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Multilevel Cycle of Anthropogenic Copper

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A comprehensive contemporary cycle for stocks and flows of copper is characterized and presented, incorporating information on extraction, processing, fabrication and manufacturing, use, discard, recycling, final disposal, and dissipation. The analysis is performed on an annual basis, ca. 1994, at three discrete governmental unit levels—56 countries or country groups that together comprise essentially all global anthropogenic copper stocks and flows, nine world regions, and the planet as a whole. Cycles for all of these are presented and discussed, and a “best estimate” global copper cycle is constructed to resolve aggregation discrepancies. Among the most interesting results are (1) transformation rates and recycling rates in apparently similar national economies differ by factors of two or more (country level); (2) the discard flows that have the greatest potential for copper recycling are those with low magnitude flows but high copper concentrations—electronics, electrical equipment, and vehicles (regional level); (3) worldwide, about 53% of the copper that was discarded in various forms was recovered and reused or recycled (global level); (4) the highest rate of transfer of discarded copper to repositories is into landfills, but the annual amount of copper deposited in mine tailings is nearly as high (global level); and (5) nearly 30% of copper mining occurred merely to replace copper that was discarded. The results provide a framework for similar studies of other anthropogenic resource cycles as well as a basis for supplementary studies in resource stocks, industrial resource utilization, waste management, industrial economics, and environmental impacts.

Nutrient Cycles of Technology

The study of anthropogenic resource cycles can enhance perspective on a variety of topics, including resource availability, resource utilization, recycling potential, environmental impacts of dissipative materials use, and environmental policy. For materials widely used in society (and which could be termed “nutrients of technology”), the characterization of comprehensive cycles should be regarded as mandatory practice, lest society’s actions lead unwittingly to resource shortages or to undesirable environmental consequences.

Copper is an example of a material that is of interest to both resource economists and environmental scientists. It is a widely utilized industrial metal, and one that is a potential toxicant at high levels (*1*). It is also one that may be potentially supply limited, at least at low contemporary prices (*2*, *3*).

The rate of use of copper has risen rapidly in recent decades (*4*, *5*). It is obvious that this usage trend cannot be sustained indefinitely, especially because copper’s depletion time (reserves/annual use) is no more than 30−50 years (*2*). The situation suggests the possible desirability of extensive reuse of copper already processed and now in use or that has been discarded. It also encourages us to wonder how much processed copper has been released into the environment in various ways over the years and whether such dissipation has significant environmental implications. Both of these issues can only be satisfactorily addressed from the perspective of a comprehensive, quantitative cycle analysis.

Our terminology in this paper follows that of Gibson et al. (*6*). They define a *scale* as a spatial, temporal, quantitative, or analytical dimension used to measure and study a phenomenon. A *level* is a position along the scale. Thus, our scale is a geographical unit scale (related to but different from a spatial scale), and our analysis is done at three levels: country, region, and planet.

There have been few attempts to develop comprehensive cycles for copper (*7*). A valuable, but limited, recent synthesis by Ayres and colleagues (*8*), centered on extraction and processing, is worth mentioning in this regard. Neither that study nor others, however, incorporate all life stages and dissipative flows or treat different geographical or governmental levels. It is clear that a broader based and geographically more complete approach would be useful, and we report in this paper on such an effort. This work is a component of the Stocks and Flows (STAF) project at the Center for Industrial Ecology, School of Forestry and Environmental Studies, Yale University.

Hierarchical Systems and Scale Considerations in Substance Flow Analysis

The systems that enable or constrain the flows of substances are not composed of a continuous progression of actors. Rather, they are hierarchical in form (*9*, *10*), from individual to site, to urban area, to province, to country, to region, to the planet. Similarly, the flows are not continuous progressions from one level to another. For example, the rate of scrap recycling in a metal mill is very high, because factory scrap is pure and markets for it exist. Cities, on average, recycle at much lower rates, because discard and collection of products from use inherently mixes materials and lowers value. A particular country may do better or worse than a particular city, because of the presence or absence of recycling legislation. Thus, because of economics, geography, and laws and regulations, it is not possible a priori to translate principles from one scale domain to another. In this way, substance flow analysis mimics biological ecology (*11*) or hydrology (*12*), in which a central issue is “understanding how detail at one (level) makes its signature felt at other (levels), and how phenomena are related across (levels)” (*13*).

