Using Input-Output Analysis to Measure the Environmental Pressure of Consumption at Different Spatial Levels

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Keywords

carbon dioxide (CO_2)
consumption
data envelopment analysis (DEA)
environmental indicators
life-cycle thinking
structural economics

Summary

Input-output modeling is a useful tool for tracing environmental impacts of consumption. Because it includes impacts originating from production layers of infinite order (capturing the entire economy), input-output modeling is highly relevant for studies operating in a life-cycle context. In this article we show how the input-output approach can be used to enumerate the problem of sustainable consumption. Based on a literature survey including research done by the authors we present measures of the emissions of carbon dioxide at different spatial levels: nation, city, and household. Further, we take more environmental effects into account and introduce the concept of environmental efficiency by combining input-output modeling and data envelopment analysis. Finally, we discuss the policy relevance of the different measures. The article demonstrates that input-output modeling has a wide range of life-cycle oriented applications when combined with other data sources such as detailed trade statistics, foreign input-output and environmental statistics, and household expenditure data.

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Volume 9, Number 1–2

Introduction

Living means consuming, and consuming causes resource depletion and environmental degradation. Some contributions to environmental pressure arise from activities associated directly with households. These are, for example, the consumption of fuels and water in the house, and the consumption of petrol (gasoline) through driving a private vehicle. The resources needed and pollutants emitted by households are called *direct requirements*.

Households also cause environmental pressure indirectly through the consumption of goods and services. The corresponding resources needed and pollutants created to satisfy consumer demand are called *indirect requirements*. These indirect requirements occur in the numerous industries situated in the countries in which the goods and services demanded by the consumers are produced. But in accordance with Adam Smith's classical statement that "consumption is the sole end and purpose of all production" (Smith [1776] 1904, Vol. II Book IV), these indirect requirements are ultimately being demanded by the households.

Indirect requirements must be understood to be of "infinite order." This means that, in the case of the provision of a train journey for example, they include environmental pressure caused not only by the train journey itself, but also through assembling the train and running the stations, producing the steel for the train and the concrete for the station buildings, producing the materials for the respective steel and concrete factories, the machines to mine the iron ore, sand, the steel to produce the mining equipment, and so on. This process of industrial interdependence proceeds upstream like the branches of an infinitely extensive tree. The sum of these direct and indirect requirements of resources and pollutants is called *total requirements*. A technique used to calculate total requirements is input-output analysis.

Because input-output analysis is based on publicly available data, the method is less labor-intensive than process analysis, which often requires collecting specific data from disparate locations. Moreover, input-output analysis can be used at different levels of life-cycle studies, from international burden-sharing analysis to the comparison of carbon dioxide (CO_2) embodiment in various commodities. That is due to the fact that input-output data can easily be linked to other data sources at macro and micro levels.

Although many input-output studies consider only one or a few environmental pressures such as energy consumption or CO_2 emissions, it is possible to link consumption to a large number of environmental effects. In the past decade several countries have improved environmental statistics and have developed systems based on National Accounting Matrices including Environmental Accounts (NAMEA); see the Overall Environmental Performance Indices section of this article. The NAMEA system encompasses environmental satellite accounts compatible with economic national accounts, meaning that economic flows, physical flows, and emissions can be linked together.

To reduce complexity when multiple environmental effects have to be taken into account, these effects need to be aggregated into a general environmental performance index. One way to do this is to combine input-output analysis and data envelopment analysis (DEA). DEA weights various pressure types together, thereby estimating an aggregated environmental performance index that we label as environmental efficiency.

The aim of this article is threefold: First, based on a literature survey, to show how input-output analysis applies to measuring the environmental pressure of consumption at different spatial levels: nation, city, and household; here emissions of CO_2 are used as an example indicator. Second, to address the question of aggregating different environmental effects into a single index for the environmental pressure of consumption. Third, to describe the policy contexts related to different indices.

The article is organized as follows. The first section includes a general introduction to environmental input-output analysis. The next section describes measures of CO_2 emissions at different levels: nation, city, and household. The section that follows describes how input-output analysis has been used to account for multiple environmental pressures and how these pressures can be transformed into an overall environmental performance index using the DEA approach. The policy relevance of the measures described in the article is highlighted in a policy section. A final section concludes.

An Introduction to Input-Output Analysis Including Environmental Effects

Input-output analysis is a top-down economic technique that uses sectoral monetary transactions data to account for the complex interdependencies of industries in modern economies. Within the scope of life-cycle assessment, generalized input-output analyses result in an $f \times n$ matrix M of *factor multipliers*, that is, embodiments of f production factors (such as water, labor, energy, resources, and pollutants) per unit of final demand of commodities produced by n industry sectors. A multiplier matrix M is calculated from an $f \times n$ matrix F containing sectoral production factor usage and from an $n \times n$ *direct requirements* matrix A according to

$$M = F(I - A)^{-1} \qquad (1)$$

where I is the $n \times n$ unity matrix. A can comprise requirements from current as well as capital intermediate demand of domestically produced and imported commodities.

The $f \times 1$ *factor inventory* Φ of a given functional unit (for example a household), represented by an $n \times 1$ commodity expenditure vector y and an $f \times 1$ vector Φ_d of direct factor usages is then simply

$$\Phi = My + \Phi_d \qquad (2)$$

My represents the indirect usage of factors embodied in all inputs into the functional unit.

