Beyond IPAT and Kuznets Curves: Globalization as a Vital Factor in Analysing the Environmental Impact of Socio-Economic Metabolism

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We bring the rapidly developing tools for analyzing "society's metabolism" to the attention of a scientific audience concerned with matters of population and, in a complementary fashion, we draw the attention of material and energy flow analysts to the role of population and population dynamics within their own paradigm. As an analytic framework, we use the classic "IPAT-model" that relates environmental impact (I), population (P), affluence (A), and technology (T). We relate the IPAT model to the tool commonly used in MFA, so-called environmental Kuznets curves, and re-analyze empirical data from various sources, for both affluent industrial and for developing countries, within these frameworks. We conclude that population and technology seem to dominate over affluence as far as environmental impact is concerned, but that both the IPAT and Kuznets models fail to take into account the intricate interdependencies *among* different socio-economic systems and the increases in their the economic, material and population exchanges. In effect, both models tend to underestimate the environmental impact and create too optimistic an image of "dematerialization" in affluent industrial countries.

KEY WORDS: IPAT model; environmental Kuznets curves (EKC); material flow analysis; national MFA for Austria, Brazil, Germany, Japan, The Netherlands, United Kingdom, United States, Venezuela; metabolic profile; international trade; socio-economic metabolism; economies in transition; material intensity.

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INTRODUCTION

This paper aims to achieve two major goals: to bring the rapidly developing tools for analyzing "society's metabolism" to the attention of a scientific audience concerned with matters of population and, in a complementary fashion, to draw the attention of material and energy flow analysts to the role of population and population dynamics within their own paradigm. As an analytic framework we will use the classic "IPAT model" which relates environmental impact (I), population (P), affluence (A) and technology (T), in order to structure the variables to be dealt with here and to create simple, systematic linkages between them that will then be discussed in more detail. We begin with a brief description of the IPAT model and its previous uses. We then proceed to describe the basic features of material flow analysis (MFA) in order to show the kinds of variables that are generated by MFA methodology and to discuss how they may figure in an IPAT model. The next section is devoted to a discussion of affluence (A); in it we will review some of the empirical results regarding how affluence relates to socio-economic material flows. Finally, we make explicit the often hidden role of population (P) within MFA, present some of the empirical evidence gained so far, and raise more intricate questions about the relationship between material flows on a macro level on the one hand and population and population dynamics on the other hand. We will discuss several historical processes by which these two factors may be supposed to interact. We also analyze the role of technology (T) and how it could be fitted into the MFA framework on a macro level, focusing on how tricky these relationships may become if an international division of labor and interdependence are brought into the picture properly. The conclusions are organized along the lines of both perspectives: In what respects is MFA an appropriate tool to use in relating population and environmental impacts? And, on the other hand, how thoroughly will population issues have to be taken into account when using MFA methods to attempt to understand the impact of affluence on the environment?

THE IPAT MODEL: BASIC FEATURES AND PREVIOUS USES

The IPAT model, first proposed almost three decades ago (Commoner, 1972; Ehrlich & Holdren, 1971; Holdren & Ehrlich, 1974), resulted from the efforts of population biologists, ecologists, and environmental scientists to formalize the relationship between population, human welfare, and environmental impacts. The IPAT model postulates that environmental Impact (I) is the product of Population (P), per capita Affluence (A) and Technology (T).

(1) I = P * A * T

Ehrlich and Holdren's original arguments (1971, 1974) came very close to the position advocated by Robert Malthus two hundred years earlier: that population growth was *the* major threat to human welfare. Ehrlich and Holdren claimed that, whatever other factors were involved, population growth caused a "*disproportionate* negative impact" on the environment (Ehrlich & Holdren, 1971). In the, 1971 publication, their formulation of this equation was:

(2) I = P * *f*(P)

where the per capita impact on the environment supposedly also depended upon population. This is the case if the "*law of diminishing returns*" applies—the same argument Malthus used for arable soil. Ehrlich and Holdren claim that this law of diminishing returns would indeed apply to nonrenewable resources such as minerals, and to (partly) renewables as freshwater supplies or fishery stocks: Beyond a certain point, "per capita costs and environmental impact escalate dramatically when the human population demands more." Similar disproportionality could also occur in the case of "*threshold effects*" where, according to the authors, population numbers would destabilize a certain balance (such as the maximum tolerable pollution for trees), or in the case of *synergism* of different effects. The authors cite the example of cities which because of population increases push out into farmland, resulting in humans' lungs being afflicted by a mixture of agrochemicals and traffic effluents and suffering disproportionate damage.

The authors concede that sometimes it could also, quite on the contrary, be that *economies of scale* apply which reduce per capita impact with growth. They conclude, however, that "in populous, industrial nations such as the United States, most economies of scale are already being exploited; we are on the diminishing returns part of most of the important curves."

This whole line of reasoning is not very convincing, for substantive reasons and even more so for methodological reasons. Substantively, all of the reasons given above amount to saying that present impacts depend upon past impacts, perhaps in a non-linear fashion. The more resources that have already been consumed, the more environmentally costly it becomes to consume yet more; the greater the amount of stocks that has already been depleted, the more risky it is to go on depleting; the more pollution there is already, the more likely it is that a critical level will be reached, and so on. None of these arguments directly links impacts to population. All of them rely on the presumption that it was population numbers that caused the past impact in the first place.

Methodologically, as long as IPAT is treated as an accounting equation, it is simply a tautology. With equation (2), even if one has independent measurements of environmental impact, what else can it depend upon but population numbers? If Impact (I) equals Population number (P) times a function *f* of Population number (P), it will always be population numbers that are responsible, and the only variable component will be *f*. It is *f* that would tell us whether the impact rises proportionally or disproportionately, positively or negatively with population. With equation (1), at least we bring a few more variables into the game, and if we are able to measure them independently of one another, the equation may fail.

This is exactly the point picked up and elaborated upon by Dietz and Rosa (1994, 1997) about twenty years after Ehrlich and Holdren's original publication. They base their discussion on one of the strengths of the Holdren-Ehrlich approach, which is the provision of a view of human-environment interactions which is more comprehensive than the narrow focus on pollution which was dominant at the time.[1] This more comprehensive view relates well to the contemporary discussion of the human "driving forces" of global environmental change (see Stern et al., 1992). Dietz and Rosa further elaborate on how to make use of the IPAT model as a testable hypothesis rather than as just an "accounting analysis," as they call it (Dietz & Rosa, 1994, 282), the latter being a model where the relationships are definitional, so that as soon as three of the variables are fixed, the fourth follows.[2] What they suggest and then actually calculate for the dependent variable of CO_2 emissions (Dietz & Rosa, 1997) is a stochastic model utilizing historical or cross-sectional data to assess impacts. In its simplest application, such a model uses graphs of bivariate relationships between Impact and driving forces, or of historical trends in Impact and driving forces. In more sophisticated versions, this takes the form of several loglinear equations which take into account not only the net direct effects but also interactions between the independent variables, the so-called "driving forces." While such stochastic models promise valuable insights and allow us to determine the relative weight of the "independent" factors in explaining the "dependent" variable, they have not been frequently used.[3]

The charm of the IPAT formula is its simplicity and generality. In order for this charm to unfold, however, sufficiently generic and reliable operationalizations of the variables must be available. This can be considered to be the case for Population numbers and—with some precaution[4]—also for Affluence, expressed as GNP (gross national product) in per capita terms.[5] Beyond that, both environmental Impact (I) and "Technology" (T) tend to be fuzzy. "Technology" (T) can be treated as a residual variable (that is, as everything not included in Population and Affluence) as long as environmental Impact is operationalized in a sufficiently sound and robust way. This is, unfortunately, typically not the case. This is the point where MFA, materials flow analysis, may prove its usefulness in questions of population and population dynamics. Materials flow analysis may be able to provide exactly those indicators for Impact that would make this model empirically rich enough to allow viable conclusions about the relative weight of the three "driving forces" Population, Affluence, and "Technology." To illustrate why we are of this opinion, we will make an excursion into the basic assumptions and measurement procedures of MFA.

MFA AS SUPPLIER OF INDICATORS FOR ENVIRONMENTAL IMPACT—BASIC ASSUMPTIONS AND METHODOLOGY

What came to be called "Materials Flow Analysis" (MFA) was first developed by Ayres and Kneese (1968) as part of an attempt to reconceptualize economy, which had been considered to grow seemingly limitlessly, by placing this "economy" into a thermodynamic framework, taking into account the law of conservation of mass. This attempt must be seen as one of the early creative approaches to dealing with the problem of a "cowboy economy on a spaceship earth" (Boulding, 1966), culminating in Meadow's "Limits to Growth" model (Meadows et al., 1972). While Meadow's criticism amounted to the claim that economic growth would have to be stalled so as not to exceed the earth's carrying capacity, Ayres and Kneese's diagnosis was more subtle. According to them, it was not economic growth as such that mattered, but the growth in human societies' material throughput that mattered. In other words, if one could find a way to reduce the amount of material input, economic growth (in terms of monetary income) could go on. While appeals to slow the growth of the world economy in favor of preserving the environment were considered to constitute a fundamentalist attack on the core mechanisms and beliefs of modern economy and society, Ayres and Kneese came up with much more "acceptable" advice: Increase the material efficiency of economies, use less material per monetary unit! However, in the following two decades, which were characterized by a backlash against all holistic or systemic perspectives on the society-environment interrelation in favor of an analytic, multidimensional focus on pollution (and on pollution only), Ayres and Kneese's approach was more or less lost sight of (Fischer-Kowalski, 1998).

In the early 1990s, a systemic perspective on materials reappeared within two different frameworks. One was a life-cycle assessment framework, in which Schmidt-Bleek (1993) defined his "MIPS" (material input per service unit indicator). His model said that for the sake of the environment, the economy should aim at minimizing material input per unit of service provided. For technical engineering and management this was a very plausible message: If you save on costs for raw materials, waste disposal, and possibly also for transport, you will also save on environmental costs by optimizing the relation between the material input needed for a certain product and the final service delivered. The other framework in which the systemic materials approach was revitalized was that of so-called "green accounting." Under the guidance of the United Nations, many countries tried to introduce environmental concerns into their systems of national accounts. On the one hand, this was done by considering expenditure for environmental protection or by evaluating environmental assets; on the other hand, this "green accounting" initiative also led to an attempt to develop a picture not only of the monetary economy, as was to be expected for national accounting, but also of the *physical* economy—that is, a national economy's stocks and flows expressed in material and energetic terms (Uno & Bartelmus, 1998; Franz & Stahmer, 1993). So it happened that for a number of national economies, researchers generated overall material flow accounts similar in their approach to that of Ayres and Kneese's from two decades before even though they were often unaware of the ancestry of their work (for Austria: Steurer, 1992; for Japan: Japan Environment Agency, 1992; for Germany: Bringezu, 1993; Schütz & Bringezu, 1993).

