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What Gets Included

Any study aiming to elucidate the complexity of material flows of modern societies, their prerequisites and their consequences, should be as comprehensive as possible, indeed its coverage should be truly all-encompassing. But this easily stated aspiration runs immediately into the key categorical problem: what constitutes the complete set of modern material uses? There is no self-evident choice, no generally accepted list, only more or less liberally (and also more or less defensively) defined boundaries of a chosen inclusion; a reality best illustrated by reviewing the selections made by the past comprehensive studies and adopted by leading international and national databases of material flows.

The first comparative study of national resource flows (Adriaanse *et al*., 1997), subtitled *The Material Basis of Industrial Economies*, excluded water and air but included not only all agricultural harvests (not just raw materials but all food and feed as well), all forestry products, aquatic catches, extraction of minerals and fossil fuels, but also hidden flows accounting for extraction, movement, or losses of materials that create environmental impacts but have no acknowledged economic value. These hidden flows are dominated by overburden materials that have to be removed during the exploitation of mineral deposits (above all in open-cast coal and ore mining), processing wastes (particularly massive flows associated with the separation of relatively rare metals from rocks), soil, sand, and rocks that have to be removed and shifted during large construction projects, and soil erosion originating from fields and permanent plantations. Hidden flows are not monitored and their quantification is, at best, a matter of approximate estimates; more often of just informed guesses.

This is even more the case with the annual totals for hidden flows associated with imported raw materials: obviously, these estimates will be particularly uncertain in the case of large affluent economies (USA, Japan, Germany) that import a wide range of materials from scores of countries. Not surprisingly, the study resorted to using worldwide averages for these calculations: for example, it applied the rate of 0.48 t of overburden for a ton of bauxite and 2 t of overburden per ton of iron ore – global generalizations that must result in considerable errors when used as national averages.

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Erosion rates are even more variable, their detailed national studies are rare and annual soil losses can differ by up to an order of magnitude even within relatively small regions, and yet the study used only the rates derived from the US inventory. Another highly uncertain inclusion was quantifying the mass of grass grazed by cattle (other animal feed was included in crop harvests).

Three years after this first comparative study came another project led by the World Resources Institute (WRI), *The Weight of Nations* (Matthews *et al*., 2000). This study presented material flows for the four nations included in the original work (the USA, Japan, Germany, and the Netherlands) as well as for Austria and extended the accounting period from 1975 to 1996 (the original ended in 1993). Its subtitle, *Material Outflows from Industrial Economies*, indicated the report's concern with outputs produced by the metabolism of modern societies. As its predecessor, this study included all fossil fuels, hidden material flows (dominated by surface coal mining overburden), as well as the processing wastes from oil and coal industries.

Similarly, estimates for process losses and overburden removal were made for all nonfuel minerals and metals, and the report also quantified earth moved during all construction activities (highway, public, and private and also for dredging), soil erosion losses in agriculture, and waste from synthetic organic chemicals and from the pharmaceutical industry. But, unlike the original study, the 2000 report also included data on additional inputs (oxygen in combustion and in respiration) and outputs, including the total output of CO_2 from respiration and water vapor from all combustion, and it separated waste streams into three gateways: air, land, water. The air gateway quantified gaseous emissions (CO_2, CO, SO_x and NO_x, volatile organic carbohydrates) including oxygen from all combustion, the outputs to land included municipal solid waste, industrial wastes, and dissipative flows to land (manure, fertilizers, salt spread on roads, worn tire rubber, evaporated solvents), and water outputs, trace organic load, and total nitrogen and phosphate burdens.

Eurostat has been publishing annual summaries of domestic material consumption for all EU countries since the year 2000, disaggregating the total flows into fossil fuels, biomass (crops and forest products), metal ores, and nonmetallic minerals (European Commission, 2001; Eurostat, 2013). Eurostat's methodological guides for economy-wide material flow accounts offer detailed procedures for the inclusion of biomass (food, feed, fodder crops, grazed phytomass, wood, fish, hunting, and gathering activities), metal ores and nonmetallic minerals, and for all forms of fossil fuels as well as for all dissipative uses of products, including organic and mineral fertilizers, sewage sludge, compost, pesticides, seeds, road salt, and solvents (Eurostat, 2009; Schoer *et al*., 2012). Eurostat aggregates also include unused materials (mining overburden, losses accompanying phytomass production, soil excavation, dredging, and marine by-catch), and quantify emissions (CO_2, water disposal, and landfilled wastes) but leave out oxygen and water.