An introduction to the input-output method and its application to environmental problems can be found in articles by Leontief and Ford (1970) and Proops (1977). The mathematical formalism is described in detail by Lenzen (2001b) and some of the shortcomings (e.g., aggregation problems, price inhomogeneity, and industry versus commodity classification) and benefits (e.g., public nationwide data available, all commodities included, and infinite production layers considered) inherent in input-output analysis are discussed by Lenzen (2001a) and Munksgaard (2000).

Life-cycle assessments (LCAs) are usually carried out using hybrid techniques combining process and input-output analysis, as suggested by Bullard and colleagues (1978); Moskowitz and Rowe (1985); Joshi (2001); Suh and Huppes (2002); Treolar (1997). Examples of hybrid input-output-based LCA techniques and applications are described in detail by Suh and colleagues (2004).

Measures for CO_2 Pressure of Consumption at Different Levels

An input-output model including the linkage of consumption and other categories of end use to production activities, and further to environmental effects, has many applications within the field of life-cycle CO_2 analysis. When it is combined with other data sources such as data on foreign trade and household expenditures, a variety of analytical possibilities appear. Based on a literature survey, we show applications of input-output modeling at three different levels of analysis: Nation, city, and household. We show that hybrid input-output-based LCA has some operational benefits as compared to process-type life-cycle assessment.

Nation Level: CO_2 Accounting and the Influence of Trade

Many countries face targets for reducing CO_2 emissions. Therefore, implementing efficient means to reduce these emissions is important, but so is selecting the appropriate accounting principle for measuring emissions. The question of whether the producer or the consumer should be held responsible for national emissions has been raised by Munksgaard and Pedersen (2001). Some other authors have discussed this explicitly in comparative studies (Ferng 2003; Ahmad and Wyckoff 2003; Wyckhoff and Roop 1994; Proops et al. 1993).[1] Others have applied the distinction implicitly, such as Proops and colleagues (1999), who compare conventional genuine saving estimates (representing a producer principle) with a trade-adjusted estimate (representing a consumer principle).

If the distinction between producer and consumer responsibility is applied at the national level, the role of international trade becomes a crucial issue. Exports of commodities to other countries will increase national CO_2 emissions when the concept of producer responsibility is applied, whereas imports of commodities will increase national emissions if the concept of consumer responsibility is used. Because most economies are open, international trade has a big impact on national emission figures.

Studies done in the field of modeling the embodiment of CO_2 in imports and exports using input-output analysis show that restricted access to data had an influence on the design of the analysis carried out. Most studies employ single-region models where imports are treated either as exogenous to the input-output model (see Schaeffer and Leal de Sá 1996; Wyckoff and Roop 1994; Common and Salma 1992), or as endogenous (that is, as an intrinsic element of the model—see Lenzen 1998b; Pedersen 1996; Denton 1975). In both cases, however, factor embodiments in imported commodities are determined by applying the domestic production recipe and energy-use structure. Only very few studies employ multiregion models (see, e.g., Ahmad and Wyckoff 2003; Lenzen, Pade, et al. 2004; Proops et al. 1999). Of these studies, only that by Lenzen, Pade, and colleagues (2004) includes feedback loops, for example, induced trade effects in foreign countries.

The different input-output model approaches (scenarios) used in these studies are illustrated schematically in figure 1 for five countries, C1, . . . ,C5. The trade scenarios as shown in figure 1 have the following characteristics.

Autonomous regions

In this scenario, imported commodities are treated as if produced by domestic recipes. This assumes that foreign industries exhibit factor multipliers that are identical to those of the domestic industries. Direct and indirect effects of production effects are included, whereas no feedback trade loops are considered. This scenario is analyzed by a single-region model as done by, for example, Lenzen (1998b); Pedersen (1996); Schaeffer and Leal de Sá (1996); Wyckoff and Roop (1994); and Common and Salma (1992).

Unidirectional trade

In this scenario, imported commodities are treated as produced in the countries of origin. This entails considering national differences with regard to production inputs and efficiency, energy use, and CO_2 emission coefficients. This scenario implies the application of a multiregion input-output model as done by, for example, Ahmad and Wyckoff (2003) and Proops and colleagues (1999). Once again no feedback trade loops are taken into account.

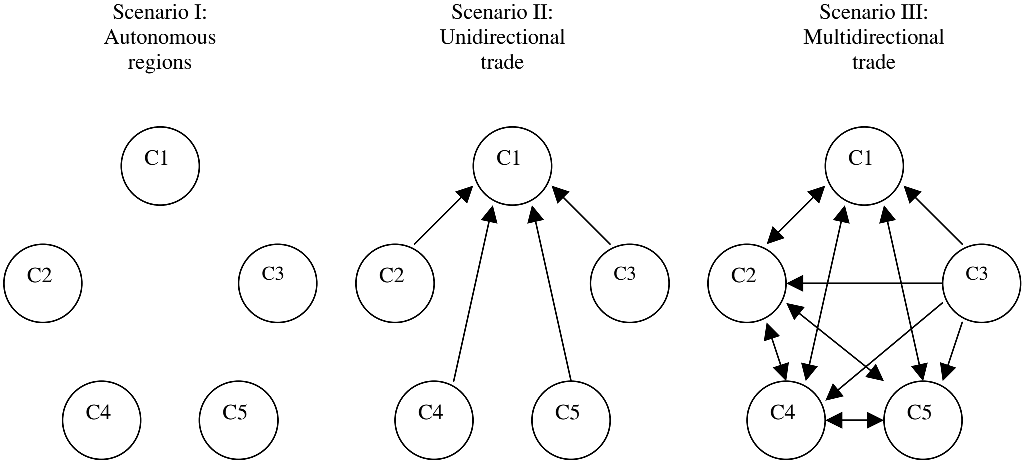

Figure 1 Schematic of three trade scenarios. *Source:* Lenzen et al. 2004a.