Since the early 1990s, the MFA approach has been picked up on by many more countries and often even introduced into their official statistics. Gradually, MFA has been methodologically refined so as to eliminate inconsistencies that had hampered international comparability.[6]

MFA can be regarded as a set of methods for describing and analyzing socio-economic metabolism. This presupposes a collective organization on the part of humans to maintain ways of life within a natural (and social) environment. Thus we are interested in examining socio-economic systems (such as national economies) as systems that reproduce themselves not only socially and culturally but also physically through a continuous exchange of energy and matter with their natural environments and with each other.

Socio-economic metabolism refers to the sum total of the material and energetic flows into, within, and out of a socio-economic system. Socio-economic metabolism serves (a) to produce and reproduce the biophysical structures of the socio-economic system in exchange with the natural environment, and (b) eventually to produce or consume deliverables from other socio-economic systems. For each socio-economic system therefore we must define (a) a boundary between the socio-economic system and the natural environment and (b) a boundary between the socio-economic system in question and other socio-economic systems. These boundaries are functional boundaries, not geographic/spatial boundaries.[7]

To describe the material part of this metabolism, material flow analysis tools have been developed to which the following basic assumptions and conventions apply:

(1) The law of "conservation of mass"

Any MFA is based upon the idea of balancing, which originates from the law of conservation of mass.

Input = Output + stock increases – stock decreases

In words: The sum of material/energetic inputs into a system equals the sum of outputs plus stock increases minus stock decreases.

(2) The metabolism of the socio-economic system is composed of the metabolisms of its compartments, namely the biophysical structures it contains. For each compartment, the law of conservation of mass also applies.

This equation follows from a systems approach, looking at an economy or society as an integrated whole much in the way biology that sees an organism, examining its "metabolism" as a highly interdependent self-organizing process rather than as just an assembly of "material flows." Following this analogy, just as the metabolism of an organism is composed of the metabolism of each of its cells, so is the metabolism of a socio-economic system composed of the metabolism of each of its compartments.

(3) Bio-physical compartments of socio-economic systems

This notion requires the explicit specification of what is considered to constitute the compartments of the socio-economic system. For socio-economic systems on a national level, the most common convention is to consider *human bodies, animal livestock,* and *artifacts* as biophysical structures maintained by socio-economic metabolism as well as by collectively organized human labor.

To be consistent, the complete metabolisms *of the humans and of the animal livestock* must be included. This comprises nutrition, intake of oxygen and water, output of carbon dioxide and water, faeces, and the deposition of dead bodies. If livestock is included as a compartment of the social system, then meat and milk, etc. may of course not be treated as inputs from the environment but must be looked upon as transfers within the system.[8]

Finally, long-lived *artifacts*—i.e., human-made and human-maintained technical structures such as buildings, machines, vehicles and the like, but also roads, dams, or sewers—must be looked upon as physical compartments of socio-economic systems. This implies, according to equation (2), that all the materials used for making and maintaining these structures belong to the social system's metabolism, as do the energy and the materials (such as water, air and various raw materials) used to make them function and to produce those goods and services for which the social system has constructed them.

(4) Stocks and flows

A reliable distinction between stocks and flows is a prerequisite for empirically determining whether a socio-economic system is still "growing" (in physical terms), is in a steady state, or is shrinking. Stocks refer to the size of the population, the size of the livestock, and the weight of the infrastructure. Accordingly, an operational distinction between "size" and "metabolic rate," as well as between the "growth rate" and the energetic and material "turnover" of the social system can be defined, and the indicator "net addition to stocks" can be calculated.

(5) Water, air and "other materials:"

Typically, three groups of input materials are distinguished: water, air, and the remaining input materials (consisting of biomass, fuels, other minerals, and manufactured products). Most MFA indicators are based on the "other materials" only. This has to do with the common-sense idea of not literally "drowning" economically valued raw materials and commodities in water and air.[9]

(6) Direct materials input and indirect flows, "rucksacks," or "hidden flows"

According to the conventions established so far, "direct materials input" refers to the non-water-non-air fraction of materials that actually cross the boundary of a socio-economic system (see Figure 1). Beyond the boundaries of the socio-economic system, there occur material flows that may be seen as prerequisite to the materials input of the socio-economic system in question, even if these former material flows remain beyond its boundaries. In the Schmidt-Bleek (Wuppertal) tradition, these indirect mate-

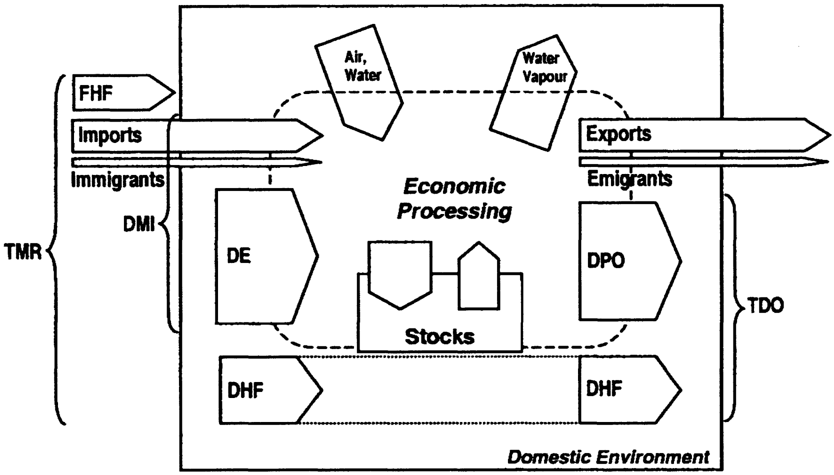

FIGURE 1. The metabolism of a socioeconomic system: The basic MFA model.

Source: Matthews et al., 2000; slightly modified.

DE: Domestic extraction
DHF: Domestic hidden flows
DPO: Domestic processed output
TMR: Total material requirement = DMI + DHF + FHF
DMI: Direct material input = DE + Imports
FHF: Foreign hidden flows
TDO: Total domestic output = DPO + DHF

rial flows are termed "rucksacks." One can distinguish between the rucksacks of imports and the rucksacks of domestic materials extraction. (Another expression used is 'hidden flows'; see for example Adriaanse et al., 1997).[10]

(7) Domestic processed output

Domestic processed output (DPO) refers to the total of all materials used in the domestic economy (i.e., which result from direct material input) at the point where they flow back into the natural environment as wastes, emissions, or deliberate disposals (such as fertilizer). These outflows can also be distinguished according to the environmental media they enter (air, water, soil). When hidden flows within the domestic environment are also included, one refers to Total Domestic Output (TDO).

From this interrelated set of variables, several indicators can be drawn up to represent a socio-economic system's impact upon the environment. On the one hand, these indicators may refer to the input side, following the argument that the more resources a system consumes, the more it is a burden to the environment (and the environment's future usability for other systems). Among these indicators, domestic extraction and "Direct Material Input" (DMI, equal to domestic extraction plus imports) will figure most prominently. Quantitatively speaking, a large part of this input is made up of fossil fuels, equaled or even outweighed by industrial and construction minerals; biomass input comes next. Imported composite products (made from various raw materials) constitute only approximately 15% of DMI (Adriaanse et al., 1997). Calculated as background processes to the direct material input, the hidden flows usually amount to the same or more than that direct input, making the figures for "Total Material Requirement," TMR, approximately twice as large as those for direct input alone (Adriaanse et al., 1997). Still another input-related indicator is "Domestic Material Consumption," DMC, which subtracts exports from DMI and so represents the amount of materials consumed by the system internally.

On the other hand, indicators may be chosen so as to refer not to the input but to the output (or rather, outflow) side, examples of the latter being DPO (Domestic Processed Output) and TDO (Total Domestic Output). If a socio-economic system (i.e., a national economy) has an even trade balance with imports equaling exports in terms of weight, and if it does not increase or decrease its stocks, then input should equal output over a certain time period. Practically, this is not the case for contemporary affluent industrial countries; in all the countries examined, stocks grow considerably, the annual net addition to stock amounting to 20–40% of direct material input. So at the time being, DPO is much smaller than DMI, and resources (i.e., future wastes) are being accumulated within the socio-economic system (e.g., Matthews et al., 2000).[11]

However, regardless of whether the *input* of resources or the *output* of wastes and emissions is at issue, we must ask whether the total weight of materials processed by a socioeconomic system is a viable indicator for "environmental impact" at all. All of the indicators mentioned are created by summing up the weights of many different materials. A few very large flows, such as those of construction minerals and fossil energy carriers on the input side or carbon dioxide on the outflow side, dominate these indicators, while smaller flows considered much more hazardous by environmental chemists are hardly evident. "Big flows are not automatically bad, and small flows are not automatically better" (Matthews et al., 2000, 2). Despite this consideration, one can say that all resource use involves environmental impact of some kind at every stage of the material cycle, from extraction or harvesting to final disposal. This means that unless technologies change, increases in resource input imply increases in environmental impacts. One should also consider that expert opinions since the beginning of the environmental debate have undergone quite extreme variations in answering the question of exactly which substances or processes should be seen as particularly environmentally harmful, while studies of the sum total of processed materials consistently tell their story in a reliable and uncontested way, even if it is only part of the whole story.[12] A measure of processed materials represents a reasonable "headline indicator" (Jesinghaus & Montgomery, 1999) for the overall scale (Daly, 1987) of anthropogenic systems *vis-à-vis* the natural environment, on the same level of generality as overall energy consumption or population numbers.

HOW DOES AFFLUENCE RELATE TO MFA INDICATORS OF ENVIRONMENTAL IMPACT?

As explained above, the idea that environmental impact need not necessarily grow proportionally to affluence lay at the very core of MFA as developed by Ayres and Kneese (1969), and this idea was picked up again by all consecutive authors. It was indeed seen as the approach's most important policy application to find ways of "delinking" (or "decoupling") material input and economic activity. The means by which this was to be achieved were seen in technology: Schmidt-Bleek's publications (Schmidt-Bleek, 1993; Schmidt-Bleek & Bierter, 1998) abound with related examples, and he was even radical enough to propagate "factor 10" reductions of material intensity as a realistic political target for highly developed industrial countries. Weizsäcker and Lovins (Weizsäcker et al., 1997) were more cautious and spoke in terms of "factor 4" changes. This idea of reducing material intensity (expressed as the mass of material input per dollar value added) or, put differently, of increasing material productivity (the inverse of intensity), took hold in many government programs and environmental policy statements. On the one hand, it was nourished by the example of labor intensity (or labor productivity); if it had indeed been possible to reduce the amount of labor needed for the production of commodities by such a margin as was experienced in the course of industrialization, why should the same not apply to materials, given appropriate framework conditions? Another encouragement could be found with energy; for example, had not the oil crisis of the early 1970s induced a major reduction in energy intensity? And what about the generic observation of the "minimization" of the size and weight of consumer durables such as electronic equipment and household facilities?[13] Research also provided support for these considerations. For example, it could be demonstrated that the emissions of sulphur dioxide decrease rather than increase with increases in a country's prosperity (Selden & Song, 1994).

