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

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Abstract

Material flow accounting and analysis (MFA) and land use accounting (LUA) are regarded as one of the most appropriate tools to provide a comprehensive picture of environmental pressures induced by and inter-linked with production and consumption activities. Due to the accelerating globalisation process, an evaluation of economic activities of one country or world region within a global context can only be carried out by extending the domestic physical accounts and including so-called indirect resource requirements associated to imports and exports. A promising method for calculating indirect requirements with regard to both material flows and land use on the macro level is to apply input-output (IO) analysis, which allows the comprehensive accounting of resource inputs activated by final demand. Concerning monetary input-output models, a few model systems have been presented, which are closed on the world level, thus covering not only all national economic activities, but also all monetary transactions related to international trade. One of the most elaborated global input-output model system has been presented under the abbreviation of GINFORS (Global interindustry forecasting system). In the course of an ongoing EU research project, the GINFORS model will be extended by sectorally disaggregated material input and land use data. This integrated economic-environmental model will then calculate “ecological rucksacks” of traded goods in terms of both material flows and land appropriation. This approach allows the comprehensive assessment of *all* resource inputs (domestically extracted and imported) related to production and consumption activities of a country or world region. Furthermore, this integrated model enables the formulation and evaluation of resource use scenarios and the quantification of potential impacts of economic and environmental policy measures on the use of natural resources.

Keywords: input-output modelling, international trade, land use accounting, material flow accounting and analysis, resource use indicators, sustainability assessments

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 last 15 years, several approaches have been developed that provide this information in biophysical terms (see Daniels and Moore, 2002 for a recent overview). These methods of physical accounting proved to be appropriate tools 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 (United Nations, 2003), material flow accounting and analysis (MFA) and land use accounting are regarded as one of the most appropriate tools to provide a comprehensive picture of environmental pressures induced by and inter-linked with the production and consumption of a country or a region.

High levels of resource use and the resulting high amounts of waste and emissions’ release to the natural system is in many policy documents of the EU addressed as one major obstacle for the realisation of an environmentally sustainable development. The sustainable management of natural and environmental 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, 2001). De-coupling (or de-linking) economic growth from the use of natural resources and environmental degradation is regarded 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, 2002).

The European Council recently agreed on a “European Strategy for Sustainable Development” (European Council, 2001). Therein the European Council states that production and consumption activities within the EU borders have impacts on other parts of the world and increase the pressure on the environment (particularly in so-called developing countries). Thus the links between trade and environment 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 ecological consequences of their production and consumption processes to other parts of the world (Muradian and Martinez-Alier, 2001; Rothman, 1998).

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 (Bringezu et al., 1994; 1998). The declining material use per unit GDP in countries of the western hemisphere (“relative dematerialisation”) (Adriaanse et al., 1997; EUROSTAT, 2002) does not automatically lead to lower overall consumption of material-intensive goods, but results to some extent from higher imports of these products from “developing” countries (Giljum and Eisenmenger, 2004; Muradian and Martinez-Alier, 2001). 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 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 paper has two main goals: (a) providing the methodological foundations for performing parallel analyses of material flows and land appropriation of economic activities within a framework of monetary input-output models and (b) presenting policy applications of this integrated modelling approach with regard to sustainability assessments on the global level.

The paper is structured as following: Section 2 introduces the basic concept of material flow accounting and analysis (MFA) and land use accounting (LUA). Section 3 presents the detailed methodological description of linking resource input data to monetary IO models on the national level, covering both material flows and land use. Section 4 describes the main applications of this approach for empirical policy-oriented assessments, taking the example of *MOSUS*, an ongoing research project under the 5th Framework Programme of the European Union. Section 5 contains the conclusions.

2 The basic concepts of MFA and LUA

2.1 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 (Adriaanse et al., 1997; Bringezu et al., 1997; Kleijn et al., 1999; Matthews et al., 2000). In an international working group on MFA, standardization for economy-wide material flow accounting was for the first time achieved and published in a methodological guidebook by the European Statistical Office (EUROSTAT, 2001).