The starting point for understanding the mechanisms that produce the resource patterns that are seen is establishing

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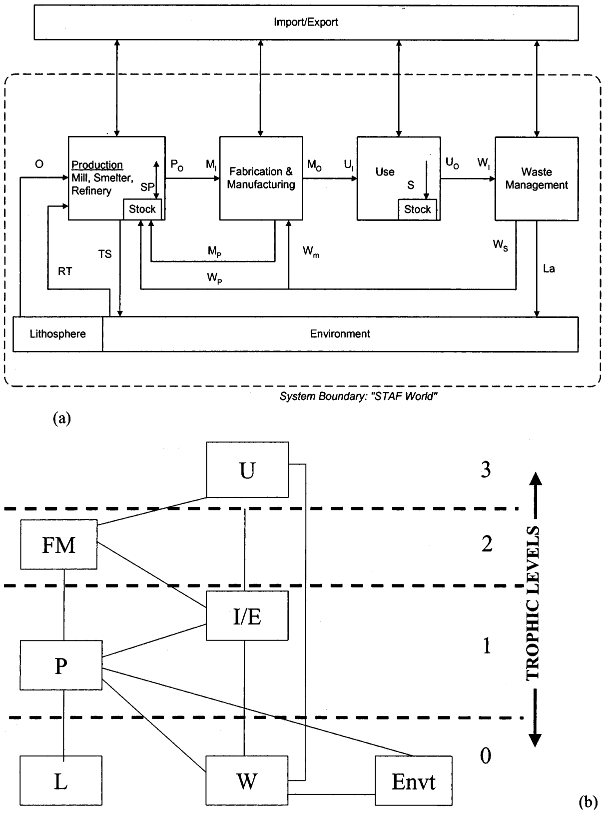


FIGURE 1. Simplified schematic diagram of a technological resource cycle: (a) the diagram with successive life stages plotted from left to right, and (b) the diagram replotted as a trophic level diagram with four levels shown on the right. The symbols are as follows: O = copper in ore, P = processing life stage, M = manufacturing life stage, U = in-use life stage, W = waste management life stage, L = lithosphere, TS = copper discarded in tailings and slag, RT = copper in recovered and recycled tailings, FM = fabrication and manufacturing, I/E = import/export, S = flow to in-use stock, La = landfill, M_p = new scrap to processing, W_m = scrap waste to manufacturer, W_p = scrap waste to processor, I = in, O = out.

the structure of the patterns themselves (*14*). This is particularly true in view of the data that are available to study the flows of resources. They are generally available for organizational entities (country, region, planet) rather than on a uniform spatial scale, and the elements of those domains are neither uniform nor avoidable. Additionally, it is clear that scale issues are present when relating resource loss to environmental impact (*15*, *16*). Accordingly, it becomes important to characterize multilevel resource flows empirically. That challenge is the basis for the analytical approach of this paper, which explicitly addresses copper flows (and related stocks) from a multilevel perspective.

Methodology of Copper Cycles

The methodology used to characterize the cycles of copper has been described in detail in earlier publications (*7*, *17*, *18*). We summarize the approach briefly here for the convenience of the reader. It is based on the framework shown in Figure 1a, which consists of the four life stages in which an anthropogenically utilized material participates: extraction and production, fabrication and manufacturing, use, and waste management. Earth's lithosphere serves as the initial source of the material and the environment as the eventual sink (though discarded materials are commonly retained for long periods of time in tailings ponds or landfills). For all but global cycles, import and export is possible at any of the four stages. We refer to these stages as "reservoirs", because they are storage locations for copper. The contents of a reservoir are termed its "stock", which can increase if the sum of the flows into the reservoir exceeds that of the flows leaving or can decrease if input flow magnitudes are less than output flow magnitudes. In practice, only the in-use stage involves significant long-term storage and no transformation. An alternative designation for the other three stages could be "processes". There are also flows to three very long term reservoirs that we term "repositories": tailing ponds, slag ponds, and landfills. The actual cycles, and our analysis of them, are considerably more complex than Figure 1a suggests; this complexity is discussed in more detail in the regional cycle publications referenced above.