Later in the discussion, a distinction was made between "relative delinking" and "absolute delinking." A reduction in environmental impact (in terms of resource consumption or pollution) per unit of GDP was termed "relative delinking." In other words, GDP or the monetary value of commodities may rise while the material indicator (be it resource use or wastes/emissions) grows more slowly or even remains constant. "Absolute delinking," on the other hand, was supposed to occur if economic growth continued, but the absolute amount of materials used declined. While several studies came up with examples of relative delinking for various indicators of materials use (De Bruyn, 1997; Berkhout, 1998; Stern et al., 1996; Rothman & De Bruyn, 1998), examples of absolute delinking are hard to find.[14]

Let us examine the delinking hypothesis in the context of the most methodologically advanced and recent studies of several affluent industrial countries.[15] Figure 2 presents a first overview of the interrelationships between changes in Affluence (GDP) and changes in Direct Material Input (DMI) during the last two decades for Austria, Japan, Germany, the Netherlands, the United Kingdom, and the United States. These countries are among the richest countries of the world and together have more than 50% of the world's income at their disposal.

Looking at Figure 2 country by country, we see striking similarities. During the last two decades, all of the national economies considered showed continuous growth in Affluence. In some of these countries, there were phases of relative stagnation, but in none of them did GDP fall below the level of preceding years. In all of them, the economy has grown by at least 50% over the whole time span and Direct Material Input (DMI) has also grown, albeit at a slower rate. Material growth amounts to 10–20% for the whole time period. In several of the countries, there were even phases of decline in material input.[16] As far as our main question is concerned, the answer which this simple bivariate analysis gives us is very clear: In all countries investigated so far, material input does not grow proportionally with affluence, but "relative delinking" can be observed. The material intensity in terms of tons of material input per unit of GDP is declining. Nowhere, however, do we find a case of "absolute delinking" in the sense of absolute reductions of material input occurring while the economy continues to grow.[17]

Let us now turn to the "backside" of industrial economies, namely wastes, emissions, and deliberate disposals of materials such as animal manure or fertilizers into the environment, and ask the same question about delinking again. As explained above, Matthews et al. (2000) developed the indicator Domestic Processed Output (DPO) on the basis of material input-

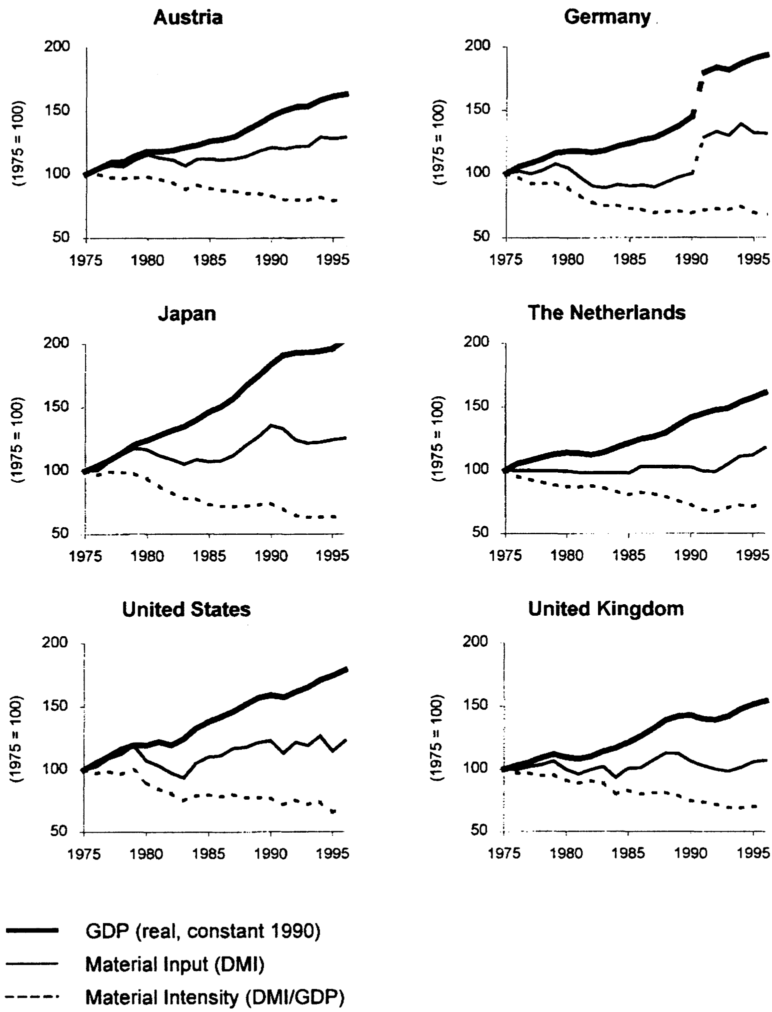

FIGURE 2. Environmental Impact and Affluence I: Material Input (DMI), Gross Domestic Product (GDP), and Material Intensity (DMI/GDP) for affluent industrial economies, 1975–1996.

Source: Matthews et al., 2000 (DMI-AUT, GER, J, NL); Adriaanse et al., 1997 (DMI-US); Schandl and Schulz, 2000 (DMI-UK); OECD (GDP); own calculation.

output balances, DPO comprising all outflows from production and consumption into the domestic natural environment. Although this calls traditional waste and emission statistics to mind (and was in fact generated with their help), DPO is a more comprehensive indicator. Since it draws on mass balances of inputs and outputs, it has a built-in countercheck on the incompleteness and discontinuities present in environmental statistics. The way in which DPO was calculated by Matthews et al. (2000) does not safeguard against distortions resulting from different national traditions of keeping environmental statistics, as a complete physical input-output analysis would do (Stahmer et al., 1997; Weisz et al., 1999; Schandl et al., 2000), but it does take us a fair way down the right path.

Figure 3 displays similar patterns for domestic outflows (that is, wastes, emissions and deliberate disposals into the domestic environment) as Figure 2 demonstrated for material inputs (DMI). Among the affluent industrial economies documented, we find a ubiquitous decline in outflow intensity, just as we saw a decline in input intensity. There nevertheless occurred an absolute increase in total DPO in all these countries during the last two decades (although at rates that stay well below the increase in GDP). So, an analysis of wastes and emissions using the comprehensive indicator DPO supports the case for a "relative delinking" from affluence for the time period under consideration, but does not support "absolute delinking."

How can these differences in the pace of monetary economic growth and material growth be explained? Before we go into a more in-depth analysis, we can test a few possible explanations for these differences in pace. Unexpectedly, deliberate environmental policies are no suitable candidate as an explanatory factor. Relative delinking seems to be a ubiquitous phenomenon among affluent industrial nations and there is no reason to assume that, for example, the United Kingdom or the United States have achieved relative delinking as an outcome of policies aimed to do so. Relative delinking is just as pronounced in the latter two countries as it is in the Netherlands or Germany, both of which have placed much more emphasis on policies of sustainability involving a slowdown of material growth. May we then on the basis of MFA indicators discard environmental policies as being irrelevant or at least ineffectual? On the level of the overall, "headline" indicators DMI and DPO, we indeed can discern only little effect from such policies. The improvement of "material productivity," regardless of whether it is measured by resource consumption (DMI) or by outflows (DPO), seems to come as a "free gift," a structural outcome of changes in affluent industrial economies during the last two decades. However, if we examine the data of Matthews et al. (2000) more closely, we do indeed

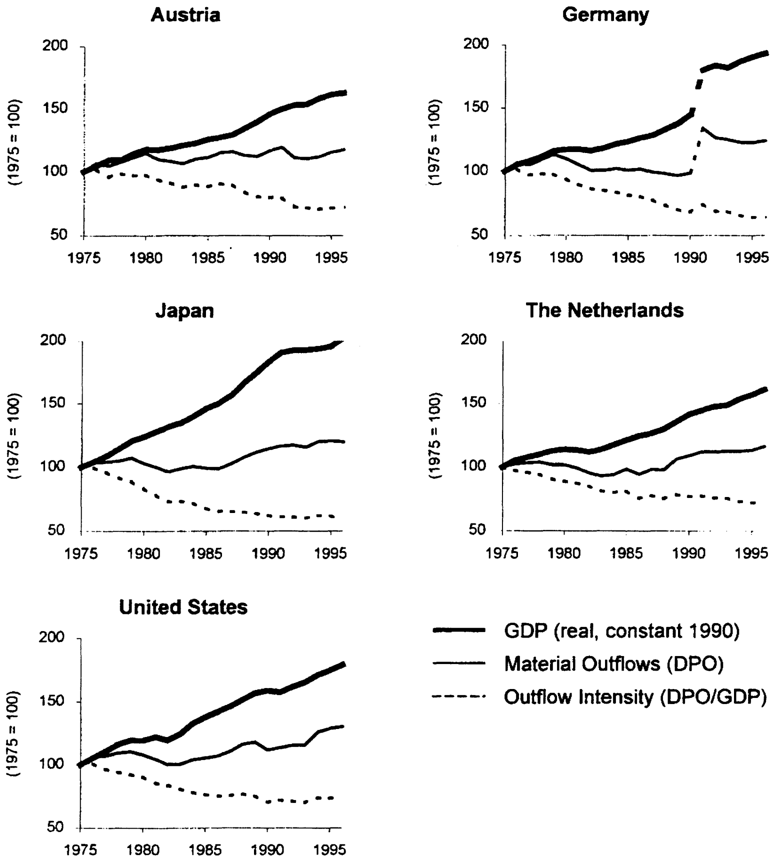

FIGURE 3. Environmental Impact and Affluence II: Material Outflows (DPO), Gross Domestic Product (GDP), and Outflow Intensity (DPO/GDP) for affluent industrial economies, 1975–1996.

Source: Matthews et al., 2000 (DPO); OECD (GDP); own calculation.

find changes that may well be attributed to the environmental policy efforts of the last decades.

