VACLAV SMIL

MAKING the MODERN WORLD

Materials & Dematerialization

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VACLAV SMIL

Distinguished Professor Emeritus,
University of Manitoba, Canada

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About the Author

Vaclav Smil conducts interdisciplinary research in the fields of energy, environmental and population change, food production and nutrition, technical innovation, risk assessment and public policy. He has published more than 30 books and close to 500 papers on these topics. He is a Distinguished Professor Emeritus at the University of Manitoba, a Fellow of the Royal Society of Canada (Science Academy), the first non-American to receive the American Association for the Advancement of Science Award for Public Understanding of Science and Technology, and in 2010 he was listed by *Foreign Policy* among the top 50 global thinkers.

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Harvesting the Biosphere
Should We Eat Meat?

Contents

Preface: Why and How

The story of humanity – evolution of our species; prehistoric shift from foraging to permanent agriculture; rise and fall of antique, medieval, and early modern civilizations; economic advances of the past two centuries; mechanization of agriculture; diversification and automation of industrial protection; enormous increases in energy consumption; diffusion of new communication and information networks; and impressive gains in quality of life – would not have been possible without an expanding and increasingly intricate and complex use of materials. Human ingenuity has turned these materials first into simple clothes, tools, weapons, and shelters, later into more elaborate dwellings, religious and funerary structures, pure and alloyed metals, and in recent generations into extensive industrial and transportation infrastructures, megacities, synthetic and composite compounds, and into substrates and enablers of a new electronic world.

This material progress has not been a linear advance but has consisted of two unequal periods. First was the very slow rise that extended from pre-history to the beginnings of rapid economic modernization, that is, until the eighteenth century in most of Europe, until the nineteenth century in the USA, Canada, and Japan, and until the latter half of the twentieth century in Latin America, the Middle East, and China. An overwhelming majority of people lived in those pre-modern societies with only limited quantities of simple possessions that they made themselves or that were produced by artisanal labor as unique pieces or in small batches – while the products made in larger quantities, be they metal objects, fired bricks and tiles, or drinking glasses, were too expensive to be widely owned.

The principal reason for this limited mastery of materials was the energy constraint: for millennia our abilities to extract, process, and transport biomaterials and minerals were limited by the capacities of animate prime movers (human and animal muscles) aided by simple mechanical devices and by only slowly improving capabilities of the three ancient mechanical prime movers: sails, water wheels, and wind mills. Only the conversion of the chemical energy in fossil fuels to the inexpensive and universally deployable kinetic energy of mechanical prime movers (first by external combustion of coal to power steam engines, later by internal combustion of liquids and gases to energize gasoline and Diesel engines and, later still, gas turbines) brought a fundamental change and ushered in the second, rapidly ascending, phase of material consumption, an era further accelerated by generation of electricity and by the rise of commercial chemical syntheses producing an enormous variety of compounds ranging from fertilizers to plastics and drugs.

And so the world has become divided between the affluent minority that commands massive material flows and embodies them in long-lasting structures as well as in durable and ephemeral consumer products – and the low-income majority whose material possessions amount to a small fraction of material stocks and flows in the rich world. Now the list of products that most Americans claim they cannot live without includes cars, microwave ovens, home computers, dishwashers, clothes dryers, and home air conditioning (Taylor *et al*., 2006) – and they have forgotten how recent many of these possessions are because just 50 years ago many of them were rare or nonexistent. In 1960 fewer than 20% of all US households had a dishwasher, a clothes dryer, or air conditioning, the first color TVs had only just appeared, and there were no microwave ovens, VCRs, computers, cellphones, or SUVs.

In contrast, those have-nots in low-income countries who are lucky enough to have their own home live in a poorly-built small earthen brick or wooden structure with as little inside as a bed, a few cooking pots, and some worn clothes. Those readers who have no concrete image of this great material divide should look at Peter Menzel's *Material World: A Global Family Portrait* in which families from 30 nations are photographed in front of their dwellings amidst all of their household possessions (Menzel, 1995). And this private material contrast has its public counterpart in the gap between the extensive and expensive infrastructures of the rich world (transportation networks, functioning cities, agricultures producing large food surpluses, largely automated manufacturing) and their inadequate and failing counterparts in poor countries.

