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NATIONAL MATERIALS FLOWS AND THE ENVIRONMENT

Iddo K. Wernick and Jesse H. Ausubel
Program for the Human Environment, The Rockefeller University, New York, NY 10021

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ABSTRACT

The functioning of modern societies requires large flows of materials to satisfy human wants both directly and indirectly; for example, 50 kg per day per American. The nature of these flows determines their impact on the natural environment. We develop and test a comprehensive framework to order materials flows in the US economy. We assess and quantify inputs to the national economy, outputs, foreign trade, and wastes from resource extraction, using mass measures of these flow components. The bulk of materials inputs satisfies demand for energy, construction, and food. Atmospheric emissions and materials embedded in long-lived structures dominate outputs, with smaller contributions from solid wastes and dissipated materials. Trade, accounting for approximately 10% of US materials flows, is dominated by bulk commodities such as fuel, food, and chemicals. Extractive wastes from fuel and nonfuel minerals account for more than double the amount of inputs and mostly remain at the site of generation. Metrics based on a consistent, periodic accounting of

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physical materials flows can provide a powerful means to assess environmental performance at the national level. Improvements in the collection and organization of the data supporting national material accounts will further their utility.

Introduction and Method

Modern societies mine and metabolize large quantities of materials. Individuals directly consume food, clothing, and other goods ranging from accordions to zoom lenses. Less directly, people consume materials for shelter and power, for travel and communication, and in agriculture and industry. In 1990 each American mobilized on average about 20 metric tons of materials, over 50 kg day^{-1}, a mass equal to an average person's body weight every day or two. At this rate a person consumes about 1600 metric tons over the course of an 80-year life. This mass would occupy a cube almost 12 meters on a side with the density of water. With the typical density of a bag of household trash, the sides of the cube would exceed 18 meters. Such heavy use of materials necessarily raises environmental concerns.

This paper reviews materials flow at the national level from an environmental viewpoint. The framework we use gauges the flow at four stages: inputs to the economy, outputs, trade with other nations, and wastes from extractive industries. In assessing inputs we divide materials into six classes: energy, construction minerals, industrial minerals, metals, forestry products, and agriculture. We class outputs in five groups: domestic stock, atmospheric emissions, dissipation, other wastes, and recycled materials. We arrange foreign trade by individual commodities and classes of commodities. Extractive wastes include residues from the mining as well as the oil and gas industries. We provide brief comments on the flow of selected materials and materials classes at each of the four stages, with a focus on the relative size and the interdependence of the materials. Then, we propose a set of measures to evaluate national environmental performance with respect to materials. Finally, we consider applications of materials flow accounts and obstacles to their improvement.

We choose the United States as the subject of our study because it operates by far the world's largest economy and uses the most material by most measures (1). Moreover, it has well developed data that are familiar to us. The framework developed here should serve for other nations as well. In fact, contrasting national case studies would improve the framework and enhance interpretation of data. We select 1990 as the main reference year to allow for publication and revision of data yet remain relevant to current issues.

Various concerns have inspired comprehensive materials studies. In the 1950s in the United States, prospects of shortages of strategic materials in the event of conflict led to *Resources for Freedom* (*The Paley Report*), a congressional study which stressed questions of resource access (2). By the early

1970s, the adequacy and depletion of the natural resource base (3–6) in light of global economic development joined strategic fears as a major cause for assessment. During the 1980s, the environmental consequences of resource consumption motivated more studies (7, 8).

Since the Brundtland Commission report in 1987 (9), the need has grown for rigorous frameworks and measures to give substance to the debate over sustainable development (10, 11). Sustainability inevitably involves choices between the well-being and security of current and future generations. Such choice is arbitrary without periodic measures that monitor changes in national, as well as local and global, environmental performance.

Most recently, the emerging discipline of industrial ecology has inspired improved materials accounting (12–15). Industrial ecology is the study of the totality of the relationships among different industrial activities, their products, and the environment. Applications of industrial ecology should prevent pollution, reduce waste, and encourage reuse and recycling of materials. Understanding the relative scales and the relationships of the materials that flow through the national economy should expose areas of opportunity to better the performance of industrial ecosystems.

Analysts have examined anthropogenic materials flows from diverse viewpoints. Ayres has examined flows using the "materials balance principle" (16) and also introduced the biological metaphor of "industrial metabolism" (17). He has also followed global and national flows of specific environmentally sensitive heavy metals such as lead, chromium, and cadmium (18). Impressed by the heterogeneity of materials, other researchers have tried to translate them into common units of ecological impact (19). Other studies compared the scale of human activities globally with background or natural fluxes (20, 21). Researchers have also used monetary input-output models and insights from structural economics to describe the dynamics of materials stocks and flows in the economy as they affect environment (22–24).

Looking at secular trends in materials consumption, some authors emphasize the diminishing importance of basic materials in industrial economies relative to increasingly refined and complex ones (25–27). Correspondingly, several studies have suggested that after industrialization societies begin to "dematerialize:" Their economies grow while relative and even absolute demand for materials declines (28–30).

All such studies would benefit from reliable, periodic information about national materials flows. The reasons such accounts do not already exist will become apparent in the course of this paper. First we mention three major difficulties with studying materials flows and how we resolve them, albeit tentatively.

The first difficulty is choosing a common currency to compare quantities of not only apples and oranges, but apples and aluminum. Quite independent units of environmental import describe materials: volume, energy content, and toxicity, for example. In the postindustrial age, the information content of materials becomes a more salient parameter, and future studies may use bits as well as kilograms as the unit of choice (31).

We choose weight as our initial standard. Although an incomplete indicator, weight conveys the sheer quantities of materials mobilized and consumed and is easily compared. Moreover, weight data are the most widely available. Because the boundaries of the system we examine are large, the natural unit of measure is million metric tons (MMT). We examine only physical and not monetary quantities. One should be able to prepare a monetary map corresponding to our physical map, indicating where value is added and lost.

The second difficulty is scope. We seek completeness by considering the reported weight of the great majority of all inputs, outputs, trades, and extractive wastes. We omit some materials used below an annual threshold of one MMT and unreported materials migrations, such as firewood consumed by individuals or black market trade.

Unless otherwise noted, we exclude water and give only the dry weight of materials. We do not explicitly treat water consumption because the mass of this ubiquitous and precious resource would obscure other materials. In 1990, consumptive use of fresh water (defined as water that has been evaporated, transpired, or incorporated into products, plant or animal tissue, and is therefore unavailable for immediate reuse) in the United States exceeded 34 trillion gallons or about 130 billion metric tons, some 25 times other inputs (32). For similar reasons, we do not consider consumption of atmospheric oxygen for biological respiration and in industrial processes. We do include atmospheric nitrogen fixed into NO_x emissions as well as that used for ammonia production.