The outflows of industrial economies documented by Matthews et al. (2000) have been broken down in terms of the environmental media they enter.[18] In Figure 4, we have selected some of the indicators that can be generated by such a breakdown and have related these indicators to GDP

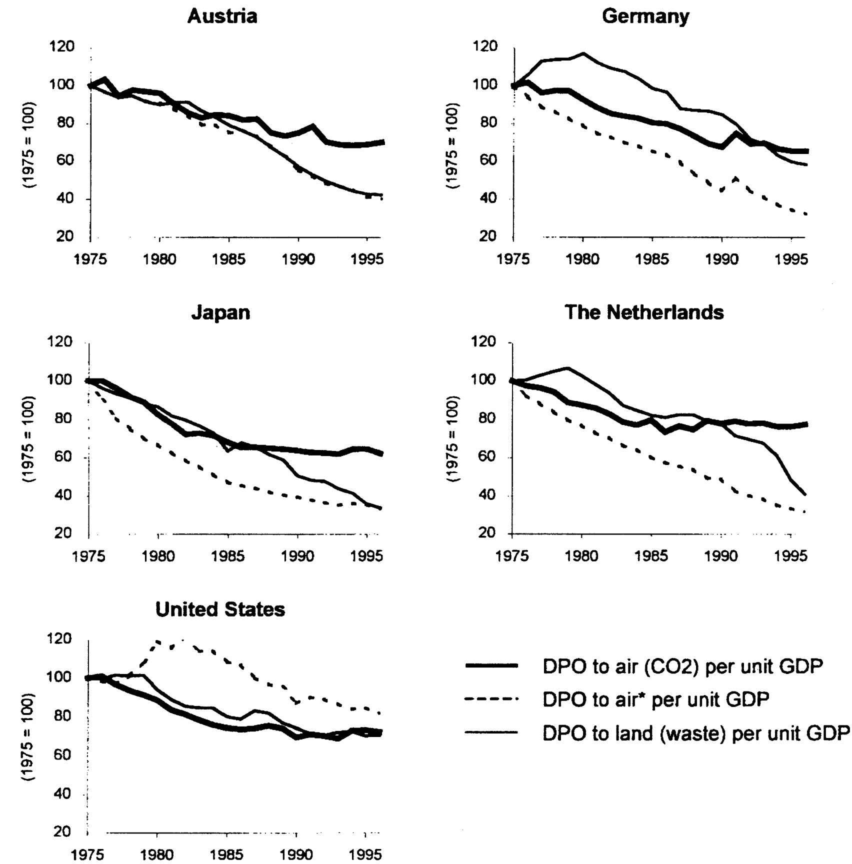

FIGURE 4. Environmental Impact and Affluence III: Outflow Intensity (DPO/GDP) by environmental media for affluent industrial economies, 1975–1996.

Source: Matthews et al., 2000 (DPO); OECD (GDP); own calculation.

in order to calculate more specific "outflow intensities." While overall DPO displayed no more than a soft "relative delinking" from GDP, air pollutants (DPO to air*)[19] and solid wastes (DPO deposited in landfills) show a clearly inverse relation to income: the more affluence increases, the lower these wastes and emissions are.[20] Most probably, the more affluent countries have used part of their affluence to reduce local and regional environmental pollution. Here we find not only "relative delinking" of environmental impact from affluence but also "absolute delinking": the size of waste outflows that could constitute a nuisance for the domestic environment show an absolute decline in each of the cases investigated. We do tend to interpret this as an effect of environmental policy aimed at fighting "pollution." But *why* then does overall DPO stay more or less constant with rising affluence? There is one obvious reason: the emissions of CO_2.

As can be gathered from Figure 4, CO_2 emissions display a more random pattern than do air pollutants and solid waste. Per unit of affluence, patterns of CO_2 emissions seem to be scattered all over the range of possibilities. At best, we may state a case of (not very consistent) "relative delinking," but not a case of "absolute delinking" such as we see with outflows that constitute a nuisance for local and regional environments. Subjected to closer scrutiny, this result might reconfirm our thesis of environmental policies' effectiveness; while countries did indeed strive to reduce sources of local and regional pollution through political measures, they did not make any consistent efforts to reduce emissions impacting on the global climate.

But let us now proceed one step further. Even if we have found with the help of MFA many indications of "relative delinking" between affluence and environmental impact, and even some cases of "absolute delinking," could it not still be population numbers that are driving environmental impact? Methodologically, it is not easy to separate these variables properly. For affluent industrial countries we find both a continuous increase in affluence as well as a continuous albeit more moderate increase in population numbers during the last decades. Within the scientific community of MFA, so-called environmental Kuznets curves (EKC)[21] are used to tackle these multiple influences. Environmental Kuznet curves model the interrelation between affluence (in terms of GDP per capita inhabitant) and environmental impacts (in terms of physical amounts per capita inhabitant) as 3rd order polynomial functions. In terms of IPAT, Kuznets curves display the gross effect of affluence on the environmental impact indicator while keeping population numbers constant. They demonstrate how change in per capita affluence (A as defined in the IPAT formula) is associated with change in per capita environmental impact (I/P as defined in the IPAT formula). In Kuznets models "Technology" (T) as it is understood in IPAT—i.e., as the conundrum of all sources of variation other than population and affluence, such as technology in the strict sense of the word, environmental policies, structural economic differences, etc.—shows up as (random) deviation from the polynomial function.

In Figure 5, we have calculated environmental Kuznets curves for the relationship between various overall per capita environmental *impacts* on

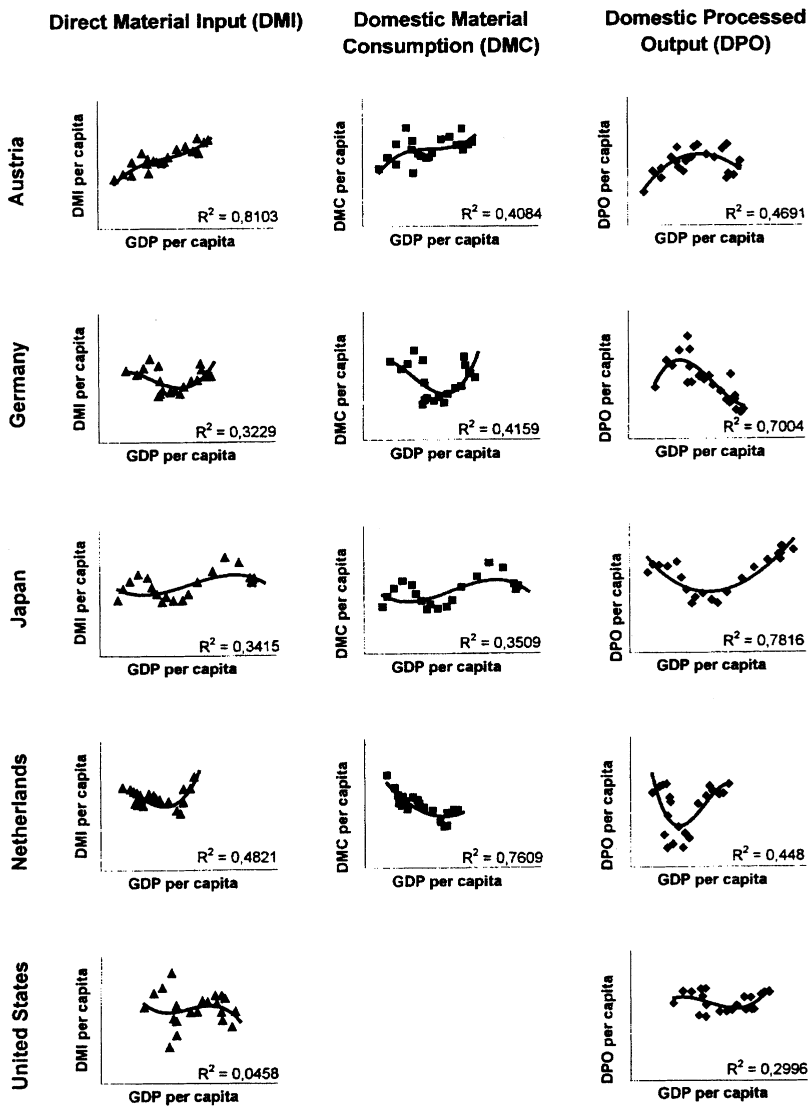

FIGURE 5. Environmental Impact and Affluence per capita Population I: Environmental Kuznets Curves (EKC) for Material Inputs (DMI, DMC) and Outflows (DPO) for affluent industrial economies, 1975–1996.

Source: Matthews et al., 2000; OECD; own calculation.

the one hand (inputs as DMI and outflows as DPO, as well as Domestic Material Consumption (DMC)—for an explanation see Figure 1)—and *income* on the other hand (GDP per capita, constant prices). We have, for the sake of simplicity, tried to exclude much of "Technology" (T) as a source of variation by displaying the results country by country in time series, and not lumping together data from several countries. These countries might differ in their production and consumption structures as well as in their waste and emission policies. By displaying them case by case, we at least control for national differences.

Figure 5 shows that the MFA headline indicators DMI, DMC, and DPO are not related to affluence in any consistent way. The polynomial functions look different for each of the countries and for each indicator, and with few exceptions their fit to the data is not very good (see R^2 in Figure 5). If we pick up on the distinction made above between relative and absolute de-linking and apply it to the per capita data displayed in Figure 5, the conclusion we may draw for the countries documented here is not very clear. In general, changes in per capita environmental impact in industrial countries during the last two decades have not at all been strongly associated with changes in affluence. There is neither a consistent decline (the more affluent, the more environmentally unobtrusive), nor a consistent increase in environmental pressure (the more affluent, the more environmentally demanding), nor is there a curvilinear pattern repeating itself across countries. Obviously, on this scale per capita income is not at all a very distinct driving force for environmental pressure. Environmental impact obviously depends on a variety of other factors. Another, more optimistic way to express this would be to say that countries that are in the process of becoming more affluent have a great deal of leeway in shaping policy regarding environmental pressures.