In 1882, the US Congress mandated the annual collection of statistics for mineral commodities produced and used in the country. The US Geological Survey was responsible for this work, then the US Bureau of Mines, and since 1995 the task has reverted to the USGS. These statistics were the basis for preparing the first summary of America's material flows aggregated by major categories and covering the period between 1900 and 1995 (Matos and Wagner, 1998). An updated inventory, with data for aggregate categories extending until 2006, was published in 2009 (Matos, 2009) and data on individual elements, compounds, and materials are updated annually (USGS, 2013).

The USGS choice of items included in its national material accounts is based on concentrating only on the third class of the material triad; leaving out food and fuel and aggregating only the materials that are used domestically in all branches of the economy. The series offers annual totals for domestic production, exports, imports, and domestic consumption; it excludes water, oxygen, hidden material flows, and all fossil fuels and it includes all raw materials produced by agricultural activities (cotton, seeds yielding industrial oil, wool, fur, leather hides, silk, and tobacco), materials originating in forestry (all kinds of wood, plywood, paper, and paperboard), metals (from aluminum to zinc), an exhaustive array of nonmetallic minerals (be they extracted in their natural form – such as gypsum, graphite, or peat – or processed before further use – such as crushed stone or cement – or synthesized, such as ammonia) and nonrenewable organics derived from fossil fuels (asphalt, road oil, waxes, oils, and lubricants and any variety of solid, liquid, or gaseous fossil fuel used as feedstock in chemical syntheses).

Very few of these inputs are used in their raw, natural form as virtually all of them undergo processing (cotton spinning, wood pulping, ore smelting, stone crushing, or cutting and polishing) and, in turn, most of these processed materials become inputs into the manufacturing of semi-finished and finished products (cotton turned into apparel, pulp into paper, smelted metals into machine parts, crushed stone mixed with sand and cement to make concrete). This compilation of agriculture- and forestry-derived products, metals, industrial minerals, and nonrenewable organics gives a fairly accurate account of annual levels and long-term changes in the country's material flows. While all imports and exports of raw materials are accounted for, the series does not include materials contained in traded finished goods: given their mass and variety their tracking would be very difficult.

Where does this leave us? Those material flow studies that conceive their subject truly *sensu lato* (that is as virtually any substance used by humans) include everything with the notable exception of water; that is not only biomaterials used in production of goods, all metals, nonmetallic minerals, and organic feedstocks, but also all agricultural phytomass (harvested food and feed crops, their residues, forages, and grazed plants), and all (biomass and fossil) fuels and oxygen needed for combustion. Slightly more restrictive studies exclude oxygen and all food and feed crops, and consider only those agricultural raw materials that undergo further processing into goods, but include all phytomass and fossil fuels. In contrast, the USGS series exemplifies a *sensu stricto* approach as it includes only raw biomaterials used for further processing and excludes oxygen, water, all fuels (phytomass and fossil), and all hidden (and always tricky to estimate) material flows. My preferences for setting the analytical boundaries are almost perfectly reflected by the USGS selection, but instead of simply relying on that authority I will briefly explain the reasons behind my exclusions.

Leaving out oxygen required for combustion of fuels is a choice that is easily defensible on the basis of free supply of a virtually inexhaustible atmospheric constituent. Claims about the danger of serious O_2 depletion through combustion were refuted a long time ago (Broecker, 1970). Complete combustion of 1 kg of coal carbon consumes 2.67 kg of oxygen, and burning of 1 kg of hydrocarbons requires 4 kg of O_2. Global combustion of about 8 Gt of fossil carbon in 2010 thus claimed about 21 Gt of O_2 or about 0.0014% of the atmosphere content of 1.5 Pt of O_2 – and even a complete combustion (a clear impossibility) of the generously estimated global resources of fossil fuels would lower the atmospheric O_2 content by no more than 2%.

