, J.-J. 2001. Using composition of land multiplier to estimate ecological footprints associated with production activity. *Ecological Economics* 37 (2), 159-172.
- Fischer, G., Shah, M., van Velthuisen, H. 2002. *Climate Change and Agricultural Vulnerability*. Institute for Applied Systems Analysis (IIASA), Vienna.
- Fischer, H., Lichtblau, K., Meyer, B., Scheelhaase, J. 2004. Wachstums- und Beschäftigungsimpulse rentabler Materialeinsparungen [Growth and employment impulses of profitable material savings]. *Wirtschaftsdienst* 84 (4), 247-254.
- Fischer-Kowalski, M. 1998. Society's Metabolism. In: Redclift, G., Woodgate, G. (Eds.) *International Handbook of Environmental Sociology*. Edward Elgar, Cheltenham.
- Fischer-Kowalski, M., Amann, C. 2001. Beyond IPAT and Kuznets Curves: Globalization as a Vital Factor in Analysing the Environmental Impact of Socio-Economic Metabolism. *Population and Environment* 23 (1), 7-47.

- Giljum, S. 2004. Trade, material flows and economic development in the South: the example of Chile. *Journal of Industrial Ecology* 8 (1-2), 241-261.
- Giljum, S., Behrens, A., Hammer, M., Hinterberger, F., Kovanda, J., Niza, S. 2004. The material basis of the global economy. Presentation of data and implications for sustainable resource use policies in North and South. Presentation at the 2004 ConAccount Workshop, ETH Zurich.
- Giljum, S., Eisenmenger, N. 2004. North-South trade and the distribution of environmental goods and burdens: a biophysical perspective. *Journal of Environment and Development* 13 (1), 73-100.
- Hammer, M., Hubacek, K. 2002. Material flows and economic development. Material flow analysis of the Hungarian economy. Interim Report. No. 02-057. International Institute for Applied Systems Analysis (IIASA), Laxenburg.
- Hans-Böckler-Stiftung (ed) 2000. Work and Ecology. Final Project Report. Hans-Böckler-Stiftung, Düsseldorf.
- Hertel, T.W. 1997. *Global Trade Analysis, Modelling and Applications*, Cambridge.
- Hinterberger, F., Aldo, F., Renn, S. 1999. Economic Growth with Less Material Input?. De-composing the Empirical Trend of De-Linking. *Nature, Society and History. Long Term Dynamics of Social Metabolism*, Wien.
- Hinterberger, F., Moll, S., Femia, A. 1998. Arbeitsproduktivität, Ressourcenproduktivität und Ressourcenintensität der Arbeit. Graue Reihe des Instituts für Arbeit und Technik. No. 1998-02. Wuppertal Institut für Klima, Umwelt, Energie, Wuppertal.
- Hinterberger, F., Omann, I., Stocker, A. 2002. Employment and Environment in a Sustainable Europe. *Empirica* 29, 113-130.
- Hubacek, K., Giljum, S. 2003. Applying physical input-output analysis to estimate land appropriation (ecological footprints) of international trade activities. *Ecological Economics* 44 (1), 137-151.
- Hubacek, K., Sun, L. 2001. A scenario analysis of China's land use and land cover change: incorporating biophysical information into input-output modelling. *Structural Change and Economic Dynamics* 12 (4), 367-397.
- Joshi, S. 2000. Product environmental life-cycle assessment using input-output techniques. *Journal of Industrial Ecology* 3 (2 & 3), 95-120.
- Kleijn, R., Bringezu, S., Fischer-Kowalski, M., Palm, V. 1999. *Ecologizing Societal Metabolism. Designing Scenarios for Sustainable Materials Management*. CML Report 148, Leiden.
- Lange, G.-M. 1998. Applying an integrated natural resource accounts and input-output model to development planning in Indonesia. *Economic Systems Research* 10 (1), 113-134.
- Leontief, W., Koo, J., Nasar, S., Sohn, I. 1982. The production and consumption of non-fuel minerals to the year 2030 analyzed within an input-output framework of the U.S. and world economy. NSF/CPE-82002. National Science Foundation, Washington, DC.
- Matthews, E., Bringezu, S., Fischer-Kowalski, M., Huettler, W., Kleijn, R., Moriguchi, Y., Ottke, C., Rodenburg, E., Rogich, D., Schandl, H., Schuetz, H., van der Voet, E., Weisz, H. 2000. *The weight of nations. Material outflows from industrial economies*. World Resources Institute, Washington.
- McDonald, G.W., Patterson, M.G. 2004. Ecological Footprints and interdependencies of New Zealand regions. *Ecological Economics* 50 (1), 49-67.
- Meyer, B., Bockermann, A., Ewehardt, G., Lutz, C. 1998. Modellierung der Nachhaltigkeitslücke: eine umweltökonomische Analyse. In: Müller, W., Bihn, M. (Eds.) *Umwelt und Ökonomie*. Vol. 26, Heidelberg.
- Meyer, B., Lutz, C., Wolter, I. 2003. *Global Multisector/Multicountry 3 - E Modelling From COM-PASS to GINFORS*. Osnabrück & Berlin.