Let us now raise the level of complexity one step further and include in our analysis the variations among countries in terms of "Technology," understood to be a compound variable of structural differences, policies etc. Figure 6 presents cross-country and cross-time data for a variable of crucial importance, namely CO_2 emissions from fossil fuel combustion. We again base our analysis on the Kuznets model, but this time enter all the data points generated by Matthews et al. (2000). We see that if per capita CO_2 emissions relate to affluence at all—although the fit to the model is fairly weak, as can be judged optically and by the low R^2 values (see Figure 6)—then they do so in a slightly positive way.[22] No such thing as a "turning point" in the relation of CO_2 emissions and affluence can be observed in this data. This is in line with the cross-sectional analysis of Dietz and Rosa

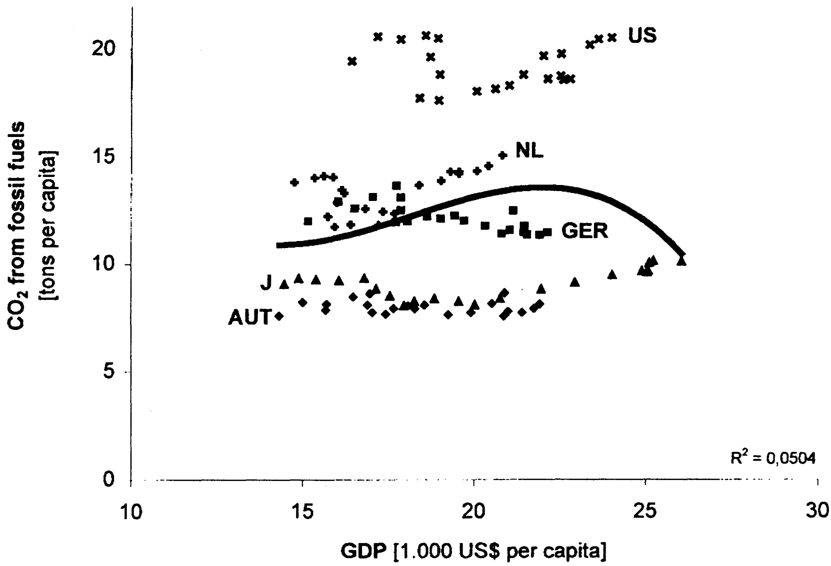

FIGURE 6. Environmental Impact and Affluence per capita Population III: Environmental Kuznets Curves (EKC) for CO_2 emissions from fossil fuels across affluent industrial economies, 1975–1996.

Source: Matthews et al., 2000; own calculation.

(1997), who within the framework of an IPAT model used similar log-linear equations on the basis of data from over 100 countries worldwide and also found an overall positive effect. Holtz-Eakin and Selden (1995) arrived by cross-sectional analysis at a possible turning point above an annual per capita income of $35,000, but we cannot confirm this on the basis of our longitudinal data. According to our model, the level of CO_2 emissions for industrial countries does not seem to depend on affluence but on other factors. The United States display an exceptional pattern: at all levels of affluence, annual per capita CO_2 emissions in the U.S. by far exceed those of all other nations, resulting in a positioning of data for this one nation that very much stands out from the rest (Figure 5). Although differences between the other countries observed are not as pronounced as they are with respect to the unique case presented by the United States, each of them does seem to have a characteristic level of per capita CO_2 emissions across levels of affluence.[23] So, for affluent industrial countries we conclude that per capita CO_2 emissions are not a function of income levels but rather a function of typical production and consumption patterns in the national economy and the resulting level of fossil fuel use (in terms of the IPAT formula, this means that CO_2 emissions are a function of "Technology").

Relating this to the results that have come out of our previous analysis, we arrive at some rather sobering conclusions. While the industrial countries seem to have used their growing affluence during the last two decades for the reduction of domestic environmental nuisances, they have at the same time increased their environmental impact on the global atmosphere, at the expense of the world climate. We can arrive at such a conclusion by virtue of the strength of MFA indicators that allow us to organize impacts that are qualitatively very different on a common scale of overall material weight. The weight of outflows is indeed a function (as mediated as it may be) of material input into socio-economic systems, and a high level of CO_2 emissions is a necessary consequence of the dominance of fossil fuels in industrial metabolism. As a fraction of DPO, CO_2 emissions play a most dominant quantitative role. In the five countries studied by Matthews et al. (2000), they make up more than four-fifths of all outflows (see Figure 7).

It certainly holds true for outflows that the rising per capita affluence of industrial economies in the last two decades tended to be beneficial for the domestic environment but very problematic on the global scale, insofar as CO_2 emissions are contributing to global warming. As the cross-country data presented here illustrate, however, this is not necessarily so, because the same degree of affluence can obviously be achieved at the expense of very different levels of CO_2 emissions.

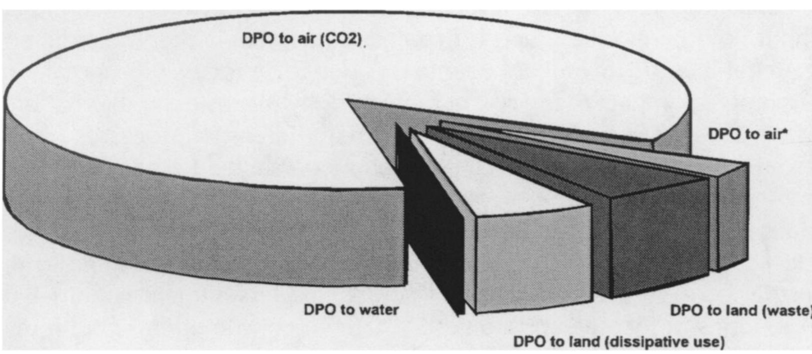

FIGURE 7. Material Outflows (DPO) from affluent industrial economies according to their composition by gateways, 1996; Austria, Germany, Japan, The Netherlands, United States (unweighted average on a per capita base).

Source: Matthews et al., 2000; own calculation.

THE REDUCTION OF MATERIAL INTENSITY IN AFFLUENT INDUSTRIAL COUNTRIES: A FREE GIFT AT THE EXPENSE OF DEVELOPING COUNTRIES?

So far, we have been able to demonstrate that a certain reduction of material intensity during recent decades seems to have been ubiquitous among affluent industrial countries, both on an overall level and on a per capita level. With the help of aggregate MFA indicators, we were able to show that material pressures on the environment have been increasing, but certainly at a lower rate than affluence, and at no higher a rate than population numbers. Why did this occur? Possible explanations that we can offer at this stage are:

a. technological change driven by the emphasis on cost reduction and profitability[24]
b. a change in consumption patterns away from materially intensive commodities towards labor intensive services and
c. a change in the international division of labor characterized by the externalization of the most materially intensive processes of raw material extraction and industrial production to the "peripheral" countries of the "South."

While (a) and (b) could be dealt with in the framework of the IPAT-model as a "Technology" explanation, (c) exceeds the model's framework and calls for a different paradigm.

Let us now return to the above questions of the environmental impact of input flows, and follow up on hypothesis (c), namely that the reduction of material intensity in affluent countries is due to a process of externalizing environmental impact to the rest of the world, by means of an international division of labor in which the most materially intensive processes of raw material extraction and industrial production are shifted to the less affluent countries in the South. These countries, then, bear the main burden of the exploitation of their natural resources, as well as the burden of increasing domestic wastes and emissions for commodities largely consumed in the industrial core. At the same time, of course, the less affluent countries do gain in terms of income and domestic material consumption—but, it may be suspected, at a disproportionately lower rate.[25]

Unfortunately, there is too little data to test this hypothesis systematically. We can gain some indications from a comparison of the material dimension of imports and exports of industrial countries with (largely preliminary) data on developing countries (Figure 8).[26] If we look at the development of imports and exports in affluent industrial countries during the last two decades, we see them rise in proportion to the material input (DMI), as is to be expected from ordinary economic statistics. In terms of weight, all affluent industrial countries documented in the statistics import at least twice as much as they export (much of these imports being raw materials), and those exports rose steadily relative to the materials that were extracted domestically (Figure 8). Quite a contrary picture can be gathered from the developing countries as displayed in Figure 8. In these countries, exports exceed imports by a factor of 2–4 in terms of weight, and they are also growing steadily. Imports, on the other hand, are stagnating or even temporarily declining. So, as far as can be suspected on the basis of this very limited data, developing countries seem to be have been increasingly playing the role of suppliers of materially intensive processes and products for affluent countries throughout the last two decades.

Muradian and Martinez-Alier (2001) tried to approach this question by means of an analysis of the material flow implications of international trade. They analyzed the South-North trade flows of non-renewable resources in physical terms (metric tons) for the period 1968–1996. At least for most of the resources considered, their results seem to point toward an increasing demand on the part of the North: imports of aluminum showed a sevenfold increase; pig iron, iron and steel shapes, petroleum products and nickel (alloys) increased by a factor of 3–4, natural gas, zinc and copper ores doubled; copper alloys and bauxite rose by 30%; and only tin ores and mineral fertilizer imports showed a substantial decline, while the rest of the materials analyzed (tin alloys, lead, zinc ores, nickel ores, iron ores, lead ores, crude petroleum) remained more or less stable. Giampietro and Mayumi (1998) have analyzed the trade relations of Japan, a country particularly dependent upon imports of forest and agricultural products, and arrived at the conclusion that the expansion of Japanese forests during the last 20 years was related to the high rate of deforestation in Indonesia. Similarly, Schandl and Schulz (2001) have interpreted the United Kingdom's exceptionally low and even still decreasing level of per capita material input as a possible consequence of the UK's terminating raw material extraction and even of its de-industrialization, industry being given up in favor of generating service-sector income. In the course of these developments, UK citizens are not necessarily lowering their level of material consumption or even the material intensity of their consumption (Jackson & Marks, 1999), but they increasingly satisfy their needs with imported commodities. Such a scenario must automatically result in the reduction of domestic material intensity, since imported commodities contribute to Direct Material Input (DMI) by their weight at crossing the borders, leaving behind all the material loads (hidden flows) involved in producing them.

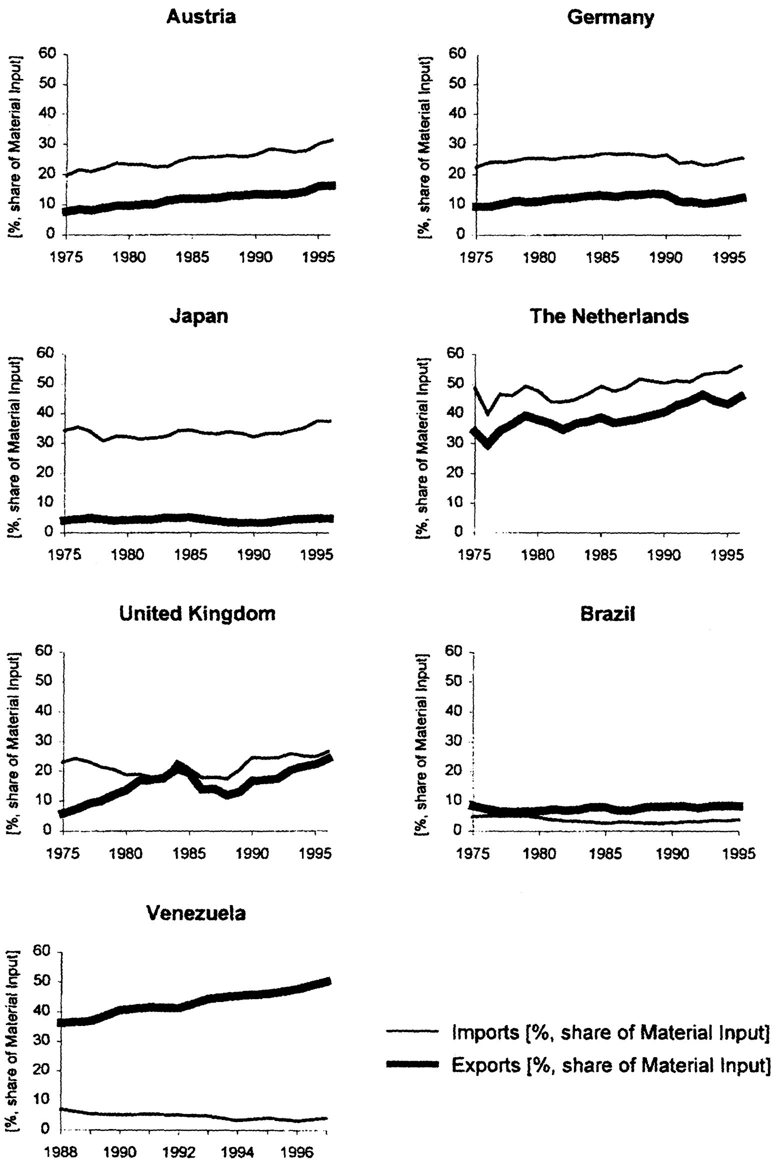

FIGURE 8. Material Profiles of International Trade: The relative weight of imports and exports of affluent industrial economies as compared to developing economies.