These contrasts make it obvious that a huge material mobilization and transformation will be needed just to narrow the gap between these two worlds. At the same time, material consumption has been a major cause of environmental pollution and degradation and further multiplication of current demand may pose a worrisome threat to the integrity of the biosphere. These impacts also raise questions of analytical boundaries: their reasoned choice is inevitable because including every conceivable material flow would be impractical and because there is no universally accepted definition of what should be included in any fairly comprehensive appraisal of modern material use. This lack of standardization is further complicated by the fact that some analyses have taken the maximalist (total resource flow) approach and have included every conceivable input and waste stream, including "hidden" flows associated with the extraction of minerals and with crop production as well as oxygen required for combustion and the resulting gaseous emissions and wastes released into waters or materials dissipated on land.

In contrast, others studies have restricted their accounts to much more reliably quantifiable direct uses of organic and inorganic material inputs required by national economies. I will follow the latter approach, focusing in some detail on key (because of their magnitude or their irreplaceable quality) materials consumed by modern economies. Their huge material claims lead us to ask a number of fundamental questions. How much further should the affluent world push its material consumption? Are any further increases associated with genuine improvements in quality of life? To what extent is it possible to divorce economic growth and improvements in the average standard of living from increased material consumption? In other words, does relative dematerialization (reduced material use per unit of product or performance) lead to absolute decline in demand for materials?

In order to answer these questions in a convincing manner I must review the evolution of human material uses; describe all the principal materials, their extraction, production, and their dominant applications; and take a closer look at the evolving productivities of material extraction, processing, synthesis, finishing, and distribution and at the energy costs and environmental impact of rising material consumption. And, as always in my books, I will not offer any time-specific forecasts regarding future global and national use of materials. Instead, I will look at possible actions that could reduce our dependence on materials while maintaining a good quality of life and narrowing the gap between affluent and low-income economies.

We must realize that in the long run even the most efficient production processes, the least wasteful ways of design and manufacturing, and (for those materials that can be recycled) the highest practical rates of recycling may not be enough to result in dematerialization rates great enough to negate the rising demand for materials generated by continuing population growth, rising standards of living, and the universal human preference for amassing possessions. This makes it highly likely that in order to reconcile our wants with the preservation of the biosphere's integrity we will have to make deliberate choices that will help us to reduce absolute levels of material consumption, and thereby redefine the very notion of modern societies whose very existence is predicated on incessant and massive material flows.

1
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.

2
How We Got Here

The Earth's biosphere teems with organisms that use materials for more than just their metabolism; moreover, in aggregate mass terms the material flows commanded by humanity do not appear to be exceptionally high when compared with the work of marine biomineralizers. But it is the combination of the overall extent, specific qualities, and increasing complexity of material uses (extraction, processing, and transformation to particular inputs destined for infrastructures and myriads of products) that is a uniquely human attribute. To set it into a wider evolutionary perspective, I will first note some of the most remarkable material uses by organisms ranging from marine phytoplankton to primates, those distinguished either by the magnitude of their overall fluxes or by their unique qualities.

Afterwards I will proceed with concise chronological surveys of human use of materials, focusing first on the milestones in our prehistory, above all on those still poorly explained feats of megalithic construction that required quarrying, transportation, and often remarkably accurate placement of massive stones. Then I will review and quantify some notable deployments of traditional materials (stone and wood) during antiquity, the Middle Ages, and the early modern era (1500–1800), concentrating on the advances in building roads, aqueducts, ceremonial and religious structures, and ships; on the origins and developments in metallurgy; and on materials used by households.

I will close the chapter with two closely related sections that will describe the creation of modern material civilization during the nineteenth century and its post-1900 spatial expansion and growth in complexity. I will focus on key quantitative and qualitative advances in the use of materials that laid the foundations for twentieth societies as they supported fossil fuel extraction, industrialization, urbanization, and evolution of modern transportation modes on land, water, and in the air. These developments were based on materials whose production required high energy inputs and whose introduction and use have been dynamically linked with enormous advances in scientific and technical capabilities. In turn, new materials have been the principal drivers of increased food production and improvements in sanitation that led to unprecedented gains in quality

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of life. They also expanded capabilities for mechanized and automated production and for long-distance travel, information sharing, and telecommunication.