Our framework also does not explicitly treat manufactured chemical products and by-products, many of which fall between our categories of inputs and outputs. Our framework could be further segmented to account more fully for intermediate products such as chemicals. Organic chemical production in 1990 was about 90 MMT (33). Inorganic chemical production was at a similar level (32). Our inputs category does account for the natural gas, petroleum, nitrogen, sulfur, phosphorus, sodium, chlorine, and metals used in making organic and inorganic chemicals. Initially benign starting materials used in chemical manufacture can acquire problematic (as well as useful) characteristics subsequent to thermal, chemical, and pressurized processing.The chemical industry generated about 350 MMT of hazardous waste (wet basis), more than half the US total in 1986 (34).

The third difficulty is the availability of data. The data presented here are gathered from various sources, primarily agencies of the federal government or published literature containing data from US government sources. The accuracy of the data depends on the accuracy of the reporting agency or author. Much of the data is self-reported, a method that has been criticized for underestimating actual waste values (35). Neither definitions of materials nor their end-uses are uniform across the data sources. We have labored to remain consistent in our own definitions to avoid redundancies and omissions in our account of the flows.

Both the accuracy and consistency of current data sources need to be improved. In the data notes and the table notes and comments we discuss our sources, their methods, and a sampling of inconsistencies between different sources and within individual sources. Looking forward, we seek a comprehensive framework that contains definitions sufficiently precise that data collectors can measure and report the same quantity or entity at different times with confidence.

Together, the considerations of common currency, scope, and quality of data recommend caution in drawing conclusions. Nevertheless, we do occasionally sum totals within and across categories and point out contrasts and resemblances. We venture to indicate the potential value of the accounts and to stimulate better analyses.

Inputs

Demand for energy, construction, and food largely forms the US menu of materials inputs (Table 1). The materials mobilized are primarily commodities such as coal, oil, sand, clay, steel, and grain, sold in bulk. The input menu contrasts with goods, i.e. consumer products, which weigh relatively little and sell more on the basis of value added during processing and manufacturing. Finished goods require heavy materials inputs, often not included in end products, in the form of facilities, equipment, and auxiliary production materials (e.g. coke and lime for steel, sodium and sulfur chemicals for paper). Thus, much of the bulk accounted in Table 1 constitutes the hidden consumption needed to support society.

Energy materials, adding to almost two billion metric tons, comprise just under 40% (by weight) of materials input to the US economy.[1] The residues of these materials present severe environmental problems, and handling and transporting this vast quantity of material requires significant energy use. Of all energy materials, coal consumption is highest. This solid fuel has the lowest energy density (i.e. BTU per kilogram) of the major fuels and is the hardest

[1]About 6% of energy materials are used for petroleum and natural gas products, such as road asphalt and plastics, not energy. Apparent US consumption of uranium concentrate (U_3O_8) in 1990, an energy material not listed in Table 1, was under 15 metric tons (61). See Table 4 for mining wastes from uranium production.

Table 1 Materials flows: US 1990—inputs

Material group	Apparent consumption[a]	(MMT)	Total US	Per capita per day (kg)	Total pcpd (kg)	Reference	Comments
Energy	Coal	843.2		9.26		32	Crude oil data are based on American Petroleum Institute (API) conversion values of 6,998 bbl./MT for foreign and 7.463 bbl./MT for domestic crude. We use an average value of 8 bbl./MT for petroleum products. Imports accounted for about 45% of crude oil and 10% of natural gas consumption. The value for petroleum products shows net U.S. import reliance for 1990.
	Crude oil	667.1		7.31			
	Natural gas	377.6		4.14			
	Petroleum products	62.8	1960.7	0.69	21.5		
Construction Minerals	Crushed stone	1092.8		11.98		74	
	Sand & Gravel	827.5		9.07			
	Dimension stone	1.1	1921.4	0.01	21.07		
Industrial Minerals	Salt	40.6		0.45		74	Anhydrous ammonia is the primary feed for nitrogen compounds, including ammonium nitrate, ammonium sulfate, urea, ammonium phosphates, and other fertilizer materials. The constituents of concrete and cement are accounted for separately in the table. What is included under the category Cement is net imports of hydraulic and clinker cement. Apparent consumption of cement in 1990 was 90.4 MMT (portland 75.6, hydraulic and clinker 11.5, and masonry 3.3). The value for lime is subtracted from crushed stone.
	Phosphate rock	39.9		0.44			
	Clays	38.8		0.43			
	Industrial sand & gravel	24.8		0.27			
	Gypsum	22.9		0.25			
	Nitrogen compounds	16.6		0.18			
	Lime	16.0		0.17			
	Sulfur	13.1		0.14			
	Cement	11.5		0.13			
	Soda ash	6.9		0.08			
	Other	17.7	248.6	0.19	2.73		

Metals	Iron & Steel	99.9		1.09		42	For 1990, U.S. apparent consumption of iron ore, agglomerates, and pellets was 81.7 MMT, iron and steel scrap consumption was 45.5 MMT and net imports of steel mill products was 11.7 MMT. Apparent consumption of bauxite, the starting mineral for aluminum production, in 1990 was 12.6 MMT, all imported (74).
	Aluminum	5.3		0.06			
	Copper	2.2		0.02			
	Other	4.2	111.6	0.58	1.23		
Forestry Products	Saw timber	122.9		1.35		75	Data for 1991. The category saw timber includes saw logs and veneer logs. We assume a specific gravity of 0.6 g/cc for hardwoods and 0.45 g/cc for softwoods on a dry weight basis, green volume.
	Pulpwood	72.8		0.80			
	Fuelwood	51.5		0.56			
	Other	12.6	259.7	0.14	2.85		
Agriculture	Grains	219.7		2.41		76	The category "Other" includes cotton, tobacco, hides, flaxseed, wool, and fishery products. Also see notes[b]
	Hay	133.2		1.46			
	Fruit & vegetables	70.5		0.77			
	Milk & milkfat	63.2		0.69			
	Sugar crops	50.6		0.55			
	Oilseeds	44.7		0.49			
	Meat & poultry (Qty, live weight)	42.3		0.46			
	Other	4.9	629.1	0.05	6.90		

[a] Apparent consumption is the consumption of the commodity at the feedstock stage (i.e. refined metal, ammonia, crushed stone). This number is arrived at by adding the domestic production and imports, and subtracting exports. Apart from metals we do not account for changes in inventory.

[b] The equivalent weight for data given in bushels, gallons, or other volume and unit measures is based on USDA conversion values. The grains category represents total disappearance from domestic use of wheat, rye, rice, corn, oats, barley, and sorghum grain. Estimates for total pasture and harvested roughage consumption in 1990 summed to over 233 MMT and are not included here. The category of fruits and vegetables includes potatoes, sweet potatoes, treenuts, cacao, coffee, and tea in addition to the general fruit and vegetable categories. Sugar crops are defined as sugar beets and sugarcane; the category includes apparent consumption of maple syrup and honey. Oilseed crops are defined here as soybeans, peanuts, and all varieties of sunflower. Eggs are included in the meat and poultry category.

to move.[2] In addition, coal has the highest carbon intensity (i.e. kilogram of carbon per BTU) of the fossil fuels. Reducing absolute energy consumption as well as changing the mix of fuels used for power generation and transportation would have substantial consequences in the materials sphere. Exploiting the properties of other materials can reduce energy use. Construction and other materials can substitute for energy materials. For instance, superior insulation can reduce energy demand.