- Meyer, B., Lutz, C., Wolter, M.I. 2004. Economic Growth of the EU and Asia. A first Forecast with the Global Econometric Model GINFORS. 26. Keio-University, Tokyo.
- Meyer, B., Uno, K. 1999. COMPASS - Ein globales Energie-Wirtschaftsmodell. ifo Studien 4, 703 - 719.
- Miller, R.E., Blair, P.D. 1985. Input-Output Analysis: Foundations and Extensions. Prentice-Hall, Englewood Cliffs, New Jersey.
- Moll, S., Acosta, J., Villanueva, A. 2004. Environmental implications of resource use – insights from input-output analyses. European Environment Agency, Copenhagen.
- Moll, S., Bringezu, S., Femia, A., Hinterberger, F. 2002. Ein Input-Output-Ansatz zur Analyse des stofflichen Ressourcenverbrauchs einer Nationalökonomie. Ein Beitrag zur Methodik der volkswirtschaftlichen Materialintensitätsanalyse. In: Hinterberger, F., Schnabl, H. (Eds.) Arbeit-Umwelt-Wachstum. Nachhaltigkeitsaspekte des sektoralen Strukturwandels. Book on Demand, Norderstedt.
- Mündl, A., Schütz, H., Stodulski, W., Sleszynski, J., Welfens, M. 1999. Sustainable Development by Dematerialization in Production and Consumption - Strategy for the New Environmental Policy in Poland. Report 3. Institute for Sustainable Development, Warsaw.
- Muradian, R., Martinez-Alier, J. 2001. Trade and the environment: from a 'Southern' perspective. Ecological Economics 36 (2), 281-297.
- OECD. 2004. Recommendation on material flows and resource productivity. Adopted by the OECD Council on 21 April 2004. No. OECD, Paris.
- Opschoor, J.B. 1995. Ecospace and the fall and rise of throughput intensity. Ecological Economics 15, 137-141.
- Scasny, M., Kovanda, J., Hak, T. 2003. Material flow accounts, balances and derived indicators the Czech Republic during the 1990s: results and recommendations for methodological improvements. Ecological Economics 45 (1), 41-57.
- Schandl, H., Eisenmenger, N. 2004. Global Resource Extraction. Poster presented at the 8th International Conference of the International Society for Ecological Economics (ISEE), Montreal.
- Schmidt-Bleek, F. 1994. Wie viel Umwelt braucht der Mensch ? MIPS – das Maß für ökologisches Wirtschaften. Birkhauser, Berlin, Basel.
- Schmidt-Bleek, F., Bringezu, S., Hinterberger, F., Liedtke, C., Spangenberg, J., Stiller, H., Welfens, M. 1998. MAIA. Einführung in die Materialintensitätsanalyse nach dem MIPS-Konzept. Birkhauser, Berlin, Basel.
- Schütz, H., Bringezu, S., Moll, S. 2004. Globalisation and the shifting environmental burdens. Material trade flows of the European Union. Wuppertal Institute, Wuppertal.
- Spangenberg, J., Bonnoit, O. 1998. Sustainability Indicators - A Compass on the Road towards Sustainability. Wuppertal Paper. No. 81, February 1998, Wuppertal.
- Spangenberg, J., Omann, I., Hinterberger, F. 2002. Sustainable growth criteria. Minimum benchmarks and scenarios for employment and the environment. Ecological Economics 42, 429-443.
- Statistisches Bundesamt. 2002. Ergebnisse der umweltökonomischen Gesamtrechnungen zur Bodennutzung durch wirtschaftliche Aktivitäten. Statistisches Bundesamt, Wiesbaden.
- United Nations. 2003. Integrated environmental and economic accounting 2003. United Nations, New York.
- Uno, K. 2002a. Economy- Energy- Environment. Beyond the Kyoto Protocol, Dordrecht, Boston, London.
- Uno, K. 2002b. Energy Projections: Comparison of Methodologies. In: Uno, K. (Ed.) Economy-Energy-Environment Simulation: Beyond the Kyoto Protocol, Dordrecht, Boston, London.

- Wackernagel, M., Rees, W. 1996. Our Ecological Footprint: Reducing Human Impact on the Earth. New Society Publishers, Gabriola Island, British Columbia.
- WWF, UNEP, Global Footprint Network. 2004. Living Planet Report 2004. WWF, Gland, Switzerland.