Multidirectional trade

This scenario implies the application of a multiregion input-output model as in unidirectional trade scenarios. In this scenario, feedback trade loops capture, for example, import from country 2 to country 4 induced by export from country 4 to country 1. This scenario needs to be analyzed by the use of a compound multiregion input-output model as shown by Lenzen, Pade, and colleagues (2004).[2] Note that many multiregion models do not explicitly cover the entire world and that usually the remainder is modeled as the "rest of the world" region (C3 in figure 1).

Using a single-region input-output model and assuming that factor use in foreign industries is identical to that of domestic industries can introduce an error into the CO_2 embodiments in internationally traded commodities and hence into national CO_2 accounts founded on consumer responsibility. To obtain an estimate of the magnitude of this error, we have investigated all three trade scenarios shown in figure 1 using input-output data for Denmark, Germany, Sweden, Norway, and Australia (assuming Australian production recipes to represent the rest of the world). Results shown in table 1 represent Danish consumer responsibility for CO_2, embodiments of CO_2 in exports and imports, and the Danish CO_2 trade balance.[3]

These results demonstrate that it is important to explicitly consider the production recipe, energy use structure, and CO_2 emissions of all trading partners in order to arrive at realistic figures for CO_2 embodied in trade, and hence for the national contribution to emissions, based on consumer responsibility. Results from the multiregion CO_2 analysis are explained in more detail by Lenzen, Pade, and colleagues (2004).

City Level

For cities, and regions within nations in general, the problem of assessing environmental performance is complicated by the need to establish a boundary and to deal with a much more specialized and open local economy. As an example for city assessment, direct (end-use) energy requirements were audited in the Urban CO_2 Reduction Project established by the International Council for Local Environmental Initiatives (Brugmann 1996; see also Bennett and Newborough 2001) with the intention of assessing greenhouse gas emissions. This project developed into what is now known as the Cities for Climate Protection (CCP) campaign, which has more than 500 member municipalities (see <www.iclei.org/co2>). The basis of the assessment procedure, the establishment of the emissions inventory, is outlined in software developed by Torrie Smith Associates (2004) in Toronto, Canada. The Association of American Geographers' Global Change in Local Places project is another, independent effort to examine the causes and effects of climate change at a local level (Kates et al. 1998).

In assessing a local area, one has to distinguish greenhouse gas emissions *occurring in* a local area from emissions *resulting from* the activities required to support the local population. This distinction is similar to the distinction between producer and consumer responsibility used in the previous section.

Table 1 Comparison of 1997 Danish CO_2 trade balances obtained from input-output models with varying degrees of trade interaction (in megatons (Mt))

Scenario	*I: Autonomous regions*	*II: Unidirectional trade*	*III: Multidirectional trade*
CO_2 responsibility	47.2	57.5	58.6
Exports	30.1	37.6	38.1
Imports	18.9	36.8	38.4
CO_2 trade balance	−11.1	−0.8	0.3

Source: Lenzen, Pade, et al. 2004.
Note: One metric megaton (Mt) = 10^9 kilograms (kg, SI) ≈ 1,102,000 short tons.

Many important indirect emissions are ignored in, for example, the CCP approach. Although accounting for environmental pressure on a purely territorial basis may be appropriate for impacts such as localized urban pollution, or urban microclimate, an assessment of global impacts such as climate change needs to take into account indirect contributions from outside the city boundary. Kates and colleagues (1998) do identify indirect emissions as being important, but they imply that accounting for them from a city perspective is difficult. Even in the particular case of indirect emissions from the provision of fuels and electricity, they state that in the CCP approach "the marginal benefit of computing and applying full-cycle coefficients did not seem justified by the benefits" (presumably a more complete emissions inventory). Kates and colleagues (1998) admit, though, that "all greenhouse gas emissions could be linked to final consumption behavior, but the extent to which such a principle should and can be applied is a central consideration in the methodology of local emissions inventories." This is a key philosophical point: A city exists fundamentally to support the lives of its inhabitants. The fact that, for example, a steel-making facility, the output of which clearly supports populations elsewhere, is located in one area does not mean it is appropriate to apportion all the emissions from the facility to the local inhabitants. This approach does not invalidate emissions reduction action taken within the steel-making facility: It means that this action benefits all future users of steel.

Indirect emissions and boundary issues become critical when comparisons are made between cities or local government regions. In CCP studies, for example, very large differences, sometimes up to an order of magnitude, have been observed in the per capita CO_2 emissions of local government areas in the same country. These differences are primarily due to the nature of the accounting of indirect emissions. For example, people who happen to live in a central business district are largely not responsible for the large amount of electricity used by the businesses in that area.[4] A comparison on the basis of local per capita emissions is therefore of limited meaning.

A comprehensive and consistent assessment of cities and regions can be achieved by applying input-output analysis and multivariate regression techniques. In a study of the Australian city of Sydney, Lenzen, Dey, and colleagues (2004) calculated households' energy requirement using input-output-based energy multipliers and examined the correlation of these energy requirements with socioeconomic-demographic variables such as income, household size, age structure, number of children, house type, employment, and education status. Indicative results are that total energy intensity (megajoules per Australian dollar of per capita income)[5] decreases by about 25% over a typical range of incomes as income increases, per capita total energy requirements of single-person households being about twice those of four-person households, and that there is a negative correlation between automotive fuel consumption and population density.