A cycle is considered characterized when the flows that connect the reservoirs and the changes in stock that increase or deplete the reservoir contents are quantified for a particular time interval. These linkages and related changes constitute an industrial "food web", similar in concept to the food webs utilized to study natural ecosystems (*19*, *20*). In Figure 1b we replot the cycle of Figure 1a as an industrial food web with four trophic levels; the highest level is that of the human user. (A trophic level in biology is a level in a food chain in which all organisms are the same number of energy transfers away from the original source of the energy entering the ecosystem.) The food web reformulation of the cycle emphasizes the dependence of copper stocks and flows on the needs and desires of the human "top predator" and is a conceptualization encompassing resource use, culture, and society.

Assembling the data for the characterization of complex resource cycles requires the use of numerous sources of varying quality, mostly available at country level. In general, the reliability of the information decreases as one moves from production to waste management in Figure 1a. This occurs because global metal markets provide detailed information so long as copper is being sold as a unique material (copper ore, refined copper, etc.). Once it is utilized in manufacturing, usually in combination with other materials, data tend to be available only in the form of products or groups of products (e.g., machine tools), for which copper content must be estimated. Flows of copper from use into waste management are even less well characterized; we combined data on waste stream magnitudes (often available) with information on the copper contents in the several waste streams (sparse and not readily generalizable to all countries or regions). We comment later in this paper about the probable reliability of the individual parameters and of the overall results.

Country level statistics on production (P), import (I), and export (E) (hereafter, designated as PIE data) of copper concentrate, blister copper, and copper cathode are published annually by the World Bureau of Metal Statistics (*4*) and by the International Copper Study Group (*21*). Copper flow estimates for mine tailings, reworked tailings (as a result of copper production from solvent extraction and electrowinning processes), and smelter slag were determined empirically using Gordon's (*22*) approach. The trade data on several major copper-containing semi-products and finished products were taken from United Nations statistics (*23*). A more detailed discussion of data sources appears in papers on regional copper cycles that are cited below.

We have not attempted to establish copper stocks and flows in every country in the world. In a number of cases, data are simply not available, especially if countries are in the early stages of economic development or are politically unstable. Our goal has been to attempt to capture at least 80% of the magnitude of each flow stream by evaluating countries which extract, fabricate, and/or use significant quantities of copper. This has resulted in complete cycles for 54 countries and two country groups and for nine world