Source: Matthews et al., 2000; Schandl and Schulz, 2000, Castellano, 2001 (preliminary data), Machado, 2001 (preliminary data); Authors of "The Weight of Nations," 2000 (personal communication); own calculation.

But if this is so, might not the inclusion of the "hidden flows" of imports correct for this distortion of the picture? Would the widely favored TMR, "Total Material Requirement," more truly represent the changes in material intensity associated with affluence? We do not believe that this is so, because of the latent structures illustrated in Figure 9.

The model in Figure 9 distinguishes four stages of the process of material production and consumption. It all departs from Nature; all materials, before they even come to be considered as resources for the satisfaction of human needs, rest in the biotic or geophysical natural environment. At this stage, their weight is at a maximum and their economic value is (still) zero. Thus, mathematically speaking, their material intensity is indefinite. In the first stage of the socio-economic processing, there is resource extraction. Certain materials are selected from the environment and extracted to be used. Be it in mining, agriculture, or forestry, the initial amount of these extracted materials is large in comparison to the next stage because they contain many unusable parts that are left behind as wastes after further processing. In mining, for example, the (unused) overburden amounts to a

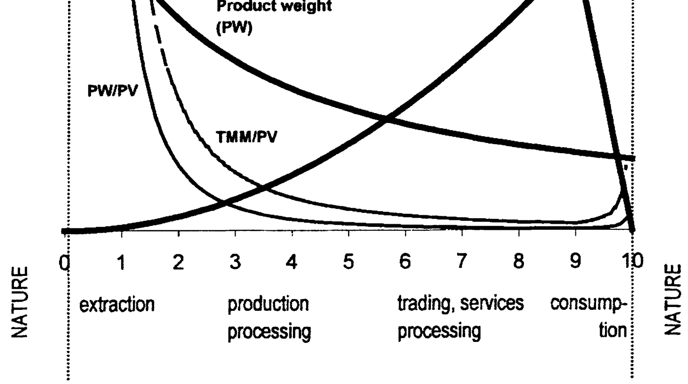

FIGURE 9. Model of extraction/production/consumption cycle in physical and economic units.

Source: own figure.

multiple of the valuable raw material extracted. Although to a smaller extent, the same applies to forestry and agriculture. At this second stage, economic value accrues only to the usable parts, is proportional to the efforts invested in extracting them, and is still fairly low. As a result, the material intensity at this stage is high: many tons make for little money value. The next stage, or rather stages, are production. Here, various selected raw materials are drawn into production, are processed, and are combined to make usable commodities. The total mass of all the products coming out of the production processes is invariably smaller than the amount of raw materials that entered production, and the longer the production chain, the greater this difference is bound to be. The rest, unless recycled or used for other processes, is "left behind" (there is inevitably something left behind). With each step in the production process, though, there is value added. So, with each step in the production process, material intensity decreases—i.e. there is less mass with higher value. Would a possible next stage, the stage of the provision of services, be any different? We think that it can be characterized by the same pattern. Products from the preceding stages are used, even if these products include no more than the food a service worker needs to keep working, the buildings in which this takes place, and the tools and electricity needed. Also, value is added. The materials used need to be replenished at some point. In the final stage, the stage of consumption, the commodities' total material weight is already very small, while their value at the point of sale for consumption is at a maximum. So, at the very point of sale for consumption, material intensity reaches its minimum: little material for a lot of money. In the course of further consumption, materials and values both decrease. Materials are gradually reduced through the process of consumption, the simplest examples being the eating of food or the wearing (out) of clothes, the value of these assets reaching zero in the end. The last stage returns to "nature" since in the end the products' remains have become wastes, no longer part of the socio-economic sphere and with no more value accruing to them. (taking account of the cost involved in disposing of these remains, one can consider their value to even be negative). In the end, material intensity can be said to be indeterminable or even negative (a finite number divided by zero or a negative number).

This profile of material intensity has to do with the fact that the economic process is as much a process of "added value" with a sudden return to the value zero[27] as it is a process of "subtracted materials," materials gradually turning into wastes. If we now think of socio-economic systems positioned along the extraction-consumption scale and think of their material input (DMI) on the one hand and their (monetary) economic product on the other hand, we may expect them to be more "materially intensive" the further down they are toward extraction (more material for less value). At the same time we can expect them to be less materially intensive the more they center around services and consumption. In terms of economic sectors, agriculture or mining will always be more materially intensive than, for example, teaching or hairdressing. In terms of national economies, a country specializing in banking, insurance, and research will have a low material intensity while another country with a strong reliance on mining, agriculture, and steel production will have a high material intensity—regardless of the material standard of living of its inhabitants (see the downward curve of DMI/GDP in Figures 2 and 5).

If we do not use Direct Material Input (DMI) to calculate material intensity and use Total Material Requirement (TMR) instead, what difference does this make? Even if we think of an "ideal" TMM that includes all the materials required from extraction onward[28] and that therefore "carries along with it" all the wastes "left behind" in the course of extraction and production processes, we still find that the characteristic profile of material intensity decreases when following the path to consumption, except that the decline is not as *rapid* (Figure 9). Dividing a constant (TMR) by an increasing number ($ value) can quite obviously result only in a negative function.

From this model we can learn that the more the socio-economic system under investigation is positioned to the right—that is, to the later stages in the production-consumption chain—the lower its material intensity is bound to be. Traditional agricultural economies, for example, have a high material intensity since even a very modest level of material comfort is characterized by much material input with little economic value. If we push the case to the extreme and think of a rural subsistence economy with no monetary income at all, the calculation of material intensity will result in an infinite number.

Let us return now to the empirical world and consider the model of an international division of labor in which peripheral countries extract raw materials (such as agricultural produce, crude oil, or metals) for sale to affluent industrial countries. In the periphery, material turnover would be much greater than what is consumed by the local population for its material comfort, and much of the income from raw material exports would be used to provide those—again very materially intensive—structures needed to produce and export raw materials (roads, harbors, mining infrastructure, etc.). Only a small amount of national income would be expended on the import of very expensive and materially less intensive commodities. As a consequence, material turnover and its impact on the domestic environment in the periphery would increase at a high rate, while these countries' affluence in monetary terms would hardly keep pace.

Unfortunately, the database available to test this assumption is empirically highly insufficient.[29] For industrializing peripheral countries, only a few preliminary MFA data yet exist. Figure 10 displays two such cases.

The cases we can present are those of Brazil and Venezuela. Data for Venezuela cover the period from 1988 to 1997, when this country became a major exporter of raw oil and paved its way to a certain level of prosperity. Data for Brazil extend from 1975 to 1995, a phase of rapid economic change. As we can see from Figure 10, material input per capita is much the same as in the industrial core. When we get a little closer to grasping the inhabitants' "material comfort" by subtracting exports from DMI—that is, when we talk about DMC (domestic material consumption) per inhabitant—we get differing results for the two countries. DMC is much lower in Venezuela, but in Brazil it is quite the same as it is in the rich industrial core countries, so that DMC seems to have little power to explain their actually common situation: that of industrializing peripheral countries (one

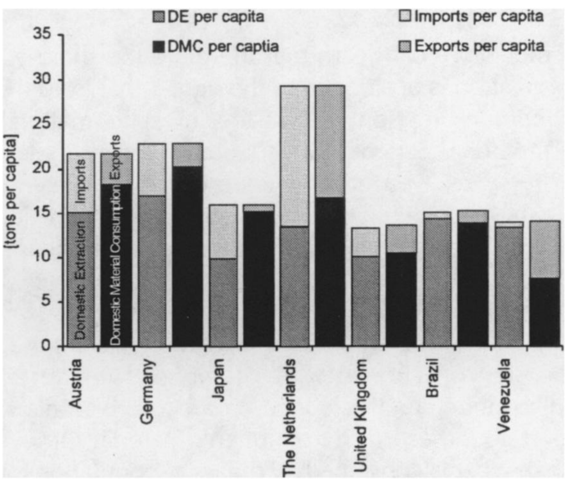

FIGURE 10. Searching for an Indicator of a Population's *Material Comfort*: Per Capita Material Input (DMI, DMC) for affluent industrial economies and for developing countries.

Source: Matthews et al., 2000; Adriaanse et al., 1997; Schandl and Schulz, 2000; Castellano, 2001; Machado, 2001; Authors of "The Weight of Nations," 2000 (personal communication); own calculation.

experiencing rapid change, the other having begun to export oil, and both in the same situation of poverty for the mass of their populations). And what about material intensity? Both cases display a material intensity (DMI/GDP) quite above that of the industrial core. We feel that this result can be interpreted as confirmation of the considerations outlined above. Both Brazil and Venezuela have a large primary (and secondary) sector, producing raw materials and first stage products (such as pig iron) and selling them on the world market at a comparatively low price. Therefore, their material intensity is high. At the same time, their populations have a comparatively low standard of material comfort and therefore a low material input serving domestic consumption (at a low price) (see Figure 11).