2.1 Materials Used by Organisms

Inevitably, all organisms use materials: that is the essence of metabolism. Global photosynthesis, the foundation of life in the biosphere, creates new biomass by incorporating annually more than 60 Gt of carbon, absorbed by leaves as CO_2 from the atmosphere (Smil, 2013), and millions of tons of the three key macronutrients (nitrogen, phosphorus, and potassium, absorbed by roots) that are incorporated into complex compounds forming plant tissues and organs. But these metabolic necessities – mirrored by the nutritional requirements of heterotrophs, be they herbivorous, carnivorous, or omnivores organisms – are not usually included in the category of material uses that is reserved for active, extrasomatic processes.

In terms of the initial acquisition, these material uses fall into five major categories. The rarest, and in aggregate material terms quite inconsequential, category is the use of collected natural materials as tools. The second category with limited aggregate impact is the use of secreted materials to build protective or prey-catching structures (as is done, often spectacularly, by spiders). The next one is the removal of biomass (and now also manmade) materials and their purposeful emplacement to create often remarkably designed structures (ranging from beaver dams to intricate nests); then comes the removal and repositioning of soils and clays (termite mounds, intricate rodent burrows); and, finally, the most massive endeavor is the extraction of minerals from water, mostly to build exoskeletons; the process dominated by marine biomineralizers including phytoplankton, corals, and mollusks.

Tool-using activities have been well documented in species as diverse as otters and seagulls and elephants and finches (Shumaker *et al*., 2011), but they have reached their greatest complexity, and have gone as far as resulting in specific cultures, among chimpanzees who use blades of grass or twigs to collect termites or small stones and stone anvils to crack open nuts (Wrangham *et al*., 1996; Boesch and Tomasello, 1998; Whiten *et al*., 1999). Spider silk is certainly the most remarkable secreted material, with a tensile strength similar to that of good-quality steel (Brunetta and Craig, 2010). At the other end of secretion spectrum might be the frothy nests excreted by spittle bugs.

Use of collected materials is quite widespread among heterotrophs. Even some single-cell amoebas can built portable, intricate, ornate sand-grain houses whose diameter is a mere 150 μm (Hansell, 2007). Perhaps the most remarkable collecting activity among insects is that of leafcutter ants (genus *Atta*) as they harvest leaves, dragging them underground into elaborately excavated nests in whose chambers they cultivate fungus (Hölldobler and Wilson, 1990). And beavers are active harvesters of wood used to build their dams. But birds' nests offer the most varied and sometimes spectacular examples of construction using collected materials; they range from simple and rather haphazard assemblies of twigs or stems to intricate constructs produced by *Ploceidae*, the family of tropical weaver birds, and they may use a single kind of a collected material or an assortment of tissues (Gould *et al*., 2007; Burke, 2012).

Birds use not only a wide range of collected plant tissues (slender blades of grass to the heavy twigs used by storks and eagles) but also feathers of other species and spider silk (most passerine birds), and some nests may contain thousands of individual pieces. Use of mud (by swallows) is not that common, but many ground-nesting birds (including penguins) collect small stones, while the elaborate structures prepared by some bower birds of Australia and New Guinea to attract females may include not only such colorful natural objects as shells, berries, leaves, and flowers but also discarded bits of plastic, metal, or glass, and some species even make courts creating forced visual perspective for the courted females (Endler *et al*., 2010). Some insect species also use collected material to build their nests: paper wasps cut tiny pieces of wood and mix them with their salivary secretions; mud wasps shape mud into cylindrical nests. In contrast, primates, our closest animal predecessors, use branches and leaves to build only simple, temporary structures on the ground or in the trees.

Soil-displacing species engage mostly in digging tunnels, burrows, and nests but also use soils and clay to build above-ground structures. The earliest burrow constructs date to the pre-Cambrian (650–700 million years ago) oceans, coinciding with the emergence of macropredation (Turner, 2000). As demonstrated by Darwin in his last published book, earthworms are capable of such prodigious efforts of earth displacement (passing the particles through their guts and excreting the worm casts on the surface) that they can bury monuments of human activity in remarkably brief periods of time (Darwin, 1881). Rodents are diligent builders of often extensive subterranean networks of tunnels and nests that may also help with temperature control and ventilation and that facilitate escape.