The main purposes of economy-wide material flow accounts and balances are to provide insights into structure and change over time of the physical metabolism of economies; to derive a set of aggregated indicators for resource use; to provide indicators for the material intensity of lifestyles, by relating aggregate resource use indicators to population size and other demographic indicators; to permit analytical uses, including estimation of material flows and land use induced by imports and exports as well as decomposition analyses separating technological, structural and final demand changes.

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 (Africa, Asia excluding Japan, and Latin America), economy-wide MFAs have been presented for Brazil and Venezuela (Amann et al., 2002), Chile (Giljum, forthcoming) as well as for China (Chen and Qiao, 2001).

2.2 Land use accounting (LUA)

It is generally agreed among scientists that – 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). Land use and land cover accounts are also one of the core natural resource accounts in the *System of Integrated Environmental and Economic Accounts (SEEA)* of the United Nations (United Nations, 2003). Changes in land use and land cover are also among the issues central to the study of global environmental change. In addition to their cumulative long-term global dimensions, such changes can have profound regional environmental implications during the life span of current generations, such as reduced biodiversity, reduced land productivity due to soil degradation, problems of land and water contamination, and the lowering of groundwater tables.

The most influential physical accounting method focusing on land appropriation has been introduced by Rees and Wackernagel at the beginning of the 1990s (Rees and Wackernagel, 1992) and is generally referred to as the ecological footprint (EF). The EF can be defined as the total land and water area required to support a population with a specific lifestyle and given technology with all necessary natural resources and to absorb all their wastes and emissions for an indefinite length of time (Wackernagel and Rees, 1996). Thus the EF is an instrument to perform natural capital assessments on the national level (Wackernagel et al., 1999). Concerning the method, the calculation of the EF is in general not based on actual land use or land cover 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. For all OECD and many of the newly industrialising countries (NICs), the largest share of the EF is made up by the land areas “reserved” for CO_2 sequestration. This category illustrates the hypothetical land that would be required to absorb the CO_2 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 (see, for example,van den Bergh and Verbruggen, 1999), such as the aggregation of actual appropriated land areas with hypothetical land areas to the total EF of a country, which hides problems related to scarcity of actual used land. Furthermore, the method of converting mass units into land areas is only feasible for biotic products (agricultural, forestry or fishery products), as for these categories productivity data is easily available. There is no possibility for directly converting other products, like abiotic raw materials or semi-manufactured and manufactured products into land equivalents, as data on the land intensity of production of these goods is not yet available. Furthermore, the land appropriation of the service sector cannot be included in this kind of calculation. Finally, the EF approach does not take the same system boundaries as the MFA concept, and thus cannot be directly related to other economic and social indicators derived from the System of National Accounts.

For all these reasons, in our opinion, a more suitable approach for including land use aspects in physical accounts is to use land cover data, available from land use statistics (for example, Statistisches Bundesamt, 2001b) or from Geographical Information Systems (GIS) (for example, EEA 2000). A parallel but separate analysis of the two categories of material flows and land use reduces the communicability of information by increasing complexity.

However, problems connected to the conversion of one category into the other and the related loss of information are avoided, which significantly increases scientific transparency and credibility of the approach (Spangenberg et al. 1999).

In some European countries, such as Germany, land use accounts have been presented disaggregated according to classifications of economic use (such as transport, housing, agriculture, industrial production, etc., see Statistisches Bundesamt, 2002).

Concerning indicators, land use has been proposed as an indicator by different institutions including UNDSD (1998), but so far no quantitative measure has been internationally accepted. A semi-quantitative approach has been suggested by Spangenberg (2003), based on a qualitative hierarchy of use intensities resulting in decreasing environmental quality. It consists of an ordinal scale of four classes, from human made via controlled and cultivated to natural, human protected areas. The purpose of this suggested system of land use classification is to derive a dynamic description of annual shifts from one category to the other, alerting decision makers and focussing political action on the most worrying trends. In this sense, the proposed system goes beyond static state indicators and even comparative static time series, offering a tool for monitoring the large scale trends of land use dynamics.