If we now look at the time series exposed in Figure 12, we can see that Venezuela and Brazil represent the pattern predicted above: DMI grows more quickly than GDP, and material intensity is even rising—quite in contrast to the industrial core, where we have found GDP to be the fastest growing variable with a resultant decline in material intensity. In conjunction with our findings on the complementary dynamics of imports

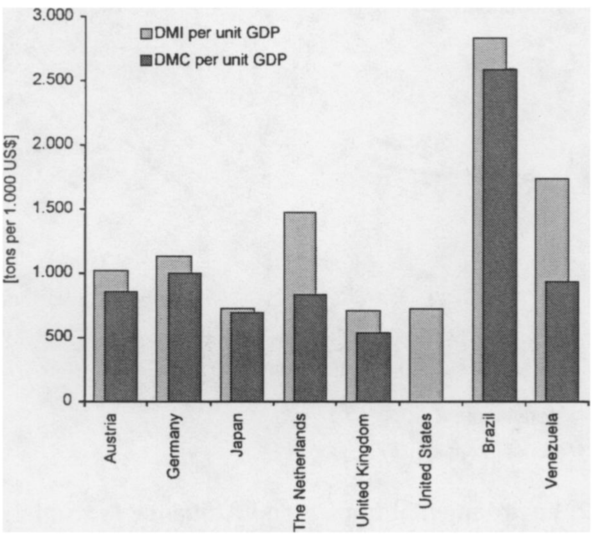

FIGURE 11. Per unit GDP Material Input (DMI, DMC) for affluent industrial economies and for developing economies, 1996.

Source: Matthews et al., 2000; Adriaanse et al., 1997; Schandl and Schulz, 2000; Castellano, 2001 (preliminary data); Machado, 2001 (preliminary data); World Resources Institute, 1998; Authors of "The Weight of Nations," 2000 (personal communication); own calculation.

and exports (see Figure 8), our hypothesis of changing material intensities in both the "North" and the "South" as a result of asymmetrical interaction in international trade seems well warranted.

The preliminary conclusion we may draw from the above is that the interrelation between environmental Impact and Affluence is much more complex than the IPAT model would suggest. Among these complexities, the question of scale figures most prominently (Giampietro & Mayumi, 2000). All socio-economic systems for which the IPAT question may be posed are embedded not only in natural environments but also in networks of social systems with which they interact. The very nature of this interaction seems to be of crucial importance for their environmental (and of course also their economic) performance, and this is even more so in the face of globalization. Material flow analysis provides some valuable tools for gaining an understanding of these intricate processes, but it is still far from supplying all the answers.

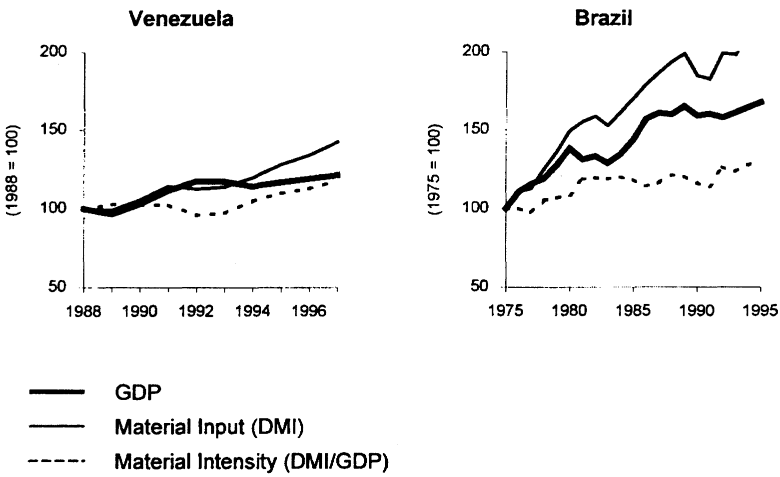

FIGURE 12. Environmental Impact and Affluence IV: Material Input (DMI), Gross Domestic Product (GDP) and Material Intensity (DMI/GDP) for developing economies, 1988–1997 (Venezuela), 1975–1995 (Brazil).

Source: Castellano, 2001 (Venezuela, preliminary data); Machado, 2001 (Brazil, preliminary data).

HOW DOES POPULATION RELATE TO MFA INDICATORS OF ENVIRONMENTAL IMPACT?

Population as a variable tends to be neglected in MFA-related studies, except for being used as denominator to help "standardize" data. The assumption behind such a standardization is very simple: if the per capita material input or the per capita emissions of two countries are alike, the inhabitants of these countries are supposed to cause the same burden for the environment each. If the number of inhabitants grows, the environmental burden is supposed to grow proportionally. Let us first pause to examine this simple model and discuss what it means.

According to MFA methodology, the human population is one of the biophysical compartments, one of the "material stocks" of a society. Reproducing this particular stock by appropriate flows is what socio-economic metabolism is all about. So, with the *way of life* held constant or, in other words, at the same level of "material comfort" and technology, flows will increase as stocks increase. If we imagine a simple agrarian society, an increase in per capita flows will occur in years where there is a rich harvest, implying more material comfort for the inhabitants; vice versa, a decrease may mean material deprivation. Typically, a feedback loop from material comfort to population numbers is assumed: If material comfort is high, people supposedly tend to have more children, and their children tend to survive infancy, and so population growth follows until it is checked by lack of resources. Within the framework of this simple model, a social system's metabolism would be closely linked to population, with per capita flows remaining fairly constant over time, while population may vary.[30] In this framework, changes in per capita flows would be synonymous with changes in material comfort, but of course not synonymous with "affluence" in monetary terms. The extent to which a system is "monetarized"—i.e., the extent to which it represents its material processes and its use values in monetary terms (or as exchange values)—is a second question that must be answered independently. We may have a system where everybody is well fed, housed, and cared for, with very little money involved, or we may on the contrary have a system with materially very poor comfort for the vast majority but great affluence for a small elite through the sale of, for example, raw oil. We may also have transitions between various states in which, for example, material comfort deteriorates while affluence on the base of raw materials exports soars; or we may have a case where material comfort remains more or less constant and the economy becomes increasingly monetarized, that is, "affluent" in GDP terms. In these transitions, traditional forms of population regulation will most likely deteriorate and give way to much more irregular patterns, and we will usually see more population growth than before or thereafter. In sum, understanding these transitions, in any of these dimensions, is a complex undertaking.

Let us assume now that raw material extraction for export kicks off such a transition. This would lead to a combined increase in affluence (income generated by exports) and in material flows (raw materials extracted and exported). Both would have little relation to population numbers. To what extent affluence and material flows grow in relation to one another would depend only on the world market price per ton of material extracted. As in the case of petroleum, this price may be comparatively high, or, as in the case of agricultural and forestry produce, it may be fairly low. If the world market price per unit of weight declines (as is the case with most raw materials), material flows would grow faster than income. This dynamic would not be causally related to population numbers or population growth. The income generated by exports could lead to a gradual change from a subsistence economy to a market economy ("monetarization") with no increase and possibly even with a decrease in the local population's material comfort except for the soaring consumption by local elites of valuable but low-weight import products. To some extent, the income generated by exports will also be invested in technological change, particularly in infrastructure (energy facilities, transport networks, etc.), and will lead to social change. This social change will most likely destabilize traditional controls of reproduction, and trigger population growth. As a consequence, material domestic consumption will have to grow proportionally or else a large part of the population will face absolute impoverishment. Let us now look at affluent industrial countries. We may assume that several mechanisms are in place to keep the material comfort of the population at least constant. If the population grows (as it does in most affluent countries, albeit slowly), material flows then grow proportionally. But we may not assume that this material comfort, however large it may be, triggers population growth by increasing reproduction—the old "Malthusian" argument certainly does not apply here (anymore). If the population grows, it is typically because of an influx of people from beyond the national boundaries. Countries usually try to regulate this immigration in such a way as to maintain the average material comfort of the inhabitants. Also, the immigrant population is expected to be able to maintain a standard material comfort closer to that of their new country than that of their country of origin. If there are few jobs available and if there is no adequate housing, affluent countries attempt to slow immigration down. On the other hand, if people did not expect substantial improvement in their material living conditions and if this expectation were not confirmed on the average, they would not migrate (apart from special circumstances of political oppression in their home countries). Taking immigration as an isolated effect, population growth in affluent countries would generate a proportional increase in domestic material flows. Globally speaking, however, the effect would be much larger; transforming an inhabitant of a nation like India into an inhabitant of a nation like the United States means adding the per capita material turnover of a US citizen while subtracting the (much lower) per capita material turnover of an Indian citizen. If we strain the little evidence we have, we might tentatively conclude that on the national scale, environmental pressure in terms of MFA grows proportionally with population numbers in affluent countries, while material flows and population numbers are only more loosely associated in developing countries.

CONCLUSION

In the introduction we asked in what respects MFA can be considered an appropriate tool to relate population and environmental impacts, and we asked how thoroughly population issues would have to be taken into account with an MFA-type analysis. Using the IPAT model, what conclusions can we now reach regarding these questions?

As concerns the utility of MFA, it seems clear that MFA methodology provides reliable—if indirect—indicators for environmental impact, about on the same level of generality as the other variables commonly used for IPAT models (population and affluence in particular), and it seems clear that MFA provides these indicators at a comparable level of methodological consistency and reliability. The public MFA data base for analysis of this kind is expanding rapidly, so within a reasonable period of time many opportunities to actually use such data for more sophisticated modeling will be opening up. However, MFA still lacks those indicators for a national or regional population's "material comfort" (as distinguished from their level of affluence) that would create a systematic link to population. The indicators in use, such as DMI per capita (Direct Material Input of the national economy), TMR per capita (Total Material Requirement), DPO per capita (Domestic Processed Outflows to the domestic environment) and TMO per capita (Total Material Outflows within a domestic environment, including domestic "hidden flows"), all fail to distinguish the "material comfort" of a national population from that part of their economy's material turnover which serves the consumption of other populations. Even DMC (Domestic Material Consumption), which was especially designed to reflect the amount of materials used domestically by subtracting exported materials from DMI, does not fulfill this purpose because it still contains all the materials required for the production of export commodities, and these materials may be a multiple of the weight of the exported commodities themselves. Most probably, through further development of MFA methods and through learning from economic accounting—which basically had to resolve the same problems and did so successfully—such indicators will be able to be provided (for some attempts in this direction see Hinterberger et al., 1998).

So far, population as a variable has received fairly little attention from the MFA community. While the human population is generally considered as a biophysical compartment of socio-economic systems and stocks are assumed to be reproduced by corresponding metabolic flows, even the net balance of human "stocks" as generated by immigration and emigration is usually neglected.[31] While population numbers are commonly used as a way to "standardize" material flows and affluence (as is done with Kuznets curves modeling the relation between these three variables), there exists no thorough analysis of the impact of change of population numbers on change in material flows so far. The general (usually unspoken) assumption in MFA is that material flows, if affluence and technology are controlled, changes proportionally to population. In comparisons of widely different socio-economic systems (such as hunting-and-gathering or agrarian communities vs. industrial nations) it is common to speak of a "characteristic metabolic profile" (Weisz et al., 2001) per inhabitant. It has been explained quite plausibly and also been demonstrated empirically (Sieferle, 1990; Sieferle, 1997) why the amount and kind of materials required to sustain a person in systems differing strongly in their Affluence and "Technology" (expressed in terms of the IPAT model) should vary by factors of magnitude. Other empirical evidence points to environmental impact changing proportionally with population within a certain range of Affluence and "Technological" conditions. For core industrial countries it could be demonstrated that various national MFA indicators changed at roughly the same rate as population did during the last decades, while the relationship to affluence seemed much less clear. But even a minor difference in "Technology" (again, with T as a compound of variables ranging from technology in the strict sense of the word to economic structure and policy) may generate substantial variance in MFA indicators, as can be seen if one examines the data from Matthews et al. (2000) and compares per capita MFA indicators across industrial countries, for equal levels of affluence. For the per capita environmental impact (as reflected in MFA indicators), it thus makes a giant difference under which socio-economic conditions of the system a person lives.