Termites are the greatest aggregate movers and users of soils in subtropical and tropical environments as they construct often impressively tall and voluminous mounds that not only shelter the massive colonies, but also provide induced ventilation driven by pressure differences (Turner, 2000).

Biomass densities of these abundant warm-climate insects range from 2 g/m^2 in the Amazonian rainforest (Barros *et al*., 2002) to around 5 g/m^2 in Australia's Queensland (Holt and Easy, 1993); to 10 g/m^2 in the Atlantic forests in northeastern Brazil in Sao Paulo, as well as in dry evergreen forest of northeast Thailand (Vasconcellos, 2010); and in African savannas their total fresh-weight biomass can be more than twice the biomass of elephants (Inoue *et al*., 2001). Species belonging to the genus *Macrotermes* select clay particles to build conical mounds that are usually 2–3 m tall but can reach 9 m, with a typical basal diameter of 2–3 m, although much wider mounds are not uncommon.

The typical mass of mounds (wall and nest body) is between 4 and 7 t, but spatial density of mounds varies widely, with as few as 1 and 2 and as many as 10/ha (Fleming and Loveridge, 2003; Abe *et al*., 2011; Tilahun *et al*., 2012). As a result, the total mass of termite mounds varies between just 4 and 8 t/ha to as much as 15–60 t/ha. A very conservative estimate of the clay mass used to build termite mounds would be 5 Gt (average 5 t/ha, an area of about 10 million km^2 of tropical and subtropical grasslands inhabited by mound-building insects) but the actual total may be several times larger. In any case, this means that the annual use of materials by these tiny heterotrophs would be of the same order of magnitude as our civilization's global extraction of metallic ores and other nonfuel minerals at the beginning of the twenty-first century.

In aggregate terms, both the mass of materials collected by vertebrate animals to build structures and the mass of soils displaced by burrowing heterotrophs, earthworms, and termites are negligible compared to the mass of compounds excreted by species capable of biomineralization, above all by phytoplankton, protists, and invertebrates. More than 30 biogenic minerals (two-thirds of them being carbonates) are produced by a small number of vascular plants (belonging to Bryophyta and Trachaeophyta), animal species ranging from Porifera to Chordata, some fungi, many protoctists, and some Monera (Lowenstam, 1981; Boskey, 2003). Some biomineralizers deposit the minerals on organic matrices, but most of them produce extracellular crystals similar to those precipitated from inorganic solutions.

In mass terms, by far the largest users of natural materials are the marine biomineralizers that are able to secrete the inorganic compounds they produce from chemicals absorbed from water. Marine biomineralizers use dissolved $CaCO_3$ to form calcite or aragonite shells, two almost identical minerals that differ only in their crystal structure ($2\ HCO_3^- + Ca^{2+} = CaCO_3 + H_2O$). Reef-building corals (Anthozoa belonging to the phylum Cnidaria) are the most spectacular communal biomineralizers, while coccolithophores (calcareous marine nanoplankton belonging to the phylum Prymnesiophyceae) encase themselves in elaborate calcitic microstructures (smaller than 20 μm), and foraminifera (amoeboid protists of the eponymous phylum) create pore-studded micro shells (tests). Unicellular coccolithophores are abundant throughout the photic zone in nearly all marine environments of the Northern hemisphere and up to about 50°S in the Southern Ocean (O'Brien *et al.*, 2012). They also form massive ocean blooms that last for weeks, cover commonly 10^5 km^2 of the ocean surface, and are easily identifiable on satellite images.

Coccolithophores cover themselves in coccoliths that are formed inside the cell and are extruded to form a protective armor; many coccoliths detached from cells also float freely in water. Coastal blooms have a coccolith to coccolithophore cell ratio of 200–400, but the ratios for open waters are much lower, between 20 and 40. *Syracosphaera*, *Umbellosphaera*, and *Gephyrocapsa* are common genera but *Emiliania huxleyi* is the biosphere's leading calcite producer (Stanley *et al.*, 2005; Boeckel and Baumann, 2008). The species is also unusual because it produces fairly large coccoliths at a fast rate, sheds about half of them and, unlike many other planktonic species, is a relative newcomer that originated only about 270 000 years ago.