3 Assessment of total resource use with extended input-output (IO) analysis

Two main approaches for assessing total resource requirements of production and consumption activities can be distinguished. In most MFA studies published so far, this calculation was carried out by a simplified life cycle assessment (LCA) of products or product groups, following a method that has been developed at the Wuppertal Institute (WI) in Germany. The so-called “Material Intensity Analysis (MAIA)” (Schmidt-Bleek et al., 1998) is an analytical tool to assess material inputs along the whole life cycle of a product, including its so-called “ecological rucksacks” (Schmidt-Bleek, 1992). At present, the WI is the most important source for data on indirect flows of traded products (Bringezu, 2000; Bringezu and Schütz, 2001b). This 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 requires the compilation of an enormous amount of material 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). Therefore, total resource requirements have only been estimated for a very small number of finished products.

An alternative and, to our view, promising method for calculating natural resource use on the macro level is to apply input-output (IO) analysis, which allows the comprehensive accounting of direct and indirect resource requirements activated by final demand. One major advantage of this approach compared to the LCA-oriented approach is that it avoids imprecise definitions of system boundaries, as the entire economic system is the scope for the analysis (Matthews and Small, 2001).[1]

IO-analysis in monetary terms has been introduced by Leontief and carried out for economic studies since the 1930s (Leontief, 1936). Since the late 1960s input-output methods have also been used to describe and analyse the economy-environment relationship.

One of the most important applications of input-output analysis is the calculation of total input requirements for a unit of final demand. By doing so, one can assess not only the direct requirement in the production process of the analysed sector itself, but also all indirect requirements resulting from intermediate product deliveries from other sectors. Thus the total (direct and indirect) input necessary to satisfy final demand (e.g. private consumption, exports) can be determined (Miller and Blair, 1985). The methodological handbook for economy-wide material flow accounting (EUROSTAT, 2001) also demands for the further development of IO-based approaches for calculating indirect flows associated to imports and exports.

3.1 Monetary versus physical input-output tables

Input-output calculations of resource use can be based on both monetary (MIOTs) and physical input-output tables (PIOTs). Which unit to use (monetary or physical) is a question of the purpose of analysis and of the availability of respective data.

Using a PIOT, the calculation of indirect resource requirements through the attribution of direct and indirect resource inputs to the different categories of final demand follows the physical structure of the economy, which differs substantially from the monetary structure (Giljum et al., 2004; Hubacek and Giljum, 2003). Calculations based on PIOTs can thus provide insights into the direct physical interrelations between economic actors (firms, sectors, countries) and the *physical* responsibilities for environmental pressure.

However, this approach of physical causality is not suited to assess *socio-economic* responsibilities for the activation of primary resource inputs. This is due to several reasons. First, allocation following direct physical flows assumes physical causality, which is prob-

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[1] Also within the LCA community, integrated environmental-economic IO analysis is increasingly recognised as a cost-effective and time extensive alternative to traditional LCA methods (see, for example, Hendrickson et al., 1998; Matthews and Small, 2001; Nielsen and Weidema, 2001).

lematic in situations of co-production and co-treatment. To give a concrete example, suppose that the overburden of gold mining is sold to the construction industry, at a much lower value than the gold but in much higher physical quantities. According to physical causality, the responsibility of the extraction is to significant extent allocated to overburden and not to gold, which weight is much lower. From an economic point of view this procedure could be misleading, since the overburden was a by-product of the gold mining process. Allocation according to monetary value follows socio-economic causality, which provides a more realistic picture of the causes and responsibilities of the *economic* process (Rodrigues et al., forthcoming). Second, direct physical flows pose a methodological problem to allocation not present to monetary flows, due to the existence of waste of production, the possibility of waste treatment and recycling, and the fact that in PIOTs presented so far waste from production is not distinguished from waste from consumption (Giljum and Hubacek, forthcoming; Rodrigues and Giljum, 2004). Finally, a main obstacle to a broad application is the lack of data, as PIOTs have only been compiled for a few European countries and thus no multi-country model systems in physical units have been presented so far. For the global questions to be addressed in this paper, we therefore follow an approach to extend monetary IO tables with biophysical data.