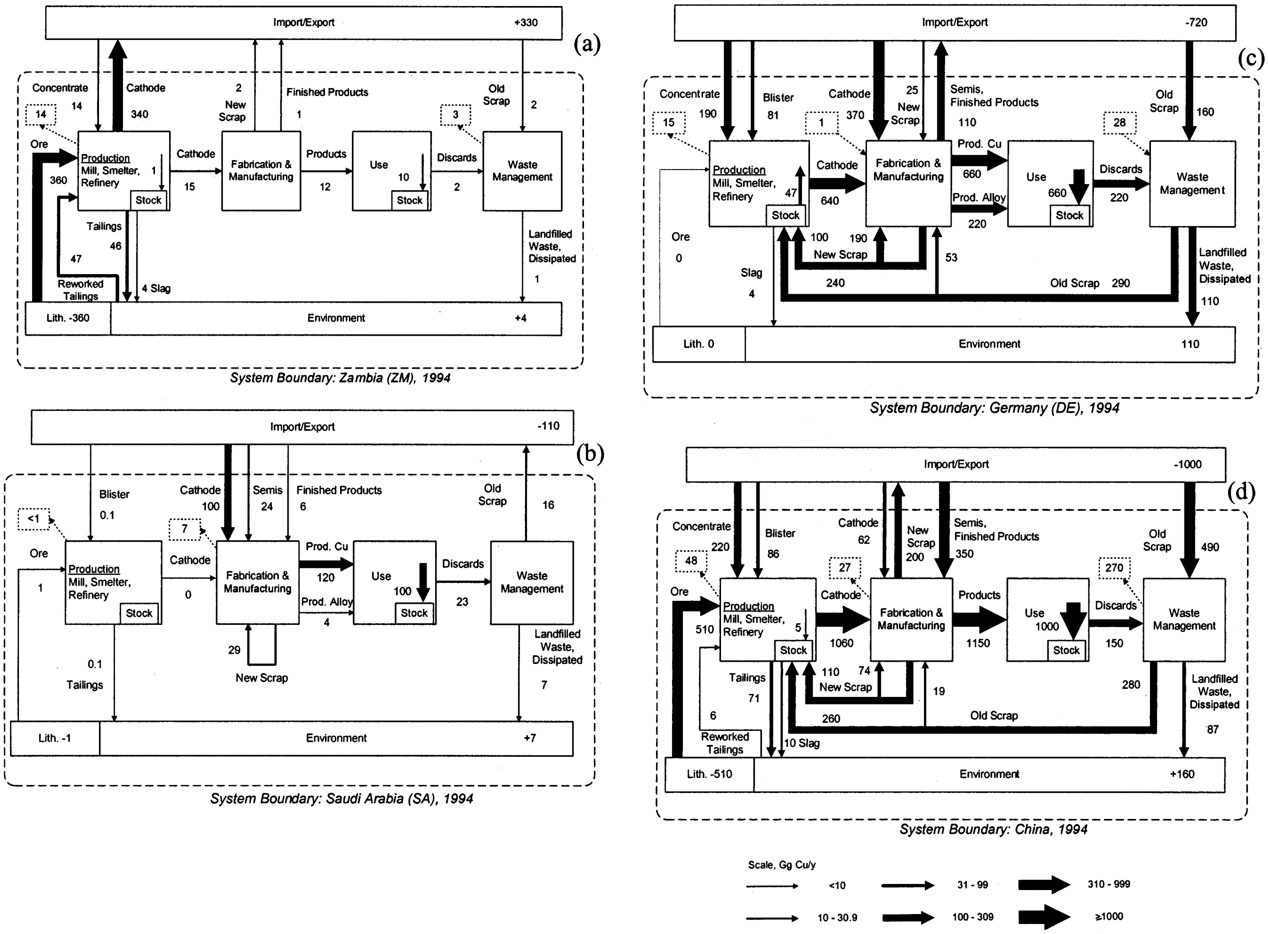


FIGURE 2. Contemporary copper cycles for (a) Zambia, (b) Saudi Arabia, (c) Germany, and (d) China. Lith. = lithosphere; Prod. Cu = products containing pure copper; Prod. Alloy = products containing copper in alloy form. The units are Gg Cu/year. Because of approximation to two digits throughout, the reservoirs on the diagrams do not always appear to be in balance, though closure is achieved in our detailed calculations.

regions. Most are continents, but some are defined partly for geographical reasons and partly for data availability and consistency considerations. The cycles for the regions are the aggregates of the data for the countries within them, and the global cycle is the aggregate of the data for the regions. Even where comprehensive country-level cycles cannot be characterized, selected data from individual countries are often useful at the regional level. As a result, the aggregated regional cycles incorporate copper flow information from more than 100 countries.

Our results do not completely address human mobilization of copper, because we omit consideration of copper contained in coal and oil and liberated by combustion. The amount varies with source and type of fossil fuel and its loss to either the atmosphere or soil is defined by the air pollution control system at the power plant. The global loss from this source has been estimated at 72 Gg/year (*24*); this is, at best, an order of magnitude estimate but appears not very large compared with the flow magnitudes arising from the directed processing and use of copper.

Country-Level Copper Cycle

Copper stocks and flows at the country level strongly reflect the state of development of the country, the wealth of its inhabitants, and the customs and practices of its society. On the STAF-copper project, we developed information for all 54 countries and 2 country groups of the world that have significant rates of extraction, fabrication, and/or use of copper. The two country groups are Benelux (Belgium, Netherlands, and Luxembourg) and Scandinavia (Denmark, Finland, Norway, and Sweden); they occur in this way in our data set because that is the way in which some of the European data that we use are reported.

Several European country-level cycles have already been presented by Bertram et al. (*25*). In the Supporting Information for this paper we supplement that information by providing ca. 1994 copper cycle diagrams for each country and country group in our study. Limited space does not permit us to comment on each country cycle diagram in the Supporting Information. As an example of these comprehensive contemporary cycles, however, we show in Figure 2 the cycles for Zambia, Saudi Arabia, Germany, and China and comment on features of these cycles that demonstrate generic characteristics of broad utility and interest.