The photic zone can extend from just a few meters to about 200 m; densities of coccolithophores can be as low as a few thousand cells per liter, while in blooms they surpass 100 000/l; daily calcification rates range from less than 10 to 80 pg of calcite per cell per day; the largest blooms can cover 10^5 km^2 for periods of weeks and their annual extent adds up to about 1.5 million km^2 (Lampert *et al.*, 2002; Boeckel and Baumann, 2008). Given these natural variabilities, it is impossible to offer any reliable estimate of coccolithophore-mediated annual global calcification in the ocean – but a conservative set of assumptions should yield at least the actual order of magnitude.

Assuming continuous coccolithophore production in 60% of the world's ocean at depths only up to 50 m, with an average concentration of just 25 000 cells/l and a calcification rate of just 10 pg of calcite per cell per day, would result in annual global sequestration of about 900 Mt of calcite. More liberal assumptions (50 000 cells/l, 20 pg/cell a day) would yield an annual withdrawal of roughly 3.7 Gt of calcite. In comparison to this ocean-wide process the periodic blooms, no matter how spectacular, make a minor contribution. A bloom covering 250 000 km^2 in the northeastern Atlantic in June 1991 had calcification rates up to 1.5 mg $C/m^3/h$, and in less than a month it had sequestered about 1 Mt of carbon in calcite (Fernández *et al.*, 1993). That would be just over 8 Mt of calcite and, if a similar rate were to apply to the about 1.5 million km^2 coccolithophore blooms that cover the ocean every year, the total sequestration would be just on the order of 50 Mt of calcite.

The same order of magnitude is obtained by assuming 50 m of highly productive photic zone, 150 000 cells/l, daily calcification at 70 pg/cell, and an average bloom duration of 30 days: that combination yields annual sequestration of about 25 Mt of calcite in coccolithophoride blooms. The best conservative estimate is thus annual coccolithophoride-mediated calcification on the order of a few gigatonnes per year, a low rate from a geological perspective because the high Mg/Ca ratio and low absolute concentration of calcium in the modern ocean limit the production by most extant species (Stanley *et al.*, 2005). The most obvious testimony to high productivities of coccolithophores in the past are the immense sequestrations in Cretaceous and Tertiary chalk deposits (including the white cliffs of Dover).

Silicon is the other mineral that is massively assimilated by marine microorganisms; above all diatoms, silicoflagellates, and radiolarians. They use silicic acid ($Si(OH)_4$) to create their elaborate opal (hydrated, amorphous biogenic silica, $SiO_2 \cdot 0.4H_2O$) structures. Tréguer *et al.* (1995) estimated the rate of that uptake to be about 7 Gt Si a year. This means that the total mass of calcareous and siliceous materials sequestered annually by marine phytoplankton is on the order of 10 Gt/year, larger than the total extraction of all metallic ores and roughly the same as annual production of all fossil fuels (coal, crude oil, and natural gas).

In comparison to marine processors of calcium and silica, aggregate use of these elements by other organisms is orders of magnitude smaller; but its forms are often not only elaborate but also quite beautiful. This is true for many mollusk shells: some of them are quite simple but others show remarkable geometric properties (Abbott and Dance, 2000). Carbonates are also bioprecipitated by reptiles and birds to build their eggs, and by snails to form their shells. Curiously, a leading student of structures built by animals deliberately leaves out such activities from his surveys: Hansell (2007) acknowledges that the Great Barrier Reef may be (as its common description claims) the world's largest structure built by living animals, but in his books he focuses on building that requires behavior, an attribute absent in coral polyps or coccolithophores that just secrete their skeletons.

2.2 Materials in Prehistory

Evolution of hominins (the human clade that diverged from chimpanzees more than 5 million years ago and that had eventually produced our species) should be more accurately seen as a dynamic co-evolution of several traits that have made us human: upright walking, endurance running, cooperative hunting, eating meat, symbolic language, and tool making, using natural materials to fashion objects that provide simple but practical extensions and multipliers of human physical capacities. That is why the archeology of