3.2 Extending national monetary IO models with material input data

First studies, which calculated resource productivities of different sectors disaggregated in monetary input-output tables and estimated 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 economy. 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., 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 environmental implications of policy goals stated in Indonesia’s national development plan.

The first application of IO analysis of material flows using an international IO model system will be realised in the *MOSUS* project (see Section 4 below).

The starting point for an explanation of the basic calculation procedure[2] (see also Hinterberger et al., 1998) is the following illustration of a monetary input-output table (MIOT):

Table 1: Simplified monetary input-output table (MIOT), including extension by an additional row of physical inputs

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

Total inputs (x') consist of inputs from other industries (Z), value added (v'), and imports (m'):

$$x' = Z + v' + m' \tag{1}$$

and total outputs (x) are deliveries to other economic sectors (Z) and to final demand (y), which can be either domestic (d) or exports (e):

$$x = Z + y \tag{2}$$

with $y = d + e$.

From this monetary flow table, one can derive the matrix of (technical) input-output coefficients by dividing the flow matrix of interindustry deliveries with total output:

$$a_{ij} = z_{ij}/X_j \; . \tag{3}$$

The technical coefficients illustrate the share of inputs from each of the sectors necessary for the production of one unit of sectoral output. Subtracting this *A*-matrix from the iden-

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[2] A more detailed calculation procedure is presented in Moll et al. (2002). This approach on the one hand distinguishes domestic material extraction for intermediate use from domestic material extraction, which directly enters final demand (e.g. private harvest of vegetables and fruits). On the other hand, imports are divided in imports for intermediate use and imports for final demand, respectively.

tity matrix *(I)* delivers the *(I-A)* matrix; its inverse form is generally referred to as the Leontief Inverse Matrix or monetary multiplier matrix (*M*).

(4) $$M = (I - A)^{-1}$$

The multiplier matrix shows which intermediate products are indirectly required to fulfil the demand for one additional unit of final demand. The general equation for the static input-output model then is

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

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 products[3]) to this input-output model requires that the inputs in physical units (in the case of material: 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 output of each sector (X_j) leads to a vector of sectoral input coefficients (C_i). In the case of material flows, this vector shows the material input required to produce one unit of (monetary) output of this sector:

(6) $$C_j = R_j / X_j$$

with C_j: Material input coefficient of sector j,
R_j: Material input for sector j,
X_j: Total (monetary) output of sector j.

The matrix of the extended Leontief inverse matrix or weighted multiplier matrix M_w is finally calculated by post-multiplying the diagonal vector of sectoral material input coefficients ($\hat{c}$) with the Leontief inverse matrix. Hereby we get the multiplier matrix, weighted by material input coefficients:

(7) $$M_W = \hat{c}\ (I - A)^{-1}$$

with M_w: Weighted multiplier matrix,

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[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, delivering an attribution of the indicator of *Total Material Requirement (TMR)* to final demand.

$\hat{c}$: 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, and to attribute these inputs to the different categories in a sectoral disaggregated form, one multiplies the weighted multiplier with final demand *(y)*. In our example, this is carried out for the vector of domestic demand (*d*) as well as for exports (*e*).

(8) $r^d = M_W * d$ 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 $r^d + r^e = r$

r^d and r^e finally illustrate the direct and indirect material inputs necessary to satisfy final demand in the categories of domestic consumption and exports. r^d and r^e sum up to total material input (r).

Material input data generally is compiled in a disaggregated way, distinguishing between major categories of material flows (for example, biomass extraction, extraction of minerals and ores, extraction of fossil fuels) and a large number of different material flows within each of these categories. This detailed information can be 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 can be related to different environmental problems (e.g. climate change; toxic pollutants, etc.) (see also Konijn et al., 1997).

3.3 Extending national monetary IO models with land use data

In the last years, several studies relating input-output analysis to land use accounting were presented (Bicknell et al., 1998; Eder and Narodoslawsky, 1999; Ferng, 2001; Hubacek and Giljum, 2003; Hubacek and Sun, 2001). This approach proved to be a useful tool for the calculation of directly and indirectly appropriated land areas of production and consumption processes and was discussed as one possible further development of *ecological footprint* calculations.