Annual consumption of construction minerals occurs on the same scale as consumption of energy materials. These materials do not cause significant environmental impacts, with some exceptions. For example, the excavation of sand from stream and river beds alters the ecosystems from which they are retrieved. End-uses for these materials also have a potential environmental downside, as they provide the means for covering land with human artifacts. Today, these artifacts cover only 1 or 2% of global land (36, 37), yet the extent and radiative properties of construction materials affect Earth's albedo and other surface characteristics important to local and global climate (38, 39). Managing the albedo of the built environment may become important in a world economy 5–10 times as large as today 50–100 years hence. Because the quantities used are massive, transporting construction materials is energy intensive. Thus, with the exception of specialty building materials such as Italian marble, they are typically retrieved from within 50 kilometers of their final destination (40).

In 1990, Americans consumed about 250 MMT of industrial minerals, approximately 5% of all materials inputs, listed here. These minerals, valued for their chemical and physical properties, have sundry uses including construction (lime and gypsum for cement, soda ash for glass, clay for bricks), agriculture (nitrogen compounds, sulfur, phosphate rock for fertilizers), and manufacturing processes (lime and soda ash to control alkalinity and for flotation).

Minerals used for agriculture alone comprise over 60 MMT, equal to more than half the total apparent consumption of iron and steel. These materials help generate abundant food and large agricultural surpluses for the United States. They also create several environmental problems arising from fertilizer use. Water pollution problems stem from agricultural runoff from land saturated with elements intended for crop uptake. Enhancing the crop uptake of mineral nutrients from fertilizers could reduce this materials stream. Fertilizers also serve to distribute harmful trace elements, such as cadmium, to agricultural soils (41). Reducing consumption of agricultural minerals without a compen-

[2]To illustrate, 97 MMT or 12% of US coal production in 1984 was captive coal, defined as coal consumed by mining companies internally (35a). In 1990, coal accounted for 40% of US freight rail traffic by weight (32).

satory increase in productivity would cause the total land area cultivated for crops to rise and lessen the area that remains, or can revert back to its natural condition, another environmental concern (37).

In accounting for metals we consider the apparent consumption of finished metals. Future studies might integrate the consumption of auxiliary materials in metals processing as well as mining and mineral processing wastes, here treated in the section on extractive wastes. Metals constitute a trifle of material inputs, about 2% in mass terms. Nonetheless, the durability and formability of this material group in addition to other desirable physical characteristics (e.g. tensile strength, toughness, thermal and electrical conductivity) have made metals essential to technical and social progress throughout human development. Iron and steel dominate the metals group and, historically, have provided the backbone of industrial society. Though unlisted in Table 1, alloying metals such as molybdenum, manganese, and cobalt, sometimes referred to as metallic vitamins, are significant components of metal flows. Consumption of these metals is relatively small, yet their ability to improve properties in bulk materials makes them essential ingredients in modern metallurgy. These elements also constitute impurities that pose problems for recycling and use in the secondary metals industry.

Recycled metal accounts for over half the metals consumed in the United States (42). However, economic, physical, and regulatory factors keep recovery below 10% for arsenic, barium, chromium, and some of the other most biologically harmful metals in the *Toxics Release Inventory*, an annual listing of US toxic wastes emissions (43).

US consumption of forestry products exceeded 250 MMT in 1990, well over twice the weight of metals. Although forestry products comprise only 5% of total materials inputs, they affect environmental quality in numerous ways and have become highly symbolic in the public debate on the environment. Forests provide an important sink for greenhouse gases and, unless balanced, excessive timber harvesting upsets the global carbon cycle. Improper logging practices can also disturb forest ecosystems, adversely affecting the habitat for both plant and animal life. Saw timber used for lumber, plywood, and other structural applications accounts for almost half the forestry products total. Pulpwood, used for manufacturing paper, accounts for almost 30%. (Wood chips from sources other than pulpwood account for the 40% of the wood input to the paper industry that is not pulpwood, an efficient use of material.) Pulp and paper industries have historically polluted water bodies. Paper comprises over 30% of municipal solid waste (44). Reuse and incineration of paper waste are the chosen strategies for recovering cellulose and energy, respectively, and for reducing the paper component in the solid-waste stream.

Combined inputs for human food consumption in the United States in 1990 sum to approximately 630 MMT, more than double industrial mineral consumption. The composition of food inputs changes with the national diet, leading to important environmental impacts, particularly regarding land use. For instance, reduced meat consumption, accompanied by a rise in fruit, grain, and vegetable consumption, alters the balance of agricultural land devoted to grazing and feed as opposed to food crops. Cultivation of legumes and rice affect the atmospheric concentration of nitrogen and methane respectively. Fertilizer and pesticide use rates are tailored to specific crops. (We have already remarked on the quantity of minerals—mainly nitrogen, phosphates, potash, and, indirectly, sulfur—consumed in food production.) We also note that energy must be expended to bring lettuce and grapefruits to cold New York from warm Florida in February.

Outputs

Materials pass through the economy on different time scales. Dams and bridges embody materials that may remain untouched for centuries. Chewing gum wrappers do not last as long. Beverage cans can have many lives. Some materials wear down through normal use, whereas others undergo phase changes and volatilize into the air. Our national account of materials outputs (Table 2) encompasses all of these fates.

Data on materials outputs are generally scarcer and harder to interpret than input data. Two important factors are the absence of uniform definitions for material end-uses and the lack of weight data for most manufactured goods. Waste outputs are often given on a wet weight basis, and in many cases the solid fraction is swamped by water. In addition, the waste's absent or unrecognized value makes waste accounting of secondary importance in many industries, though high disposal costs and regulatory requirements influence this state of affairs by forcing firms to pay attention. Dissipation data are entirely based on estimated rather than direct empirical information, as explained in the data notes.

Forty percent of US material outputs contribute to the domestic stock of materials that are incorporated into the built environment and industrial infrastructure. Atmospheric emissions, primarily produced by fossil-fuel combustion, account for a similar fraction of outputs. Approximately 3% of materials dissipates directly into the environment. About 5% of outputs recycles directly into the economy. Other wastes account for the remaining share of outputs.

Domestic stock comprises objects not consumed during normal use and designed to last for a period greater than one year. Typically, increasing the mass of domestic material stocks links with economic development. Indeed, accelerated turnover of the goods that augment this stock generally serves economic interests under the present US tax and accounting systems (45) in part because the economic transactions leading to the production and distribution of durable goods do not cover the full social costs of disposal.

Almost 90% of the 1990 material contribution to US domestic stock, 1677 MMT, was in construction. Yet, the Environmental Protection Agency (EPA) estimates that US construction and demolition generate only about 29 MMT of waste annually (46). One explanation for this difference is that the physical capital in construction amasses at an astounding rate. Another possibility is that the data do not accurately reflect all the wastes associated with construction and depreciation. These explanations are not mutually exclusive.