In any cycle where characterization is complete and accurate, mass balance is achieved, that is, input flows are equal to output flows plus changes in stock. This constraint applies to each reservoir in the cycle. In practice, it is often the case that mathematical closure is not achieved, perhaps because some flows are determined inaccurately, because flows refer to different but unstated aggregations or because the amount of material added to or subtracted from stock is unknown. Unless additional information exists to guide stock or flow adjustments, our approach for reservoirs in which mass balance does not result from the available data is to utilize a dashed-line box and arrow to indicate, in a manner that is transparent to the reader, the amount needed to achieve reservoir closure. Accordingly, the cycle in Figure 2a shows that an outflow of 14 Gg Cu/year is needed to achieve mass balance for the production reservoir. Closure gaps of this sort occur in the cycles of most countries, but they are generally less than 10% of total flows to or from the subject reservoir and thus do not markedly influence the qualitative results arising from the cycle characterization.

The cycle for Zambia (Figure 2a) is typical of a country that mines and processes large amounts of copper and immediately exports nearly all of it. Only about 4% of the copper mined in Zambia is fabricated into products and put into use within the country. Flows to waste management are small, and there is no evidence in the data of any recycling of that material.

Saudi Arabia (Figure 2b), in contrast, mines almost no copper but does have a fabrication and manufacturing industry. Almost all of the output from this latter cycle stage is transferred to in-use stock within the country. The rate of discarded copper is only about 20% of that flowing into use, and most of the discarded copper is exported for recycling.

The cycle for Germany (Figure 2c) represents a highly industrialized country without significant virgin copper resources. Unable to rely on an internal supply, Germany imports copper in different forms at every industrial life stage—production, fabrication and manufacturing, and waste management. Its reuse of discarded and imported scrap is so extensive that nonvirgin copper supplies about 45% of all inflows to its industrial facilities. Nonetheless, Germany landfills about 110 Gg Cu/year, the most of any country in Europe.

The Chinese copper cycle (Figure 2d) illustrates a fully integrated, high-flow industrial economy. Substantial copper is mined within the country, and rates of production and fabrication and manufacturing are large. More than 85% of flow into use is added to stock. Old scrap imports significantly enhance the supply to industry. Landfilled waste is small relative to overall flow and smaller in magnitude than Germany even though the Chinese population is much larger.

Other features of the country-level cycles can be seen in the Supporting Information; we comment here on a few of the more interesting. (1) Countries that seem to be at relatively similar stages of industrial development appear to use copper in their manufacturing sectors in significantly different ways. One example is the “transformation ratio”, the fraction of fabrication and manufacturing copper outflow that is in alloy form rather than elemental form. This fraction is 0.26 for France and 0.56 for Italy. (2) Waste management flows differ among countries. Thailand, for example, appears to recycle very little copper, while Taiwan recycles a very high proportion. (3) Virtually all countries are adding substantial amounts of copper to in-use stock. This cannot continue indefinitely, and large future outflows of copper to waste management should be anticipated.

Regional-Level Copper Cycle

Regional-level copper cycles are produced by combining information from the appropriate country-level cycles. In addition, we include miscellaneous information, such as copper import or export rates, for countries located in a specific region but about which data are too sparse to allow complete country-level cycles to be constructed. Several of the regional-level cycles we characterized have already been published: Europe (*7*), Africa (*26*), Asia (*27*), and South America (*28*). In the present work, we present data for those four regions (slightly updated in some respects for overall consistency) and for five additional regions, in uniform format. The nine regional-level cycles appear in Figure 3.

We have insufficient information to specify uncertainty for most country-level stock and flow magnitudes. At regional levels, however, we feel able to assign confidence ratings, following the approach advocated by Moss and Schneider (*29*), in which confidence levels are assigned to copper flow determinations on the basis of the collective judgment of the authors regarding the reliability and quality of the data. Moss and Schneider advocate a five-point quantitative scale for confidence levels. In no case do we regard the data that we report as possessing “very high” confidence (i.e., with a value accurate to ±5%). Thus, for several flows in the different regions, we specified confidence levels of “high” (accuracy thought to be ±5−33%), “medium” (±33−67%), “low” (±67−95%), or “very low” (>±95%). On the regional copper cycle diagrams, we indicate the degree of confidence by varying the form of the flow arrows, shown in Figure 3. The technique is particularly easy to appreciate in Figure 3b, the Asian regional cycle, where several different confidence levels are present.