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.[4] 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. Equation 9 shows the land input coefficient for sector *j*:

$$C_j = L_j / X_j \tag{9}$$

with C_j: Land input coefficient of sector *j*,

L_j: Land input for sector *j*,

X_j: Total (monetary) output of sector *j*.

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 (in our example, domestic demand and exports):

$$l^d = M_W * d \text{ and } l^e = M_W * e \tag{10}$$

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 $l^d + l^e = 1$

In parallel to the category of material flows, the sectoral land input vector can 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.

3.4 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

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[4] 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, data on embodied land inputs for traded products so far is almost entirely missing (see Giljum and Hubacek, 2001; Hubacek and Giljum, 2003).

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 has been discussed (Schmidt-Bleek 1994). This procedure was intended to follow the approach of "MIPS" (material intensity per service unit) 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 for the first time allows the parallel analysis of these two categories within a consistent and comprehensive framework. One possible application of this approach is to perform parallel analysis of resource intensities and land intensities of different economic sectors. This type of analysis could clarify, whether the most material intensive sectors are also the sectors with the highest intensity of land use. Thus, the land-use intensity of resource use and vice versa can be determined and (changes in) resource productivities can be compared to (changes in) land-use intensity. Furthermore, possible trade-offs between reductions of material intensity and land intensity, respectively, could be identified. Finally, it could be discussed, whether land intensity could be one possible criterion to evaluate different types of material flows.

Both methods (and therefore the parallel calculation of resource-use and land-use) can be broken down into different types, categories or qualities of material/land use and thereby present much more detailed and complex pictures as long as necessary data is available for the relevant countries, regions and sectors.

Another possible extension off 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. For example, 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.[5]

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[5] 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 Modelling global resource use: the *MOSUS* project

Concerning monetary input-output models, a few model systems have been presented, which are closed on the world level, thus covering not only all national economic activities, but also all monetary transactions related to international trade. One of the most elaborated global input-output model system has been presented by Meyer et al. (2003) under the abbreviation of GINFORS (Global interindustry forecasting system; former known as the COMPASS model). This model system originally distinguished 66 countries/regions and, depending on the type of country model, up to 36 economic sectors. The basic structure of the model can be envisioned as a wheel, in which the bilateral trade models are the axis. The spokes are the country models, which always consist of a macro model and for most OECD and APEC countries of an input-output model and an energy model. The tyre represents the linkage of the countries via the global equality of savings and investments.

In the research project *MOSUS* ("Is Europe sustainable? MOdelling opportunities and limits for restructuring Europe towards SUStainability"), funded by the 5th framework programme of the European Union (see *www.mosus.net* for details on this project), the GINFORS model system will be updated and extended by material input and land use data for all countries / regions covered by the GINFORS model. This integrated economy-environmental model system will then be used to simulate sustainability scenarios formulated for Europe's development until 2020 (see Section 4.3 below). Thus, the *MOSUS* project is the first to relate total resource use (comprising material flows and land use) to socio-economic indicators, e.g. growth and employment, in a truly global (multinational and multi-sectoral) view.

4.1 Extending the GINFORS model system with biophysical input data

Using the GINFORS model system for calculating indirect material flows and land appropriation (ecological rucksacks in material and land units) allows the comprehensive assessment of *all* direct and indirect material flows (domestically extracted or imported) related to production and consumption activities with less effort and higher consistency than applying the LCA-based method.

Less effort results from the fact that only material inputs of those economic sectors have to be collected, which are extracting primary materials (mainly agriculture, forestry and fisheries for biotic materials, and mining and construction for abiotic materials). Information concerning material and land inputs for traded products in physical units is not necessary, as the model uses its inherent bilateral monetary trade models for allocating physical inputs along international product chains. Higher consistency is a consequence of the fact that with the IO-based approach imprecise definitions of system boundaries are avoided, as the entire economic system is the scope for the analysis (see above).