The materials that inhabit the built environment, and those that support the industrial infrastructure, constitute the remaining 10% of domestic stock. For example, US materials consumption for land-based transportation was estimated at about 22 MMT in 1990 (47). Materials for machinery (mostly steel) and electrical uses (mostly copper and aluminum) account for over 11 MMT, and refractory uses account for over 7 MMT (48). An example of how domestic stock accumulates is that, as of 1987, over 680 MMT of recoverable iron resided in scrap piles across the United States, an amount equal to almost seven times the 1990 iron and steel input (49).

The variety of other products in the domestic stock category precludes precise statements about their environmental effects. This variety complicates efforts to retrieve primary materials from waste streams and masks the release of potentially harmful substances that occurs in the use and final disposal of consumer products.

The quantity of materials emitted into the atmosphere rivals all the sand and stone used for building. The carbon in CO_2 from fossil fuel combustion makes up the vast majority of emissions, followed by water vapor. Table 2 also reminds us that through emissions other trace elements are liberated from their geological formations and distributed in the atmosphere, reemphasizing the important role of energy strictly from materials considerations. Energy costs and other factors often make impractical the recovery of emissions (with the notable exception of sulfur), and scrubbers designed to clean smokestack emissions generate sludges and other spent scrubber materials. Source reduction through improved efficiency continues to be the main strategy for addressing this sizable material flow.

Although dissipated materials such as pesticides constitute a relatively small portion (~3%) of materials outputs, they have a considerable impact on the environment. In fact, these materials are a major focus of industrial ecology. As with atmospheric emissions, reconcentrating dissipated materials is frequently infeasible. Their dispersion changes the balance of elements biologically available to the plants and the other animals with which humans have evolved. Metal-loaded soil is inhospitable to plant life in general. In some

Table 2 Materials flows: US—outputs

Destination	Amount (MMT)	Per capita per day (kg)	Reference	Comments
DOMESTIC STOCK	1880.3	20.61		
Construction	1677.1	18.39	48, 75, 77	This figure is obtained by subtracting the amount of construction minerals recycled, dissipated, discarded and going to other uses from apparent consumption of construction minerals. Also included in the total are clay, asphalt, imported cement, gypsum, lime, steel, aluminum, copper, manganese, nickel, silicon, zinc, and lumber used for construction. These materials are used for residential and non-residential construction, in cement and concrete products, for construction fill, road base and cover, railroad ballast, and other permanent uses.
Other	203.2	2.23	48, 75, 77	Obtained by summing apparent consumption of industrial minerals, metals, forestry products, and energy materials used for industrial and consumer products and subtracting the amount recycled, dissipated, and discarded.
ATMOSPHERIC EMISSIONS[a]	1734.7	19.02		
CO_2 (carbon fraction only)	1367.0	14.99	77	Most (98%) CO_2 emissions are from energy sources.
Hydrogen	254.6	2.79		Calculated hydrogen fraction from water vapor emitted during fossil fuel combustion. Total water vapor emitted is 2290 MMT or about 600 billion gallons.
Methane	29.1	0.32	77	Sources of methane emissions include solid waste, coal mining, oil and gas production, leakage during transmission, and agriculture.
CO (carbon fraction only)	29.0	0.32	77	Most (78%) CO emissions are energy related.
NO_x	19.4	0.21	77	Most (95%) NO_x emissions are energy related.
VOC	17.6	0.19	77	
SO_2 (sulfur fraction only)	10.4	0.11	77	
Particulate matter	5.5	0.06	77	Includes PM-10 emissions defined as particles with a diameter of less than 10 microns. Does not include PM-10 fugitive dust.
DISSIPATION[b]	144.5	1.58	42	Data do not include the dissipated amounts of dimension stone, fluorspar, mica, perlite, steel, asphalt & road oil, petrochemicals, and natural rubber.

OTHER WASTES	555.2	6.09		
Processing waste[c]	136.2	1.49	42	Data do not include processing wastes for barite, calcium, cement, diatomite, gypsum, industrial sand and gravel, magnesium, phosphate, aluminum, chromium, nickel, and refinery products.
Post consumer waste[d]	276.4	3.03	42	Data do not include post consumer wastes for cement, clays, diatomite, fluorspar, gypsum, industrial sand and gravel, perlite, talc, nickel, tin, and petroleum waxes.
Coal ash	85.0	0.93	60	Data are for 1984. This figure includes fly ash, bottom ash, boiler slag, and flue gas desulphurization [FGD] sludge. About 10% of coal used for energy recovery is ash. 20% of coal ash wastes find other uses in the economy, primarily in road construction (51).
Yard waste	35.0	0.38	44	Yard waste is organic matter and has no input accounted for in Table 1.
Food waste	13.2	0.14	44	This value is for food wastes entering the municipal solid waste steam and does not reflect waste generated in the food processing industry. Food processing wastes are overwhelmingly water.
Water and waste-water sludge	9.4	0.10	46	Based on an annual estimate from USEPA Office of Water Regulation and Standards.
RECYCLED	243.8	2.67	42	

[a] In seeking to satisfy a materials balance for the total mass of fossil fuels listed in Table 1, we note that by summing the fossil fuels emissions data in Table 2 with coal ash, we find a total of 1707 MMT. This is short of fossil fuel inputs by over 250 MMT. Several factors are responsible for the discrepancy. Crude oil and natural gas are not all combusted for energy; the fraction consumed as nonrenewable organic products (e.g. asphalt, plastic, lubricants) totaled 112.9 MMT in 1990 (74). The moisture content of coals can range up to 20% of total weight, overestimating reported tonnages. Additionally, trace elements such as fuel bound nitrogen and sulfur account for some of the discrepancy. US coals averaged 10.9% ash content and 1.6% sulfur content, in 1983 (59).

[b] Dissipation refers to the estimated annual quantity of materials released directly into the environment, where no attempt to recover the material is practical; examples are the application of fertilizers, pesticides and road salt. In this category we include TiO_2 used for paint and pigments. However, we do not account for materials dissipation resulting from normal wear of items such as bridges, brake pads, and coatings.

[c] Processing waste comes from the processing and manufacture of materials into a finished product following extraction from the original resource. Only the dry weight of the material is included, and any liquid or ancillary materials associated with mineral concentrator tailings, such as waste from nonmineralized rock, are not included. Because of the difficulty in determining the portion of waste released directly into the environment, all the estimated waste and losses from the processing phase are assumed to be disposed of in a controlled manner. We note that manufacturing wastes include varying amounts of water (frequently >90%). Deriving their dry weight directly from existing data sources is difficult.

[d] Postconsumer waste includes Municipal Solid Waste (MSW) and is generally defined as the estimated annual quantity of materials disposed of in a controlled fashion following use in product form.

cases, even minute contaminant concentrations (10s of ppm) damage plant growth and overpower their genetic adaptability (50).