Household Level

Indicators of the environmental pressure of households make it possible to examine differences with regard to sociodemographic characteristics such as income, age, education, urbanization, and number of children.

Different family types have different lifestyles and consumption patterns and hence affect the environment in different ways. Household indicators are useful for assessing the environmental effects of household types, making it possible to identify family types representing high environmental pressure. Furthermore, household indicators reveal the environmental effects of changes in household characteristics, therefore revealing the environmental consequences of future demographic and economic scenarios.

Studies linking energy requirements and input-output and household expenditure data for entire countries have been undertaken by a number of authors. The technique was introduced by Herendeen in the early 1970s and first applied to the U.S. economy of 1960–1961 (Herendeen and Tanaka 1976), to the Norwegian economy of 1973 (Herendeen 1978), and again to the U.S. economy of 1972–1973 (Herendeen et al. 1981). The demographic factors considered in these early studies were total expenditure (related to income), number of household members, and regional population density. The main results of these early studies were that (1) a substantial part of a household's energy requirements is constituted by nonenergy commodities; (2) total energy requirements increase less than proportionally with income; that is, total energy intensity decreases with income, (3) per capita energy requirements decrease with the number of household members; and (4) urban households exhibit a lower energy intensity than rural households.

These results were confirmed in similar studies in other countries, such as the Netherlands (Vringer and Blok 1995; Biesiot and Noorman 1999), Germany (Weber and Fahl 1993), New Zealand (Peet et al. 1985), Japan (Aoyagi et al. 1995; Kondo et al. 1996), and Australia (Lenzen 1998a).

In a Danish study by Wier and colleagues (2001) on energy consumption and derived CO_2 emissions, a range of sociodemographic household characteristics were included. The study found that the above-mentioned main results held including urbanization, but in addition, house type and age influenced energy requirement significantly too. This is because of increased transportation and heating needs for families living in houses and in rural areas, compared to families living in flats (apartments) and in urban areas. Furthermore, age has a small, but significant influence, because young households have lower direct energy requirements. Level of education and employment status do not make any noteworthy difference in Denmark.

Thus, household-level indicators provide important information on the environmental pressures of different lifestyles and consumption patterns. By using input-output analysis in combination with environmental statistics and household budget data, it is possible to achieve improved understanding of the influence of various household characteristics on environmental degradation.

Environmental *intensities* express an environmental impact (in physical units) per unit of commodity price, and therefore hold information on the physical amount of, for example, energy or CO_2 emissions embodied in various commodities consumed in households. Several studies have applied the input-output technique in calculating energy and CO_2 intensities, finding that there is a large variation across commodity types—suggesting that changes in consumption pattern may change environmental pressure substantially. Additionally, comparing household consumption pattern across countries reveals large differences in the relative contributions from various commodity types. Thus, figure 2 shows a comparison of breakdowns of household energy and CO_2 requirements into nine commonly used categories of human needs.

The data were extracted from the references listed in figure 2. In order to provide a comprehensive overview of input-output-based household energy studies, we have included older studies as well. It appears that the portion of direct requirements (vehicle fuel and household energy) in the total is around 55% for European countries, but only about 30% for Australia. Munksgaard and colleagues (2001) and Biesiot and Noorman (1999) have reported that in the case of Denmark and the Netherlands, and in the case of the United States, this portion has been decreasing steadily since 1950 and since 1980, respectively. The most striking differences between the energy requirements of households in different countries are the following: Household energy accounts for the smallest part of the total in Australia, followed by the United States (1972–1973), New Zealand and Germany, and finally the Netherlands, Norway, and Denmark, reflecting these countries' climates. In contrast, mobility makes up a larger part in Australia, New Zealand, and the United States, because these countries are larger and/or more sparsely settled. In the remainder of the countries, energy requirements are fairly similar, given differences in category definition and base year.

Within CO_2 requirements, the following features can be observed: Food accounts for an unusually large part of Australian emissions because of considerable nonenergy CO_2 emissions due to land clearing in Queensland for the purpose of beef cattle grazing. Again, Australian emissions from household energy use are comparatively small. Emissions from household energy in France are relatively small, because electricity production in France is mostly based on nuclear power. Once again, the remainder of countries show a similar emission structure, with differences possibly caused by discrepancies in category definition.