The cycles for the regions are aggregations from countries that generally possess widely varying economies, degrees of development, and mineral wealth. The African cycle in Figure 3a is a case in point. Copper ore is mined and processed in quantity in only two countries and largely exported from the region. Only about 20% of the amount mined is fabricated into products within Africa; however, Africa ends up importing about 40% of the copper it uses in finished products. Overall, the African cycle is characterized as heavily weighted toward extraction rather than use.

The Antarctic cycle (Figure 3b) is unique in that international treaties forbid mining and require countries operating scientific stations to recover and export all materials when no longer needed. The cycle on the continent is thus restricted to the use and waste management stages, and the flow magnitudes are far less than 1% of those of any of the other regions.

Asia (Figure 3c) is a major extractor, a major manufacturer, and a major user of copper. Aided by a high import rate, it has comparable high copper flows through the first three reservoirs as well as a substantial flow through waste management. This balance is quite unlike that of Africa, for example.

The Commonwealth of Independent States (the former Soviet Union, Figure 3d) has a copper cycle very much like that of Africa, though flows are somewhat larger and the rate of discarded copper exceeds the amount entering in-use stock.

The cycle for Europe (Figure 3e) is much like that of Asia but with somewhat smaller flow rates. As with Asia, Europe mines a significant fraction of the copper used but imports more than it mines. Both continents are major manufacturers and make internal use of most of what they manufacture.

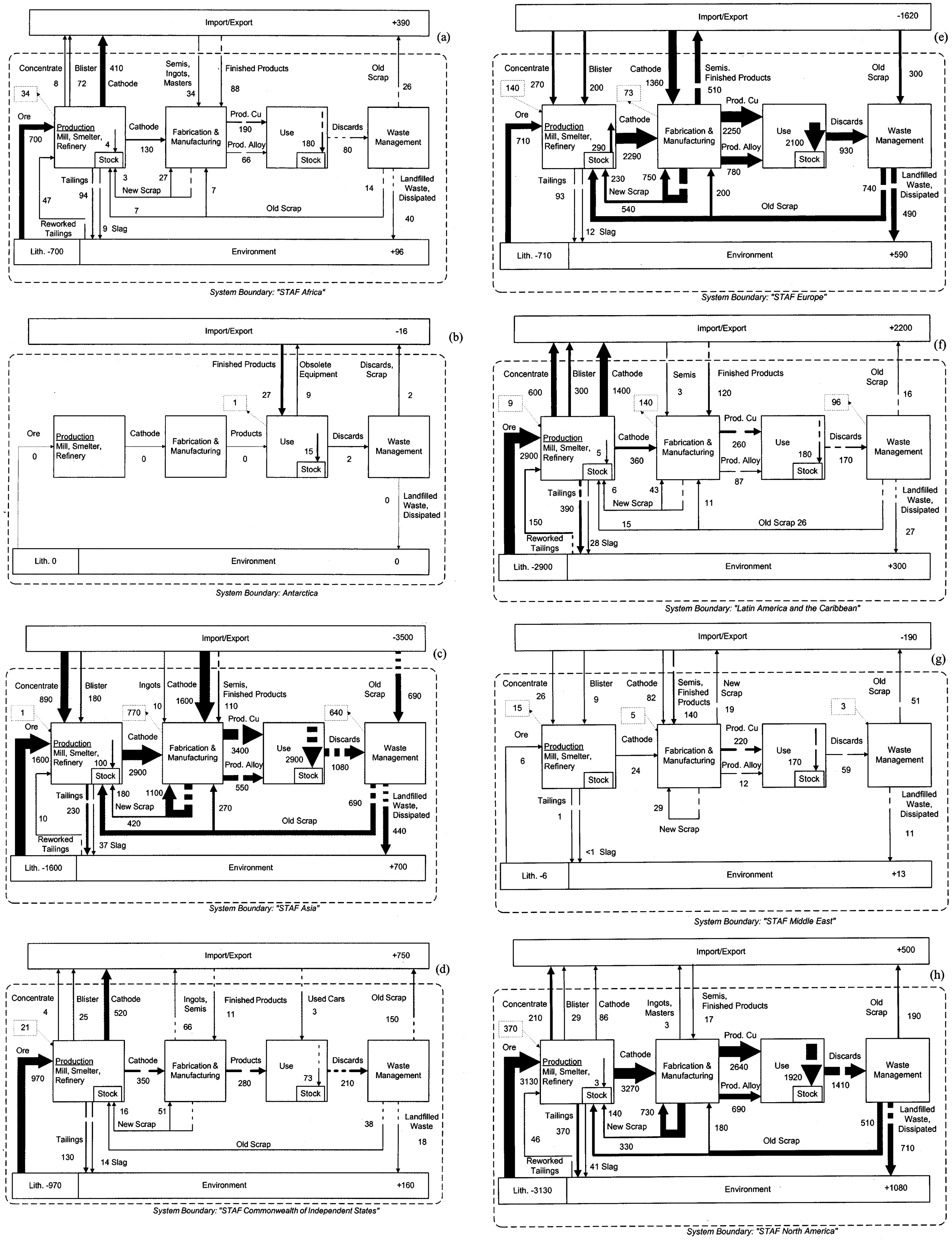
Latin America and the Caribbean (Figure 3f) is an enhanced version of Africa: a major extractor, a major exporter, and a modest user.