Other (solid) waste estimates span a wide range. Our figures are comparatively low and are for dry weight only. Both process and postconsumer wastes contribute to the total, reflecting the implicit as well as the explicit consequences of economic activity. The substantial contribution of coal ash to wastes again illustrates the role of energy in materials flows. Of the few solid waste disposal options available, each is fraught with environmental risks. Both industry and government have begun to pursue more aggressively the opportunities for recovering the value, utility, and stored energy in this accumulating fraction of waste materials (51–54). This quest is one of the principal objectives of industrial ecology.

Household hazardous wastes include used products such as adhesives, cleaners, cosmetics, and batteries. Estimates of the size of this vexing waste stream range from .0015%–.4% of municipal solid waste, or 0.002–0.589 MMT using 1990 data, which is too low to appear explicitly in Table 2 (46).

Dry weight data for agricultural wastes are not available, but the EPA estimates 1 billion gallons (3.7 MMT) per day as an upper limit on daily waste generation from the US agricultural sector (46).

Recycled materials totaled approximately 244 MMT in 1990, about 5% of our estimate for materials outputs (42). Environmental considerations for recycling are material specific and, in all cases, impact energy consumption for processing and transportation. Fully restoring the function and value of organics, such as paper and plastic, may not make sense if it means increasing energy use and therefore consumption of energy materials. For metals, recycling usually requires less energy than production from virgin materials. For example, secondary aluminum production consumes only 5–10% of the energy needed for the electrolytic refining of primary alumina (55). Reprocessing steel and iron scrap can save over 60% in energy consumption (56).

Our list of outputs equals approximately 88% of the input total, an encouraging but perhaps deceptively good match. The bulk of the 600 MMT discrepancy is due to human and animal food consumption. Human fecal matter decomposes during treatment and is not fully accounted for in material terms. Neither is manure from livestock, which the US EPA estimates at about 2 billion metric tons annually on a wet basis (46), of which approximately 20% is dry matter. Additionally, we have not accounted for residuals in the timber and food-processing industries, frequently used for energy recovery.

Trade

Approximately 90% of US materials flows (by weight) appear confined to America when materials imports and exports are measured against our basic categories of inputs and outputs. Still, Americans import approximately 2.4

Table 3 Selected materials flows: US 1990—foreign trade

Category	Exports (MMT)	Imports (MMT)	Net annual per capita (kg)	Reference
Agricultural products	135.5	14.9	(482.6)	32, Tbl. 1123
Coal	96.0	2.4	(374.5)	32, Tbl. 945
Minerals	47.8	54.2	25.6	74
Metals and ores	27.0	76.4	197.8	74
Chemical and allied products	41.3	14.4	(107.6)	32, Tbl. 1079
Petroleum products	34.1	96.9	251.3	32, Tbl. 945
Timber products	16.4	18.4	22.8	32, Tbl. 1165
Paper & board	6.2	11.9	22.8	32, Tbl. 1165
Oil (crude)	5.6	307.4	1207.6	32, Tbl. 945
Natural gas	1.7	31.0	117.2	32, Tbl. 945
Automobiles[a]	1.2	5.9	18.8	32, Tbl. 1019
TOTAL	412.7	633.8	884.4	
Air transport	1.5	1.7	—	32, Tbl. 1076
Waterborne transport	406.9	524.9	512.4	32, Tbl. 1079
Trucks	151,000 (units)	766,000 (units)		32, Tbl. 1019
Other industrial & consumer products	?	?		

[a] Based on an estimated average vehicle weight of 1.5 metric tons.

kg net of material per capita per day (Table 3). The US monetary foreign trade imbalance corresponds to the mass imbalance presented here. In contrast, Japan is a heavy materials importer but maintains a positive monetary trade balance.

In mass, agricultural products, coal, and chemicals dominate US exports, whereas oil, oil products, and metals and ores dominate imports. Data on the mass, as distinct from the economic, value of US trade in manufactured products are not directly available. Because information content, rather than bulk, largely determines the value of manufactured products such as microchips, drugs, and clothing, the total weight of traded products would probably alter little the picture offered by Table 3. Even automobiles, among the most mass-intensive manufactured imports, amount to only about 1% of all imports by weight.

Measured by weight, most imports to the United States are transported by water. A minor fraction is shipped overland. For example, about 70 MMT (280 kgs per capita annually) of crude oil flowed into the United States from its North American neighbors in 1990, presumably through pipelines. Light, valuable items fly. In 1990, air freight formed less than 0.5% of US foreign trade by weight but over 22% by value (32). The disparity in Table 3 between import-export totals and waterborne transport totals must partly result from the mass of goods shipped by land and pipe as well as finished goods traded, for which mass values are not given. Further work in this area could account for flows more fully and would be timely in light of environmental concerns about the North American Free Trade Agreement and the General Agreement on Tariffs and Trade.

Examining the material flow across the borders of other countries is instructive. For Japan, the mass ratio of raw materials imports to product imports is greater than 10 to 1. Japanese exports consist of products exclusively (57). Data from Sub-Saharan Africa and Latin America for the late 1980s show that manufactured exports were commonly under 5% of total exports by value (presumably less by weight), and imports of machinery and transportation equipment averaged well over 25% (58).

Extractive Wastes

The retrieval and preparation of crude minerals and ores for human consumption create large amounts of wastes (Table 4). Although these materials seldom enter the economy directly, their generation is essential to its operation. Resource extraction activities require extensive land use, infrastructure, and auxiliary materials, such as barite ($BaSO_4$) for making muds to seal oil wells and nitrogen-based explosives for clearing rock.

Generally speaking, wastes from the extractive industries remain in the mines and wells where they are generated. Apart from oil and gas wastes, rock mobilized to access desired minerals and ores constitutes the majority of the extractive wastes. Waste rock may be harmless. However, displacing dirt and rock and exposing raw earth to wind and water affects local acidity levels and transports trace elements to water sources and neighboring biota. Chemical leaching and other operations for retrieving metals from ores can also create damage, spreading hazardous chemicals that seep into the earth.

To access coal seams, both surface and underground coal mining must remove overburden, gob in the underground case. The amounts mobilized vary from seam to seam, ranging from under 3 cubic yards per short ton for surface-mined coal in Wyoming to 48 cubic yards per short ton in Oklahoma. The average for coal surface mining in 1983 was 9 cubic yards of overburden per short ton of coal mined (35a). Coal mined for processing consists of 70% or more combustible material on average. The properties of coals from different sites vary considerably, even within the same seam. Variables include the content of sulfur, ash, pyrites, mercury, and sodium, as well as moisture content. Coal cleaning wastes include the 30% or less shale and clay in coal seam partings, as well as impurities such as sulfur and ash. The variability means waste generation from coal cleaning is site specific, and relevant data are scarce.