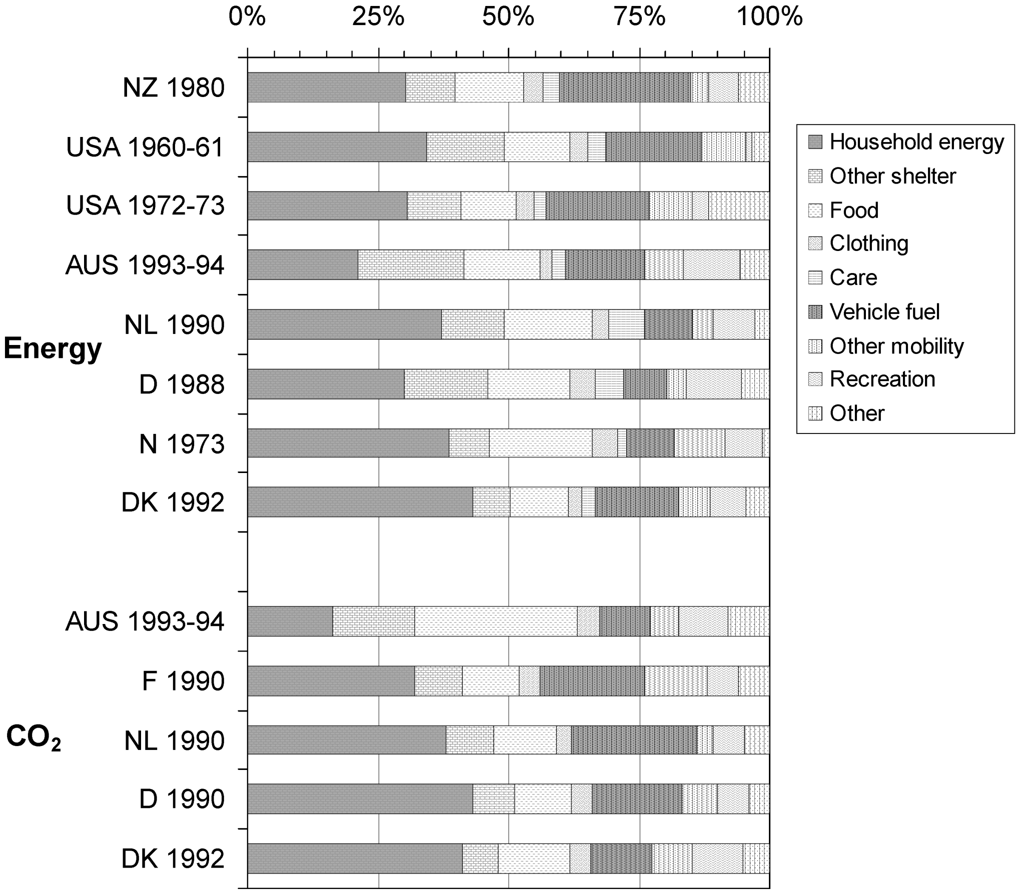

Figure 2 International comparison of household energy and CO_2 requirement breakdowns (commodity breakdowns as percentages of the country total). For all CO_2 figures "care" has been aggregated with "other." *Sources and abbreviations:* United States (USA), 1960–1961: Herendeen and Tanaka (1976); 1972–1973: Herendeen et al. (1981). Norway (N), 1973: Herendeen (1978). New Zealand (NZ), 1980: Peet et al. (1985). Germany (D), 1988: Weber and Fahl (1993), 1990: Weber and Perrels (2000). Netherlands (NL), 1990: Vringer and Blok (1995), Biesiot and Noorman (1999). Australia (AUS), 1993–1994: Lenzen (1998a). Denmark (DK), 1992: Munksgaard et al. (2001). France (F), 1990: Brevil (1992).

Using input-output based environmental intensities make it possible to compare different types of commodities according to environmental pressure. Furthermore, it is possible to analyze across countries the influence from variation in consumption patterns on environmental pressures.

Overall Environmental Performance Indices

Most input-output-based environmental studies consider only energy consumption and CO_2 emissions and do not take into account other environmental pressures. But consumption and production have impacts on other types of environmental degradation. A change in commodity mix may have positive effects regarding one type of environmental pressure and negative effects regarding another.

Today, several countries have improved environmental statistics and have begun to develop environmental accounts compatible with national input-output tables, often using NAMEA systems (Pedersen 1999). Using the integrated NAMEA system, economic flows, physical flows, and various types of emissions can be linked together. As a result, it becomes possible to estimate emission profiles for various commodities, countries, or households, including several types of environmental effects. The disadvantage of emission profiles, however, is that the large amounts of information may be difficult to interpret, making it complex to assess whether improved environmental performance in general occurs, or not. For a discussion of approaches to reducing complexity, see for example, the report by Udo de Haes and colleagues (2002). One way to improve transparency is weighting different types of environmental pressures—according to their relative damage—together in a broad environmental performance index, aggregated across environmental pressure types.

From a neoclassical economic point of view, the ideal environmental index would measure the reduction or increase in social welfare following a change in environmental pressure. One way to aggregate across different types of environmental pressure, that is, to weight different types of environmental goods (or "bads"), would be to assign weights to each pressure type according to society's preferences measured by marginal utility, which in turn equals prices. Environmental goods are, however, most often not supplied and demanded on any market and hence have no observable prices. Estimating prices of environmental goods is in principle possible, but costly, and entails large uncertainty.

One aggregated approach to comparing different types of environmental pressures is the total material requirement or TMR (Eurostat 2001; Bringezu and Schütz 2001), which, for a country, is the total direct and indirect material input to the national economy. Deducting material requirements for exports leaves us with yet another approach to the TMC (total material consumption). In line with these approaches is the ecological backpack (Schmidt-Bleek 1993, Weizsäcker et al. 1998), which is the life-cycle-wide material input in all upstream production layers minus the mass of a product itself, but including the (hidden) material requirement that never enters the economy (ancillary flows and excavated or disturbed flows).[6]

Another approach to aggregate different types of environmental pressure is the ecological footprint (Wackernagel and Rees 1996) estimating a population's resource consumption and waste assimilation requirements in terms of corresponding productive land area needed to balance out the negative ecological impact of the activities. CO_2 emissions, for example, are converted by estimating forest land required to absorb the emissions. The ecological footprint was originally proposed as a policy tool, meaning that any region should not make use of a bigger footprint than its own land area. The concept has been debated, the main criticism being that the concept does not consider economic values and discounting and that "nature" is treated in an excessively aggregated and simplifying way (see, e.g., the commentaries in *Ecological Economics*, vol. 32, 2000).[7] Essentially, these objections hold for all types of physical indices, including the TMR, TMC, and ecological backpack mentioned above.