What we have concluded so far can be formalized within the IPAT model and does not transcend the theoretical framework provided there. Some of our considerations and empirical indications point beyond that model, though, and point even more so beyond Kuznets analysis. If we take into account the intricate network of interrelations that exist between different (national) socio-economic systems—the exchange relations becoming ever more dominant for economic, material, and population flows, and of course also for technologies, thereby substantially affecting each system's performance and internal development—then we will have to look beyond these two models. On the one hand, we must conclude that Kuznets analysis is bound to produce very different results when applied longitudinally within systems than when applied across them, and on the other hand we must conclude that the IPAT model leads to results that depend on the scale on which it is used. In effect, both IPAT and Kuznets models will tend not only to belittle the environmental impact of core industrial countries and their populations but also to see the change that happens in these countries in too optimistic a light. While there exist various sound analyses indicating that this is so, a model that has the capacity for a comprehensive and simultaneous view of intra- and inter-system dynamics is not in sight, at least not yet.

ENDNOTES

1. It is interesting to note the cycles of the debate: While, in the late Sixties and early Seventies, systemic criticism of the "limits to growth," with a certain focus on resource inputs, dominated, the later Seventies and Eighties can be characterized by sequential single-issue discussions of pollutants. In the Nineties then, with a focus on the global environment and issues like climate change and ozone depletion, a more comprehensive systemic perspective was employed again. According to this, Ehrlich and Holdren (1971) are typical representatives of their "generation" of environmental scientists, while Dietz and Rosa (1994) are among those who—after an intermezzo—strive to re-introduce the systemic perspective.
2. Although they see some merits also in this accounting analysis approach and refer in particular to Mazur (1994) who has used not IPAT itself, but a similar model to assess the relative contribution of population and other factors to energy consumption in the US.
3. For example: in an early application, Hoch (1972) uses regression models to estimate the effects of population size and density of US urban areas on air pollution levels, wages and crime rates. Stochastic modeling has also been applied in studies of deforestation (Allen & Barnes, 1985; Dietz et al., 1991; Rudel, 1989). All three of these studies find that population size, growth rate, or density has a stronger effect on deforestation that does economic activity. Jänicke (1993) has applied similar models to the analysis of structural economic change and environmental impact, but has not analyzed population effects.
4. Particularly concerning exchange rates with international comparisons and the corrections for inflation with time-series data.

5. As long as we take "affluence" to be a measure of wealth and not of welfare or even well-being, as some aspire to do, we see no problem in accepting GDP as what it is, namely as a measure of economic activity in monetary terms.
6. Most recently, EUROSTAT (the Statistical Office of the European Union) published guidelines for "economy-wide MFA," based upon the advice of many of the scientific and statistical institutions that had been involved in developing materials flow analysis methods (Steurer et al., 2000). At the same time, the OECD has published a report endorsing the broader use of MFA for environmental accounting (Schandl et al., 2000).
7. Upon closer consideration, the "territorial boundaries" of nation states can be seen not simply as "geographical" but as referring to power realms and mutually accepted social definitions.
8. Some approaches also consider *plants* as a compartment of the social system (Stahmer et al., 1997). If agricultural plants are considered to be part of the socio-economic system, the boundary between this system and its environment is "pushed outward," to the mineral level, except for fishing, hunting and gathering. This does not correspond to any existing economic statistics, and besides it is difficult to distinguish between "social system plants" and "natural plants" (Fischer-Kowalski & Weisz, 1999). So while the inclusion of plants may be warranted for some theoretical reasons—for example because agricultural plants are maintained by human labor just as livestock are—it is usually not considered practical.
9. In modern industrial economies, "other materials" amount to only about 5% of the overall material input, the rest is water and air (Fischer-Kowalski et al., 1997). However, the distinction becomes fuzzy upon closer examination, as the "non-water-non-air" fraction is not free of water and air. Moreover, the content of water and air of the various materials changes due to natural processes such as evaporation and oxidation, and also due to technical processes within the socio-economic system. For the calculation of a mass balance, these processes have to be taken into account. So far, the methods applied have proved to be not completely consistent (see for example the country reports in Matthews et al., 2000)
10. Usually, these rucksacks comprise the non-water-non-air wastes and emissions that occurred during the production process of an imported good in the country of origin, and particularly large material flows that occur as side effects of domestic extraction (such as overburden in mining or eroded soil in agriculture). The sum of Direct Material Input and hidden flows has been termed "Total Material Requirement" (TMR). Be aware it is not "total" in the sense of including water and air! So far, there exists no term to signify the "grand total" of all material flows including water and air crossing a system's boundary. Among others, this terminological problem must still be resolved. When summing up or averaging TMR across countries, one must be aware that this involves double counting (namely, the hidden flows of imports).
11. Following an idea from Daly (1987), who considered the size or scale of human socio-economic systems in relation to natural systems as a crucial point, one might look at the growth rates of stock as a core indicator of environmental impact. On a limited planet, the continuous growth of societal biophysical structures must oust non-human controlled habitats from this planet. Besides, while annual direct material flows can be calculated from economic statistics in a fairly reliable fashion, "Net Addition to Stock" (NAS) tends to be calculated as a residual variable. The estimation of the size of the biophysical stocks themselves is not so easy, either; while humans and livestock are well known, the stock of durable consumer goods and built infrastructure (the latter amounting to more than 90% of stocks, typically) can be calculated only within a certain span of uncertainty.
12. At present, the concern of global warming has indeed brought attention to the environmental risk attached to non-toxic but very large material flows (such as CO_2 and methane). It is interesting to note that Ayres and Kneese (1969) correctly foresaw this.
13. For an early example see Larson et al., 1986.
14. This is basically a question of scale. For single commodities or single production pro-

cesses or even for whole economic sectors (Schandl & Zangerl-Weisz, 1997; Jänicke & Weidner, 1997), cases of strong delinking may be found. The further up on the hierarchical scale one looks—for example, national or regional economies—the more difficult it becomes.

15. Much of the data presented here is derived from two pioneer studies published by the World Resources Institute in collaboration with European and Japanese partners (Adriaanse et al., 1997; Matthews et al., 2000). In a collaborative effort, the partner institutions tried to resolve the conceptual and methodological problems involved and arrived at data sets that are actually comparable across national economies. These data are published in a user-friendly way so as to allow the scientific community to participate in their further analysis (the data can be downloaded from <http://www.wri.org/materials/weightofnations.html>).
16. Most of the discontinuities in DMI can be explained by specific national conditions, such as particularly large extractions of oil (as in the UK, for details see Schandl and Schulz, 2001), the German unification in 1991, or a severe reduction in public spending on infrastructure construction (such as in Japan in the early eighties, see Moriguchi, 2000).
17. Some of the growth in DMI is due to an increase in international trade rather than Domestic Material Consumption (DMC). As we shall see below, DMC changes in some countries may come very close to "absolute delinking."
18. At the first stage, when they are released from the socio-economic system into the environment. Later, these material outflows may of course dilute to other media, such as nitrates from fertilizers washing out into groundwater. In the framework of Matthews et al. (2000), only the immediate transgression from the socio-economic system into the environment is registered.
19. DPO to air* is DPO to air without the emissions of CO_2.
20. The same, by the way, holds true for the material loads in wastewater and also for domestic "hidden flows"—i.e., overburden from mining and soil erosion (Matthews et al., 2000).
21. Kuznets (1955, 1966) used these functions originally to describe the interrelation between the growth of gross national income and the degree of inequality of income distribution. His aim was to demonstrate that inequality increased in early stages of economic growth and declined at higher levels of GDP per capita.
22. With the exception of Germany, where special conditions prevail. The German unification led to a reduction in the use of lignite in favor of natural gas, thereby causing a lower level of CO_2 emissions.
23. According to the Matthews et al. (2000) data, the same applies equally to solid waste and air pollutants when compared *across* countries.
24. Even when the price of raw materials is declining as was the case during this period for practically all raw materials (see U.S. Geological Survey <http://www.usgs.gov/>), they still constitute a relevant factor in production costs. Also, especially in the face of increasing international trade, there are rising costs of transportation that strongly depend on the weight of the commodities to be transported.
25. This is the major assumption from the "World Systems Theory" tradition (e.g., Bunker, 1985). Similarly, Ekins (1997) pointed out that it was possible that the consumption of environmentally intensive goods is increasingly being met by imports.
26. Data calculation for Venezuela and Brazil was part of the project "Amazonia21—Operational features for managing sustainable development in Amazonia," funded by the INCO-DC Program of the European Comission, DG XII.
27. In their early work, Ayres and Kneese (1969) found this to be the point in which modern economics is at variance with such basic physical laws as thermodynamics or the law of conservation of mass. See similarly Odum (1971) for the reverse cycles of energy and value.
28. This is not the case with the TMR indicators used according to the Wuppertal Institute's methodological traditions: This TMR includes only overburden and erosion from domes-

tic extraction, and for imported commodities it contains only a fraction of the background materials used for the chain of extraction and production (see Schütz 1999, Eisenmenger & Hutter, 2001). Besides, these data rely on many estimates and tend to be much less reliable than data on Direct Material Input.

29. There are several ongoing research efforts working to fill this gap, however. Both the Wuppertal Institute and the team of the IFF-Social Ecology in Vienna are involved in projects aimed at supporting developing countries in their efforts to generate national MFA data corresponding to international standards.
30. As different historical examples illustrate, the amount of "overshoot" that may occur depends on family structures, gender relations and reproductive culture. While the collateral "Western European Family Type" common to many agrarian societies of the former Roman Empire leads to marriage depending upon the economic performance of the prospective husband, and therefore little "overshoot" of population over resources, the typical family structure of most other agrarian societies is patrilineal, with early marriages economically supported by the extended family; in the latter case, population overshoot can be higher and will be periodically checked by famines, epidemics and civil wars (Oesterdiekhoff, 2000).
31. Even the arrows representing immigration and emigration in Figure 1, reminding of the need to consider these processes, are usually absent in related systemic models, for example in Matthews et al., 2000.

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