There is thus no danger of any worrisome diminution of supply (to say nothing of exhaustion) of the element, and yet, once the choice is made to include it in material flow accounts, it will dominate the national and global aggregates. For example, as calculated by the comparative WRI study, oxygen was 61% of the direct US processed material output in 1996, and in Japan in the same year the element's share was 65% (Matthews *et al*., 2000). Consequently, magnitudes of national material flows that incorporate oxygen needs would be nothing but rough proxies for the extent of fossil fuel combustion in particular economies.

The reasons for excluding hidden flows from the accounts of national material flows are no less compelling: after excluding oxygen they would dominate total domestic material output in all countries that have either large mineral extractive industries (especially surface coal and ore mining) or large areas of cropland subject to heavy erosion. Not surprisingly (after excluding oxygen), in the WRI analysis these hidden flows account for 86% of the total domestic material output in both the USA and Germany, but with much less mining and with limited crop cultivation the rate was lower (71%) in Japan (Matthews *et al*., 2000). The undesirable environmental impacts of these associated flows should not be ignored when analyzing particular extractive or cropping activities, but the flows cannot be quantified with high accuracy. They are dominated by unusable excavated earth and rocks, mine spoils, processing wastes, and eroded soil; and earth and rocks moved around as a part of construction activities will make up a comparatively small share.

But the principal problem with the inclusion of hidden flows is not their unsurprising dominance of domestic output of materials in all large, diversified economies, but the indiscriminate addition of several qualitatively incomparable flows. An unusable mass of stone left in a quarry after it ceases its operation may be no environmental burden, even no eyesore, and once the site is flooded to create an artificial lake that hidden material flow may be truly hidden as part of a new, and pleasing, landscape. On the other hand, bauxite processing to extract alumina (to give one of many possible common examples) leaves behind toxic waste (containing heavy metals) that is also often slightly radioactive waste and is very caustic (high pH).

And no less fundamental is the difference between *in situ* hidden flows generated by mineral extraction (abandoned stone, gravel and sand quarries, and coal and ore mines with heaps, piles, layers, or deep holes or gashes full of unusable minerals or processing waste) and by rain- and wind-driven soil erosion that transports valuable topsoil not just tens or hundreds but as much as thousands of kilometers downstream or downwind. The first kind of hidden flow may be unsightly but not necessarily toxic, and its overall environmental impact beyond its immediate vicinity may be negligible or nonexistent, but erosion is a globally important, often regionally highly worrisome, and locally devastating process that reduces (or destroys) the productivity of crop fields, silts streams, contributes to eutrophication of fresh and coastal waters, and creates lasting ecosystemic degradation and substantial economic losses.

My reasons for excluding water are based on several considerations that make this indispensable input better suited for separate treatment rather than for inclusion into total material requirements of modern economies. The first, obvious, reason is, once again, quantitative: with the exception of desert countries, water's inclusion would dominate virtually all national material flow accounts and would misleadingly diminish the importance of many inputs whose annual flows are a small fraction of water withdrawals but whose qualitative contribution is indispensable. For example, in 2005 the total water withdrawals in the USA were just over 5 Gt (Kenny *et al.*, 2009), while all materials directly used by the country's economy (the total dominated by sand, gravel, and stone used in construction) added up to less than 3.8 Gt (USGS, 2013).

Moreover, there are fundamental qualitative differences between these two measures. The most voluminous water withdrawal (accounting for nearly 60% of the total), that of cooling water for thermal electricity-generating stations, is not a consumptive use because all but a small (evaporated) fraction of that water becomes available almost instantly for further downstream uses. In contrast, materials that become embedded in long-lasting structures and products are either never reused or are partially recycled only after long period of being out of circulation. And the majority of the second most voluminous water use, about 30% of the US 2005 total used for irrigation, is also nonconsumptive: all but a tiny fraction of the irrigation water is evapotranspired by growing plants, reenters the atmosphere, and eventually undergoes condensation again and is precipitated. And if the inclusion of water were driven by resource scarcity concerns, then a critical distinction should be made between water supplied by abundant precipitation and water withdrawn at a high cost from deep and diminishing aquifers that cannot be replenished on a civilizational timescale.