A Data Envelopment Analysis Approach

One way to overcome the problem of having to weight different types of environmental effects is to apply Data Envelopment Analysis (DEA). DEA was introduced by Charnes and colleagues (1978) as an alternative approach to the measurement of productivity or efficiency in firms or enterprises that are either using or producing commodities not directly bought or sold in a market, which consequently have no observable prices. Productivity is normally assessed as the value of output per unit value of input (output productivity) or the amount of inputs used per unit of output (input productivity). Without prices the values cannot be estimated, but using the DEA method another type of productivity or efficiency analysis may be carried out to compare different functional units (for example, firms). Briefly, the DEA method optimizes an artificial "price" or "weight" for each unit in the analysis in terms of the value of output divided by the value of input. The philosophy behind this approach is that the DEA method obtains exactly those "prices" (or "weights") that give the best possible performance of this particular firm. If its efficiency is still worse than that of other firms, then we can conclude that this firm does not perform well.

Correspondingly, DEA can be used to compare units with regard to environmental performance. Environmental efficiency may be understood as the lowest possible environmental pressure per unit produced or consumed. Functional units may be different firms, plants, sectors, commodities, countries, or households. The DEA method weights various pressure types together, estimating an aggregated environmental performance index.

Previous empirical DEA analysis on environmental performance has mainly focused on comparing three types of units: Environmental performance of various *countries* have been compared by, for example, Lovell and colleagues (1995), Taskin and Zaim (2001), and Zofio and Prieto (2001); of various *sectors, firms, farms, or plants* by Ball and colleagues (1994), Bevilacqua and Braglia (2002), Färe and colleagues (1996), Golany and colleagues (1994), Hadri and Whittaker (1999), Hailu and Veeman (2001), Jung and colleagues (2001), Piot-Lepetit and colleagues (1997), Piot-Lepetit and Vermersch (1998), Reinhard and colleagues (1999, 2000), Sarkis and Cordeiro (2001), and Tyteca (1997); and finally of *environmental management systems* by Courcelle and colleagues (1998), Sarkis (1999), and Sarkis and Weinrach (2001).

Most studies concern one environmental pressure type, most often nitrogen (Ball et al. 1994; Piot-Lepetit et al. 1997; Piot-Lepetit and Vermersch 1998; Reinhard et al. 1999), energy-related emissions such as CO_2, sulfur dioxide (SO_2), and nitrogen oxides (NO_X) (Färe et al. 1996; Golany et al. 1994; Taskin and Zaim 2001; Tyteca 1997; Zofio and Prieto 2001), or waste (Courcelle et al. 1998; Sarkis 1999; Sarkis and Weinrach 2001). Other studies, however, apply DEA analysis across several pressure (emission) types; see the work of Bevilacqua and Braglia (2002), Hailu and Veeman (2001), Jung and colleagues (2001), Lovell and colleagues (1995), Reinhard and colleagues (2000), and Sarkis and Cordeiro (2001).

DEA Environmental Indicators at Household Level

In an ongoing study (Wier et al. 2003), we apply DEA to compare overall environmental performance across commodities and household types. The study benefits from the inclusion of recent and detailed data on environmental effects that extend the system applied in Wier and colleagues (2001). According to relative contribution, we aggregate various emissions and resource needs into seven types of indices showing environmental effects and resource needs:

- Air pollution index for hazardous substances, including various types of emissions of polycyclic aromatic hydrocarbons and heavy metals.
- Potential Acidification index, including SO_2, NO_X and NH_3.
- Global Warming Potential index including greenhouse gases: methane (CH_4,), N_2O, and CO_2.
- Ozone Depletion Potential index, including various types of chlorinated fluorocarbons.
- Photochemical Ozone Creation Potential index including CH_4, nonmethane volatile organic compounds, and carbon monoxide (CO).
- Index for the physical quantity of water consumption.
- Total Material Requirement (TMR) index, measuring domestic and foreign direct and indirect material and natural resource consumption.

In addition, DEA is used to estimate an overall environmental performance score (or index) based on the seven types of environmental effects or pressure. For reasons of brevity, selected household types (five best and five worst performing households) are presented in table 2. For all environmental pressure types, numbers in brackets refer to rankings and are measured as household environmental pressure relative to total household expenditure. The third column from the right presents the overall environmental performance index (or score) based on the seven environmental effect indices (or pressure types) and relative to total expenditure, meaning that it illustrates how environmentally friendly each household's consumption basket is per unit of value consumed. In this regard, young high-income families living in urban flats perform best, having a score of 156%, meaning that this family type could reduce its environmental pressure

Table 2 Environmental performance index for selected Danish household types—top 5 and bottom 5, 1997