Table 4 Major materials flows: US—extractive wastes

Category	Amount (MMT)	Reference	Comments
Surface coal mining wastes	>10042.4	59	Data for 1983. Figure is for wastes from surface mining only which accounted for 60.7% of all coal mined. Based on DOE estimates of an average 6.88 cubic meters overburden per short ton of coal mined and using the density of granite (2.7 MT/m') for overburden.
Coal cleaning wastes	>84.1	59	Data for 1983. Represents the refuse from mechanically cleaned coal (32.5% of all coal mined). This number is based on an estimate of 32 tons of refuse for every 100 tons of coal cleaned mechanically. For the remaining 68.5% the data were not collected. Residues from coal mining are classified as subtitle D wastes and not normally reported.
Oil & Gas Produced Waters	(20.87 billion bbl.) 3318.2	60	Data are for 1985 and do not include some states. Produced waters are mixtures of naturally occurring water in geological formations, naturally derived constitutents such as benzene and radionuclides, and added chemicals. We assume water density for our mass value. Over 90% of this waste is reinjected into the ground.
Oil & Gas Drilling Fluids	(361.4 million bbl.) 57.2	60	Data are for 1985. Drilling fluids include drill cuttings removed during well boring, drilling muds pumped into wells to facilitate extraction, protect various geological layers, and remove drill cuttings. We assume an average density of .996kg/l.
Metals overburden	755.0	60	Data are for 1987.
Metals tailings	409.1	60	Data are for 1987. Mine tailings are calculated as the differences between the amount of crude ore and the amount of marketable product.
Phosphate overburden	262.3	60	
Phosphate tailings	108.1	60	
Uranium tailings	188.0	61	
Minerals Processing	93.8	78	Data are for the mid to late 1980s. The amount shown represents the total weight of the 20 waste streams considered by EPA to be 'high volume low-hazard' wastes from the mineral processing. One estimate for hazardous wastes from the mineral processing industry is 6.7 MMT including water.

Water encountered in oil and gas drilling operations combined with small amounts of minerals and other chemicals, derived naturally and added for drilling, to form so-called produced waters. These waters account for 96–98% of US oil and gas wastes (60). Producers reinject over 90% of the waters into impermeable geological formations. Although these waters are mixed with chemicals to enhance recovery, their treatment is designed to make them mostly inert. Drilling fluids, which include the rock removed during drilling and muds used to provide well back-pressure, lubrication, and sealing, make up the remaining 2–4%. These wastes are currently considered innocuous and generally remain on site.

For political and technical reasons, the US EPA ruled in 1986 that mining wastes should not be considered hazardous. Waste data are not collected for mined materials such as clay, stone, sand, and gravel because their environmental risk is judged negligible. Some data are withheld by companies. Of the overburden and tailings for which data were collected, in 1987, most were from copper (43%), phosphate rock (24%), gold (18%), and iron ore (10%) mining and processing. Uranium mill tailings, regulated separately from other metals by the Nuclear Regulatory Commission with assistance from EPA, amounted to 188 MMT in 1990 (61), comparable to gold mining wastes. Among nonmetallic nonfuel minerals (asbestos, gypsum, lime, sulfur, phosphate rock) we list only phosphate rock because waste generation from this sector is prominent. Thus, the data are incomplete.

Nonhazardous wastes from mineral processing, a further step in the refining of metals and minerals, amounted to approximately 94 MMT, according to EPA estimates from the late 1980s. Slightly more than half of this waste is phosphogypsum (primarily $CaSO_4$) from phosphoric acid production, which is unsuitable for other uses because it contains radionuclides and other contaminants. Iron slag accounts for a little more than a third. Iron and steel slags and some of the other so-called wastes in this category are in fact marketable and useful in the economy.

Environmental Metrics

We now turn to the use of the national materials flow accounts to improve environmental performance. We believe the accounts can form the basis of a set of environmental metrics that indicate the changing and comparative performance of a national economy. Devising metrics that incorporate materials flow data and provide information of consequence to environmental quality will require discussion, experimentation, and refinement (62). Table 5 presents our initial attempt at a set of metrics, most of which address either the productivity or efficiency of resource use. The list is not exhaustive, and some of the metrics are already in use. The metrics require economic as well as weight data. Below we comment briefly on selected proposed metrics:

1. Absolute national and per capita inputs aggregated by class and by individual material. We began this paper by mentioning that on average each American consumed about 50 kg of materials daily in 1990. This figure results from the addition of all inputs divided by population. Although the components of the aggregate differ in qualities and accuracy, we believe the total is meaningful and would be useful to track over time and to compare across nations. Similarly, an analysis of materials use over time and across nations would be useful for classes of materials, such as energy, and individual materials, such as lead.

2. Composition of the national materials (input) basket. With economic development and technical change, the demand for materials evolves. Knowing whether and why the shares of major materials classes change would be interesting.

Within the energy sector, the evolution of the ratio of coal:oil:gas, or in more elemental terms the hydrogen (H) to carbon (C) ratio in fossil fuels has environmental import (5, 63). Determining the balance between high-energy materials such as metals and organics and low-energy materials such as sand could also be useful. Shifting the balance in favor of low energy materials could bring environmental benefits, and great potential may lie in old materials, such as stones, that can be upgraded to glass and other forms.

The ratio of inputs to the economy of various nonenergy materials might also indicate trends relevant to national environmental performance. Ashby, for example, related the physical properties found in metals, ceramics, glasses, and polymers to those most often sought in material goods (e.g. Young's modulus, yield strength, and toughness) (64). He concluded that advances in metal alloys may be near an end and that many functions formerly fulfilled by metals will be provided by impact-resistant ceramics and polymers, stiffened by increasing the density of carbon-carbon bonds in the direction of loading, or filled with a material, such as sand or glass, of higher modulus. We suspect that the environmental and materials science communities have much to learn from each other about trends, needs, and capacities.

3. Intensity of use indicators. Intensity of use metrics quantify materials consumed against physical or monetary outputs. Often, materials such as steel, copper, and tin have been indexed to the Gross Domestic Product (GDP) in constant dollars (65). A historic example of declining intensity of use is the decarbonization of the economy, or decline in carbon inputs per unit GDP over the past century (66). Intensity of use measures may help gauge developmental status and define realistic goals that integrate economic growth and improved environmental quality. The concept could be applied more widely, assessing, for example, ratios of agricultural minerals to crops. A host of materials other than water and land now flow quite directly into agriculture. Measuring the

Table 5 National materials flows: sample metrics

Metric		Dimensions	Formula	Environmental significance
Total inputs		MMT and MMT/Capita	Aggregate total consumption of all materials classes and individual material classes, on absolute and per capita basis	Benchmarking national resource use
	Fuel mix (H/C)	Dimensionless	Consumption ratio of Btu's from Natural gas : Petroleum : Coal	CO_2 emissions
Input composition	Processed metal : ceramic : glass : polymer ratio in finished products	Dimensionless	Consumption ratio of said materials in finished products and structures	Gross shifts in materials use, materials efficiency and cyclicity, mining and processing waste, energy use
Input intensities	Intensity of use	MMT of inputs/$10^6 GDP	Material consumption quantity for selected input materials/GDP in constant dollars	Relationship of resource use to economic activity
	Agricultural intensity	Dimensionless	Agricultural materials consumption/Total crop production	Materials efficiency, eutrophication of water bodies, topsoil erosion, ecosystem disruption, energy use
	Decarbonization	MMT of Carbon inputs/$10^6 GDP	Carbon inputs/GDP in constant dollars	Relationship of carbon emissions to economic activity
	"Virginity" index	%	Quantity of all virgin materials/Total material inputs	Materials efficiency and cyclicity, mining and processing waste, energy use