At this point, it might be useful to call attention to yet another (comparatively minor) problem with aggregate measures of material flows that, to the best of my knowledge, has not been raised by any assembler of national and global accounts: that of the water content of sand and of harvested biomass. Even when looking just at those biomaterials that are used as industrial inputs, their water content ranges from less than 15% for raw wool to more than 50% for freshly cut tree logs (the range is wider for food crops, ranging from only about 5% for dry seeds to more than 90% for fresh vegetables).

Freshly excavated sand can contain more than 30% water, purified sands contain 15–25%, storage in drainage bins reduces that level to about 6%, and drying in rotary bins or in fluidized bed dryers expels all but about 0.5% of moisture for sands used in such processes as steel castings or hydraulic fractioning under pressure. Obviously, the best solution would be to report the masses of any moisture-containing materials in terms of absolutely dry weight in order to make their flows comparable to those of materials that contain no moisture. This is not the case in practice, and hence all national material aggregates contain far from negligible shares of water.

Foodstuffs and fuels are obviously indispensable for the survival of any civilization, and their flows have been particularly copious in modern high-energy societies enjoying rich and varied diets, while traditional biofuels remain important in many low-income countries. Moreover, unlike water or oxygen, their inclusion would not dwarf all other material flows combined: for example, even in the fuel-rich USA the mass of annually consumed coal, crude oil, and natural gas is equal to about 50% of all nonenergy minerals. So why leave them out? Exclusion of food and fuel is justified not only because these two large consumption categories have been traditionally studied in separation (resulting in a rich literature on achievements and prospects) but also because they simply are not *sensu stricto* materials, substances repeatedly used in their raw state or transformed into more or less durable finished products.

Unlike raw biomaterials (wood, wool, cotton, leather, silk), metals, nonmetallic minerals, and nonrenewable organics (asphalt, lubricants, waxes, hydrocarbon feedstocks) foodstuffs and fuels are not used to build long-lasting structures and are not converted or incorporated into the still increasing array of ephemeral as well as durable industrial, transportation, and consumer items. Foods are rapidly metabolized to yield energy and nutrients for human growth and activity; fuels are rapidly oxidized (burned) to yield, directly and indirectly, various forms of useful energy (heat, motion, light): in neither case do they increase the material stock of modern societies.

Finally, I must defend a conceptual change that concerns the handling of materials placed into the category of dissipative flows by the EU's material balances. According to the EU definition, the eight categories of dissipative losses are a collection of disparate residuals: some of them add up to small total flows (think about solvents escaping from dry cleaning or about rubber tires wearing away on roads), others are more substantial (manures, sewage sludge, and composts applied to cropland) but dissipative losses contributed by both of these material categories are not monitored and are very difficult to quantify. The USGS approach accounts for the largest flows in this category (salt and other thawing materials – including sand and grit – spread on winter roads, nitrogenous and phosphatic fertilizers, and potash applied to crops and lawns) by including them in the industrial minerals group.

While salt and sand are abundant materials whose production is not energy-intensive, inorganic fertilizers are critical material inputs in all modern societies that cannot be ignored and that will receive a closer look when I examine advances in the production of synthetic materials. But I would argue that most of the remaining dissipative flows add up to relatively small amounts whose inherently inaccurate quantification appears to outweigh any benefits of including them in any grand total of consumed materials. And while manures and sludges represent relatively large volumes to be disposed of, they are more about recycling water than biomass: sludge contains least 80% water, fresh manures 70–85%; moreover, in many (perhaps most) instances, sewage sludge should not be recycled as it contains heavy metals, pathogens, pesticide and drug residues, steroids, and hormones.

This leaves me with an argument for a single addition to the USGS list, for the inclusion of industrial gases. Although air (oxygen) is needed for combustion of fossil fuels, the dominant energizer of modern civilization, adding air to the total material input would have (as I have already explained) a skewing and confusing effect similar to that of counting all uses of water; but assessing the use of gases separated from the air in order to enable many industrial processes is another matter. In simple quantitative mass terms the global use of oxygen, hydrogen, nitrogen, and rare gases such as argon or xenon constitutes only a minor item, but in qualitative terms their use is indispensable in industries ranging from steelmaking (basic oxygen furnaces are now the principal means of producing the metal) to synthesis of ammonia (using nitrogen separated from air and hydrogen liberated from methane) and efficient lighting.