The calculation of indirect resource requirements (ecological rucksacks) of all goods (whether domestically consumed or imported) and the attribution of primary material and land inputs to final demand of all economic sectors is then carried out by the GINFORS model according to the monetary structure of interindustry deliveries and cross-country trade flows. This allows a sectorally disaggregated assessment of the overall (direct and indirect) material and land requirements of final demand for each production sector in each of the countries/regions specified in the model.

In the *MOSUS* project, data collection concerning primary physical inputs in a time series of 1980-2002 (1992-2002 for Eastern European countries) is currently underway and will be completed in autumn 2004. The extended environmental-economic model will be available for scenario simulation and policy evaluation at the beginning of 2005.

4.2 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 we would simulate in the scenarios, resource availability would never be a restricting factor. In the global scenario simulations carried out in MOSUS, a distinction between the categories of material flows on the one hand and land use on the other hand is made concerning the future availability of natural resources.

Up to 2020, the year for which the scenarios in MOSUS are formulated, we assume that there will be no 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, material inputs will 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, 2002).[6]

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

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[6] However, for some renewable resources, such as fish, scarcity will be an increasingly serious problem to be addressed by policy makers in the next decades (for example, EEA, 2003).

land use regulations. Unmodified land multipliers used in the different country models could thus deliver unrealistically high results. A much more appropriate assumption is that land use will actually restrict future economic activities. Consequently, the land use models used in MOSUS will 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).

4.3 Policy applications

The integrated simulation tool currently generated in the *MOSUS* project will be used for a number of applications in later project phases.

First, the model will allow a comprehensive quantification of the European 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 will reveal, whether or not a tendency towards the re-location of resource intensive production towards the global South can be observed. Thus it will be analysed, whether the process of relative dematerialization, which can be observed in Western Europe, is going along with a dematerialisation of imported products or whether Europe's dematerialization is connected to a "re-materialisation" in other world regions. By doing so, comprehensive indicators on European resource use will be provided, which will extended and update existing indicators of resource use of the European Union (Bringezu and Schütz, 2001a) 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, the research carried out in the *MOSUS* project will allow accounting and analysis of the economic sectors (industries) and world regions/countries by which these resource flows are activated. Thus, interlinkage indicators, such as resource productivities and labor intensity of resource use of sectors of the European economy and their changes over time will be calculated. Furthermore, the project will analyse the role of domestic and total material inputs for European growth potentials and job creation and identify economic policy strategies, which would facilitate a reduction of resource use in an economically efficient way.

Third, and most importantly from the policy perspective, the integrated model will be used to simulate and evaluation sustainability scenarios for Europe. In the *MOSUS* project, three main scenarios are developed, each of them up to the year 2020. The *baseline scenario* projects further trends observed between 1980 and 2003, if no particular sustainabilityoriented policy strategies and instruments are put into force. The *weak sustainability scenario* reflects sustainability policy goals and measures derived from strategic documents of the European Community, such as the 6th Environment Action Programme (European Commission, 2001) and the Sustainable Development Strategy of the European Union (European Council, 2001). The *strong sustainability scenario* defines policy goals and instruments, which are more ambitious from the point of view of sustainable development compared to those included in the EU documents.

The scenarios will 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 and outside Europe. These scenarios shall explore opportunities as well as barriers and limits for restructuring Europe towards sustainability, giving special emphasis on potentials for technological changes for supporting these restructuring processes. In particular, possibilities for de-coupling economic growth from environmental pressures shall be identified on a country and sector-specific level.

Based on the scenario evaluation covering the economic, environmental and social dimension, policy strategies and actions capable for reconciling long-term economic development and competitiveness in Europe with social cohesion and environmental protection requirements will be elaborated. The final product will be formulated and tested best policy tools to implement the Sustainable Development Strategy in Europe.

5 Conclusions

This paper consisted of two main parts. In the first part, the methodological foundations for extending monetary input-output models with physical data concerning 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 addressing important questions such as trade offs between sustainability goals of material dematerialisation and de-intensification of land use.

In the second part, empirical policy applications of this integrated modelling approach with regard to sustainability assessments on the global level were discussed, taking the example of the ongoing European research project *MOSUS*. Economic-environmental IO model systems, such as the system developed in *MOSUS*, 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.

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