Recycling indices	Metals recycling rate	%	Quantity of recycled and secondary metals production/Primary production from ores	Materials efficiency and cyclicity
	Renewable net carbon balance	%	Forest growth/Forest products harvested	Global carbon balance of sources and sinks, land use, ecosystem disruption
	Green productivity	%	Quantity of solid wastes/Quantity of total solid physical outputs	Materials efficiency and cyclicity
Output intensities	Intensity of use for residues	MMT/$\$10^6$ GDP	Generation quantity for selected materials waste streams/GDP in constant dollars	Relationship of waste generation to economic activity
Leak index		%	Quantity of materials dissipated into the environment/Total material outputs	Materials efficiency and cyclicity, media contamination
Conversion efficiency	Industrial conversion efficiency	%	Total output for an industrial sector/Total inputs	Materials efficiency
	Process to post-consumer wastes ratio	%	Process wastes from industry/Post consumer waste	Relating generally unseen to seen consequences of industrial production
Physical trade index		%	Mass value of net trade in manufactured products/Mass value of net trade in raw resources	Domestic resource consumption, domestic environmental burden caused by exported goods
Mining efficiency	Mining wastes	Dimensionless	Quantity of wastes generated/Ton of finished product	Solid wastes, acid mine drainage
	By-product recovery	Dimensionless	Total by-product recovery/Total output	Materials efficiency, solid wastes

amounts of these materials used for food and fiber production indexed to production might provide important information about performance.

4. Virginity and recycling indices. A virginity or raw materials index could indicate, nationally and per capita, absolute amounts of raw materials, and ratios of raw materials to national materials inputs. The indices would monitor the distance to a society that has largely stopped extracting materials from the earth and sustains itself through its materials endowment and recycling. As society capitalizes on the "mines above ground" or scrap piles, traditional mining and thus mining wastes grow dispensable and the materials loop closes. Of course, the demand for materials with highly specific properties also alters the pool of resources that can be used as inputs (67).

Among specific materials of interest for recycling are metals and wood. The high ratio of secondary to primary metals consumption indicates both the efficiency of metals use and success in overcoming the recycling problems caused by contaminants. For forestry products a simple environmental measure would be the net carbon balance from forest growth and harvesting.

5. Waste (or emission) intensities. Comparable to intensity of use, these metrics focus on residuals and emissions per unit of output measured in physical or economic terms. Corporate practice increasingly evaluates the ratio of wastes to total output, including products and salable byproducts (68). Similar national indicators would assess "green" productivity by evaluating the amount of materials considered as waste against various outputs.

6. Leak indices. Measuring the fraction of outputs dissipated to total outputs as a leak index would quantify the proportion of materials lost to further productive use and dispersed into the environment. Applying this measure would allow for easier identification and isolation of holes in the system and focus efforts to plug them. Environmental monitoring activities would have to be modified to support a genuine mass-balance account by identifying, for example, input-output discrepancies at production sites.

7. End-product materials efficiency. The relation between primary or total materials consumption and end-products is important. A parallel in the energy field is the relation between primary energy and end-use as a measure of system efficiency. Implementing a comparable materials measure would be more difficult, but might be possible within sectors, where products are measured against total inputs and waste.

8. Ratios of raw and manufactured materials traded. Exporting raw materials consumes national resources and scars landscapes. In contrast, using domestic industry to convert materials into export products can damage the environment in other ways. The ratios may indicate whether nations are displacing or exporting pollution and, if so, what kinds.

9. Extractive waste ratios. Geological characteristics primarily determine overburden and tailings, but judgments also affect mine wastes. A measure,

subject to some physical constraints, of mine wastes per ton of ore mined or primary metal produced could be explored. Some companies already use measures such as water and energy use per ton of finished product. Measuring the efficiency of by-product recovery, such as methane deposits trapped in coal seams, sulfuric acid from smelter emissions, and metals captured from flue dusts provides further opportunity. Mining concerns are increasingly alert to these dimensions of their operations (69). In fact, in numerous sectors firms are experimenting with new ways for managerial accounting to track environmentally significant materials flows (70). Several of these approaches might be evaluated for scale-up to monitor national materials performance.

Discussion

Having laid out a framework, supported it with data, and proposed how it might be used, we return to questions of feasibility and value.

The main obstacle to development is data. Relevant data are collected for one purpose or another. For our purposes, collection is patchy and sporadic. Synchronizing data collection among various federal departments and agencies to build more complete data sets for selected years could amplify the benefits of existing efforts. Equally important would be the development of consistent classifications of material commodities and end uses. Erroneous assumptions regarding materials classification lead to omitting and double counting of material components.

Procedural changes could ease the development of national materials accounts. However, weight data are simply not collected in important areas, because some companies fear disclosure of proprietary information, or because the perceived value or direct environmental threat of a materials flow is considered too small to justify collection efforts. As a result, high levels of uncertainty are associated with many materials streams (e.g. mining and industrial wastes). For most manufactured products economic considerations dominate, and weight data are neglected.

Moreover, weight data do not provide the complete picture. The environmental impact associated with materials flows differs considerably among and within materials classes. Total US dioxin and furan emissions, which annually amount to less than one metric ton, provide a vivid example (71). National material accounts would need to include these flows as well.

To realize their value, national materials accounts would have to be calculated periodically. A frequency of once every three to five years might balance the labor of collection with the utility of the product, and still allow for identification of trends and understanding of the primary and secondary effects of changes in the economy, industrial practice, and government regulation.

A fair question is whether national boundaries make sense for materials analysis. The answer is partly opportunistic: the data are collected at the

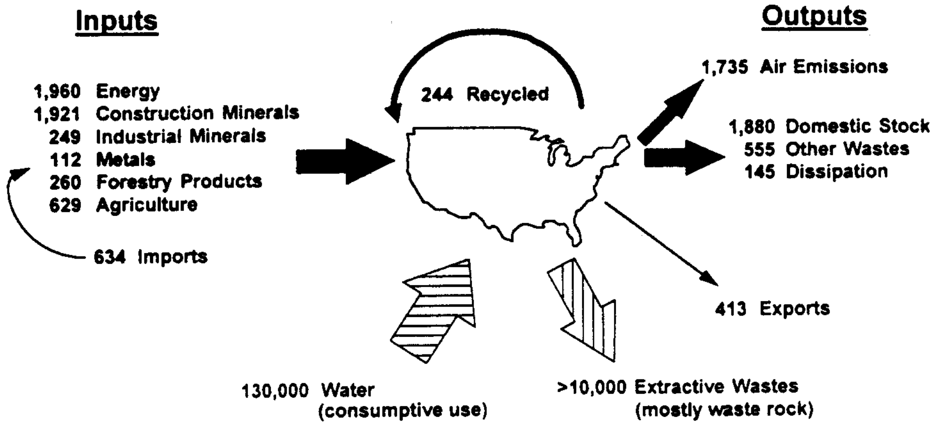

Figure 1 US Material flows, circa 1990. All values in million metric tons (MMT).

national level. Does enlarging system boundaries to encompass a nation forfeit critical environmental information? Clearly national materials accounts do not obviate the need for monitoring environmental variables at the level of localities and firms. Rather, measures based on comprehensive national accounts complement these smaller scale metrics in two ways. They help to identify macroscale trends important to the environment in much the same way that national economic indicators, such as GDP, are useful. They also capture the physical data lost in the patchwork of the current regulatory structure.