	Polycyclic aromatic hydrocarbon/ metal index	*Potential acidification index*	*Global warming potential index*	*Ozone depletion index*	*Photochemical oxidation index*	*Water consumption index*	*Total material requirement*	*Performance score (per expenditure)*	*(Ranking)*	*Average expenditure per head*	*Performance score (per head)*	*(Ranking)*
	g/1000 DKK	mol/1000 DKK	kg/1000 DKK	mg/1000 DKK	g/1000 DKK	m^3/1000 DKK	kg/1000 DKK	%		1000 DKK/ Head	%	
Top 5												
High-income												
Young families in urban flats	0,5	8,9	65,5	106,8	41,1	1,2	285,5	156	(1)	118	137	(1)
Young families in rural houses	0,7	10,8	85,3	114,7	96,7	0,5	308,8	139	(2)	194	91	(11)
Elderly families in rural houses	0,6	14,2	113,4	101,8	69,9	0,7	338,7	110	(3)	170	78	(21)
Middle-aged families in urban houses	0,4	12,5	90,9	104,3	82,2	1,0	314,8	109	(4)	126	83	(19)
Elderly families in urban flats	0,4	10,4	78,5	97,7	63,7	2,0	289,4	105	(5)	191	58	(26)
Bottom 5												
Middle-income												
Elderly families in urban flats	0,7	12,3	88,1	102,3	77,2	1,7	305,9	95	(23)	123	80	(20)
Middle-aged families in urban houses	0,5	13,8	98,4	103,7	103,3	1,0	322,1	95	(24)	103	86	(17)
Middle-aged families in rural houses	0,5	14,8	106,2	101,2	116,1	1,0	333,9	94	(25)	83	111	(3)
Elderly families in urban houses	0,6	13,1	98,3	103,9	93,1	1,1	318,1	93	(26)	134	68	(24)
Elderly families in rural houses	0,7	13,6	113,4	106,8	111,4	1,2	360,2	89	(27)	133	66	(25)

Note: Numbers in parentheses refer to rank. In 1997, 1 Danish kroner (DKK) ≈ US$0.15. One gram (g) = 10^{-3} kilograms (kg, SI) ≈ 0.035 ounces; one kilogram (kg, SI) ≈ 2.204 pounds (lbs); one milligram (mg) = 10^{-3} grams (g) ≈ 3.52×10^{-5} ounces; one cubic meter (m^3, SI) = 10^3 liters (L) ≈ 264.2 gallons. One mole (mol) of a substance = 6.022×10^{23} atoms, molecules, or other particles; the mass in grams of this amount of a substance is numerically equal to the molecular weight of the substance.

by 56% and still perform best. The second best family type is elderly high-income families living in urban flats. The family type having the lowest score is elderly middle-income families in rural houses. Their score is 89%, meaning that they perform 89% as well as the best family, and they would have to reduce their environmental pressure by 11% to be as environmentally friendly per unit of economic value obtained as the family type having the best performance.

As appears from table 2, high-income families perform generally best—all five best performing families are in this income bracket. The reason for this is a generally lower pressure in the forms of acidification, global warming, and photochemical oxidation (all related to energy and food consumption), plus generally lower water and material consumption. Thus, the results show that high-income families have a lower consumption of energy, food, water, and material-intensive goods relative to total household expenditure than lower income families, suggesting that food, energy, and water are necessities and that high-income families can afford investing in energy and water conservation.

On the other hand, in general high-income families also have high expenditure levels. As shown in table 2, average expenditure per household member is higher for these households compared to households in the "bottom 5 group." This is reflected in the estimates in the last column, presenting another way of measuring environmental performance: performance relative to household size (i.e., it measures the environmental friendliness of a household expenditure level when controlling for differences in number of family members across family types). It appears that high-income families from this point of view perform badly in environmental terms, not because their consumption pattern is less environmental friendly, but simply because they have high expenditure levels per household member. One exception, however, is young high-income families in urban flats—these households perform very well with regard to both types of environmental performance. They tend to have an environmentally friendly consumption basket, reflected in the good performance score relative to expenditure. This is mainly due to low demand for heating, food items, and gasoline. But surprisingly, they also have a relatively low expenditure level per household member, reflected in good performance score relative to household size. This may be partly explained by this family type having the lowest amount of disposable income compared to other family types placed in the same income bracket.

Middle-income households hold the least environmentally friendly consumption baskets—all five worst performing family types are in this income bracket when looking at environmental performance relative to expenditure. In contrast, households in the low-income bracket perform better, due to relatively low contributions to ozone depletion, photochemical oxidation, and material requirement. Note that middle-income families have better environmental performance relative to household size (compared to environmental performance relative to expenditure), simply because middle-income families are generally larger than the average family.

Another general result worth noticing is that the ranking of family types changes considerably across effect types. For example, middle-aged high-income families in urban houses perform very well regarding emissions of hazardous substances to air, but are—at the same time—performing badly regarding ozone depletion. This underlines the need to include a variety of environmental effects in the analysis when doing environmental assessment.

A general pattern can be observed for acidification, global warming, photochemical oxidation, and material consumption, because—in all age and income brackets—families living in rural houses perform the worst in terms of environmental friendliness, based on their relatively high consumption of energy and transportation.

Policy Relevance of the Measures

For environmental policy making, the relevant question will always be if a certain change in the environment is good or bad, and further, how good or how bad? To guide political decision making, environmental measures must therefore point to normative implications. Environmental measures must be able to provide information to support such a value judgment, ideally based on explicit value systems (e.g., Olsthoorn et al. 2001).

In this perspective we emphasize the policy relevance of the measures described in Section 3 and 4:

National accounting of CO_2. Accounting based on the consumption approach makes it possible to monitor whether national consumption over time is exerting a greater strain on the environment. Using the production approach makes it possible to verify if international agreements on reduction targets are fulfilled and, further, if the link between economic growth and environmental impact can be broken.