The Middle East (Figure 3g) has a unique cycle resulting from its wealth and from its lack of mineral resources. It mines and fabricates almost no copper but imports and adds to in-use stock an amount comparable to that of Africa, Latin America and the Caribbean, and Oceania.

North America (Figure 3h) has the copper cycle that is the most balanced within its boundaries of any of the regions. Its net import of copper is small compared with the amount mined and processed internally.

Oceania (Figure 3i), like Africa, the Commonwealth of Independent States, and Latin America and the Caribbean, is primarily an extractor and exporter rather than a user.

Comparisons of flows for various countries within a region, and among regions, can be done in various ways. An example is shown in Figure 4a, where the annual rates of copper use in Asian countries (ca. 1994) are shown on a map of the region. It is of interest to note that the rates are identical for China and Japan at 1200 Gg Cu/year, far higher for those two countries than for any of the others. South Korea and Taiwan have annual rates that are roughly equivalent at about 400 Gg Cu/year, about one-third of those of China and Japan.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(a)
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Blister 72
410 Cathode
Semis, Ingots, Masters 34
Finished Products 88
Old Scrap 26
34
Ore 700
Production Mill, Smelter, Refinery 4
Stock
Cathode 130
Fabrication & Manufacturing
Prod. Cu 190
Prod. Alloy 66
Use 180
Stock
Discards 80
Waste Management
Tailings 94
47
3
27
New Scrap
7
14
7
Old Scrap
Landfilled Waste, Dissipated 40
Reworked Tailings
9 Slag
Lith. -700
Environment +96
System Boundary: "STAF Africa"
Import/Export -16
(b)
Finished Products 27
Obsolete Equipment 9
Discards, Scrap 2
1
Ore 0
Production Mill, Smelter, Refinery
Cathode 0
Fabrication & Manufacturing
Products 0
Use 15
Stock
Discards 2
Waste Management
0 Landfilled Waste, Dissipated
Lith. 0
Environment 0
System Boundary: Antarctica
Import/Export -3500
(c)
Concentrate 890
Blister 180
Ingots 10
Cathode 1600
Semis, Finished Products 110
Old Scrap 690
1
770
640
Ore 1600
Production Mill, Smelter, Refinery 100
Stock
Cathode 2900
Fabrication & Manufacturing
Prod. Cu 3400
Prod. Alloy 550
Use 2900
Stock
Discards 1080
Waste Management
Tailings 230
10
180
1100
New Scrap
420
270
Old Scrap
690
Landfilled Waste, Dissipated 440
Reworked Tailings
37 Slag
Lith. -1600
Environment +700
System Boundary: "STAF Asia"
Import/Export +750
(d)
Concentrate 4
Blister 25
Cathode 520
Ingots, Semis 66
Finished Products 11
Used Cars 3
Old Scrap 150
21
Ore 970
Production Mill, Smelter, Refinery
Stock
Cathode 350
Fabrication & Manufacturing
Products 280
Use 73
Stock
Discards 210
Waste Management
Tailings 130
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Old Scrap
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Landfilled Waste 18
14 Slag
Lith. -970
Environment +160
System Boundary: "STAF Commonwealth of Independent States"
Import/Export -1620
(e)
Concentrate 270
140
Blister 200
Cathode 1360
73
Semis. Finished Products 510
Old Scrap 300
Ore 710
Production Mill, Smelter, Refinery 290
Stock
Cathode 2290
Fabrication & Manufacturing
Prod. Cu 2250
Prod. Alloy 780
Use 2100
Stock
Discards 930
Waste Management
Tailings 93
230
750
New Scrap
540
200
Old Scrap
740
Landfilled Waste, Dissipated 490
12 Slag
Lith. -710
Environment +590
System Boundary: "STAF Europe"
Import/Export +2200
(f)
Concentrate 600
Blister 300
Cathode 1400
Semis 3
Finished Products 120
Old Scrap 16
9
140
96
Ore 2900
Production Mill, Smelter, Refinery 5
Stock
Cathode 360
Fabrication & Manufacturing
Prod. Cu 260
Prod. Alloy 87
Use 180
Stock
Discards 170
Waste Management
Tailings 390
150
6
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New Scrap
11
15
Old Scrap 26
Landfilled Waste, Dissipated 27
Reworked Tailings
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Environment +300
System Boundary: "Latin America and the Caribbean"
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Blister 9
Cathode 82
Semis, Finished Products 140
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Old Scrap 51
15
5
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Stock
Cathode 3270
Fabrication & Manufacturing
Prod. Cu 2640
Prod. Alloy 690
Use 1920
Stock
Discards 1410
Waste Management
Tailings 370
46
140
730
New Scrap
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Environment +1080
System Boundary: "STAF North America"