Moreover, important decisions relating to materials policies are made at the national level. We believe few if any nations have the means at present to assess meaningfully their environmental performance with respect to materials or to set priorities. If at the systems level nations genuinely hope to shift from a linear to a more circular industrial economy, the dimensions of the shift must be better understood (72). Figure 1 presents our rough schematic account of US 1990 national materials flows. Figure 2 presents the identical data at the level of the individual, which may have additional educational and political impact. More refined frameworks and more certain numbers are needed.

In addition to providing improvement benchmarks for domestic performance, national materials accounts would allow international comparisons. The type and quantity of materials used by a society describe its economic activity, level of industrial development, and environment. Japan provides an interesting example. According to a rough estimate, Japanese materials use in 1990 summed to 52 kg per capita per day, a figure similar to our estimate for the United States (57). The amount of building materials going to domestic stock came to 7.7 metric tons per capita per year in Japan as compared to 6.7 metric

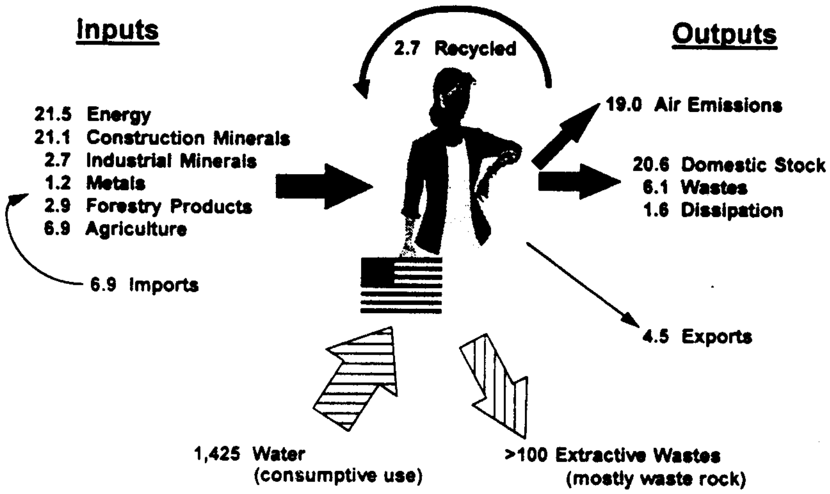

Figure 2 US Material flows, circa 1990. Per capita per day (in kilograms).

tons per capita per year in the United States, perhaps reflecting Japan's higher fraction of capital investment and recent building boom.

The dynamic pattern of materials flows of various nations could serve as references for other nations exploring paths of development. An unanswered question of great interest mentioned at the outset of this paper is whether industrialized nations are beginning overall to dematerialize. Are they reducing materials use, with the help of a broad array of measures, in the same way societies have begun to advance consistently in efficient energy use (30)? Comprehensive materials accounts could address this question.

As a tool, national materials accounts could be extended and applied in various ways: for example, on different geographical scales, in individual economic sectors, on the basis of toxicity or other environmental and health concerns, and in contrasting anthropogenic fluxes with natural or background reservoirs and fluxes (21). They would also provide the context for detailed horizontal studies of individual elements and comprehensive materials-balance studies.

National materials accounts could also help set the environmental research agenda for materials science and engineering (73). Three corrective strategies recur: reducing inputs, increasing the fraction of outputs that reenter the economy, and identifying alternative materials that satisfy human wants while lessening environmental damage. To our knowledge, the materials research community has not carefully evaluated its work from this perspective.

With materials consumption at 50 kg per day per American, even the rough profile developed here demonstrates the urgency of meshing environmental and materials research. We need to begin to consider our materials legacy as a dowry to future generations, rich in valuable ore.

In fact, future materials fluxes may be much larger than today, even with limited inputs and more looping. To make the fluxes environmentally compatible, we need a clearer picture than we have today. We can imagine an industrial ecosystem in which emissions, including carbon and water vapor, would be captured, solid wastes used productively, and waste streams separated and valuable materials recovered. The discipline of creating national materials accounts could be extremely useful in creating a consistent, realistic long-range technical vision.

Data Notes

Mineral consumption data from the US Bureau of Mines (USBM) (42) are consistent with their Mineral Commodity Summaries and Minerals Yearbook publications. The classification for materials is not universal. Furthermore, for some materials no data are given for apparent consumption, dissipative use, postconsumer waste, processing waste, and recycled amounts. Dissipation data are entirely based on estimates from mineral commodity specialists at the USBM. Original sources for the Rogich et al data include the Departments of Energy, Agriculture, and Commerce, the US International Trade Commission, the US Forest Service, the Environmental Protection Agency, Franklin Associates, and Modern Plastics magazine.

Data reported in separate tables of the *Statistical Abstract of the United States (SAUS)* are at times inconsistent, giving different mass values when reporting on the same commodity due to differences in definition or methods of data collection. Examples of such discrepancies include the quantity of petroleum imports and exports (*SAUS* 1993, tables 945 & 1194) and the total mass of waterborne commerce (*SAUS* 1993, tables 1079 & 1080).

Agricultural data are obtained from the US Department of Agriculture. They refer statistical methodology questions to the agency responsible for compiling the data, usually the USDA.

Waste data are in most cases traceable to the US Environmental Protection Agency (EPA). Data collection often begins with sampling and industrial surveys, and the results are statistically calculated to produce final estimates. For the case of hazardous wastes EPA reports a 95% confidence interval. For municipal solid waste data, the reporting group (44) uses a "materials flow methodology" based on a formulation by EPA's Office of Solid Waste and its predecessor in the US Public Health Service. Data sources for *EPA Solid Wastes Report to Congress* (46) include state and federal program offices, published and unpublished literature, the regulated community, and technical research including surveys and fieldwork done by EPA at selected landfills.

Coal wastes data were collected using the *EIA-7A Coal Production Report* from companies owning mining operations that produced, processed, or prepared 10,000 or more short tons of coal in 1984. These mining operations accounted for 99.4% of total US coal production in that year.

For oil and gas wastes, EPA and American Petroleum Institute (API) estimates differ significantly. Some states are not included in the reported data.

Metals mining waste data do not include information from beryllium, magnesium, manganiferrous, molybdenum, nickel, and tungsten segments. Tailings are calculated as the difference between the amount of crude ore and marketable product. Some wastes are not reported for reasons of confidentiality.

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