Responsibility for CO_2 *emissions*. The distinction between producer and consumer CO_2 responsibility is not only a field for theoretical thinking. The question of whether a Danish power producer or a Norwegian consumer is responsible for the CO_2 emitted in Denmark has actually led to the use of different accounting principles in Denmark and Norway. The result was that electricity exported from Denmark remained unaccounted for in both countries. The EU Commission, however, has refused to accept the Danish accounting principle of deducting CO_2 embodied in electricity export.

Environmental trade balances give information about the environmental pressure exerted on other countries by domestic consumption. Besides estimating environmental burden sharing between countries, one practical use of such an indicator is to judge the fairness of international agreements on CO_2 burden sharing. The appropriate apportioning of national contributions to climate change entails the calculation of greenhouse gas emissions embodied in international trade. The latter can be carried out conveniently using a multiregion input-output model. The results from these models have an impact on concepts of equity and on producer and consumer responsibility, and therefore hold implications for negotiations at the Conferences of Parties in the UN Framework Convention of Climate Change, the forum for international negotiations on greenhouse emissions policy.

Environmental multipliers founded in a multiregional input-output model serve as a tool to analyze the potential for minimizing the global environmental impacts from consumption. By comparing national environmental multipliers, (e.g., CO_2 multipliers) for comparable industries or commodities it is possible to point out which countries are most efficient in producing given types of commodities as seen from an environmental point of view. Such an analysis might be useful in estimating the environmental benefits from restructuring international trade.

Indicators of the environmental pressure of households are useful in assessing the environmental effects of different household types, making it possible to identify family types representing high environmental pressure. Furthermore, household indicators reveal the environmental effects of changes in composition of family types, therefore allowing assessment of the environmental consequences of future demographic and economic scenarios.

General environmental index. The development of an environmental performance index holds information on the environmental effects of a given policy. If the policy is directed toward households, firms, or sectors, it is relevant to consider environmental performance indices for these units. If national or international policies are considered, the environmental indices could be estimated at a national level. In combination with economic indicators such as GDP, the environmental performance indicator provides a good foundation for policy making based on comprehensive information in aggregated terms. The development of a national environmental index can form a basis for comparing the environmental performance of different countries and thereby represents one way to green the GDP.

Conclusions

Structural economics such as input-output modeling is a useful tool for analyzing environmental impacts of consumption. By including impacts originating from production layers of infinite order, input-output modeling is highly relevant for studies operating in a life-cycle context. By covering a range of spatial levels from nation to commodity, this literature survey shows a great variety of input-output model applications in the field of measuring the environmental pressure of consumption.

Using the example of CO_2, we have demonstrated in this article that an integrated input-output framework has many applications when combined with other data sources and tools. The inclusion of foreign trade statistics makes it possible to analyze the embodied environmental burden in commodities traded between countries. This points to a national environmental accounting principle founded in consumer responsibility and to the concept of environmental balances between countries. Developing both of these indicators within a multiregional framework including foreign input-output and environmental statistics forms a basis for valid estimations of the environmental burden sharing between countries. These accounting principles are also relevant to comparisons of cities versus rural areas within a country.

Standard input-output tables often link commodity groups to producing industries, making it possible to estimate the embodiments of, for example, CO_2 or energy for different commodity groups. Combining input-output analysis and household expenditure data makes it possible to analyze the influence from differences in sociodemographic characteristics such as income, age, education, urbanization, and number of children.

Due to a lack of data, most input-output-based studies consider only one or a few environmental pressures such as energy consumption and CO_2 emissions. The available data have now improved. Today, several countries have developed environmental accounts compatible with traditional economic national accounts. This makes it possible to estimate environmental profiles for various commodities, countries, or households, including several types of environmental pressures. To overcome the complexity of comparing different environmental profiles, data envelopment analysis can be applied to weight different types of environmental pressures together in a general environmental performance index.

In conclusion, this survey points to two approaches to developing the applications of input-output models. One approach is to develop comprehensive multiregion models in order to obtain more reliable estimates of the environmental pressure in foreign countries caused by satisfying the needs of domestic consumers. Another perspective is to develop methods such as DEA as a complement of input-output analysis in order to establish general measures of environmental quality.

Acknowledgments

This article is based on different research projects kindly supported by the Danish Energy Agency, the Danish Social Science Research Council, the School of Physics at the University of Sydney, Australia, and CSIRO Sustainable Ecosystems, Canberra, Australia.

Notes

1. Of these Ferng (2003) and Ahmad and Wyckoff (2003) are addressing the problem of carbon leakage, that is, that imports are directed toward countries not covered by the Kyoto agreement on carbon dioxide reductions.
2. “Compound” means that the input-output matrices of all countries are combined with all environmental data in one multiregion input-output matrix, which is then inverted to calculate multipliers.
3. The concept of a CO_2 trade balance was introduced by Munksgaard and Pedersen (2001).
4. Larivière and Lafrance (1999), for example, exclude industrial electricity consumption from their regression analysis of Canadian cities, because it is not explained by any city characteristics.
5. One megajoule (MJ) = 10^6 joules (J, SI) ≈ 239 kilocalories (kcal) ≈ 948 British Thermal Units (BTU).
6. *Editor’s note:* For a description and analysis of materials-based methods of aggregation of environmental pressure, see the pair of articles by Daniels and colleagues (Daniels and Moore 2001; Daniels 2002).
7. *Editor’s note:* See also the discussion of the strengths and weaknesses of the ecological footprint by York and colleagues (2004).

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