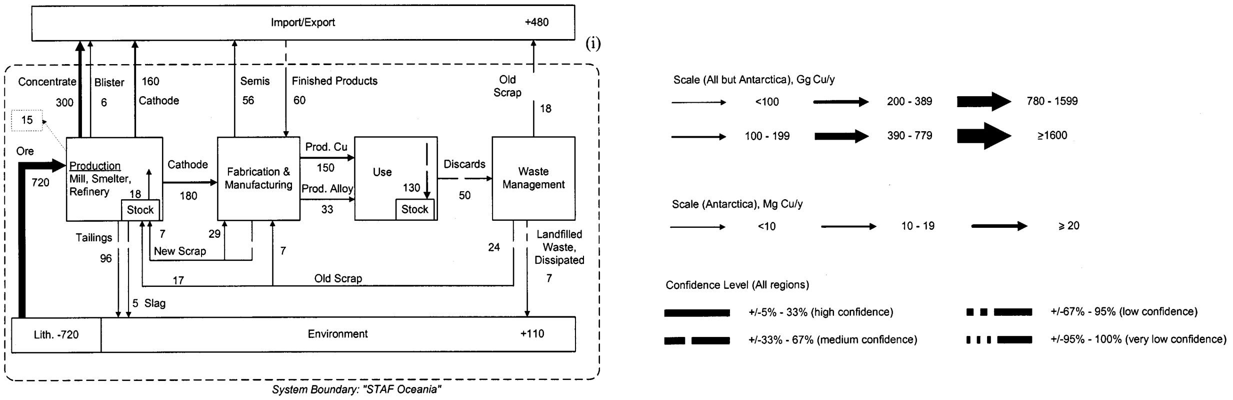

FIGURE 3. Contemporary copper cycles for the regions: (a) Africa, (b) Antarctica, (c) Asia, (d) Commonwealth of Independent States, (e) Europe, (f) Latin America and the Caribbean, (g) Middle East, (h) North America, and (i) Oceania. The units are Gg Cu/year, except for Antarctica, which is Mg Cu/year. Because of approximation to two digits throughout, the reservoirs on the diagrams do not always appear to be in balance, though closure is achieved in our detailed calculations.

The rates for Malaysia and Hong Kong are a factor of 2 lower still. Several countries are grouped around annual use levels of about 20−100 Gg Cu/year. One is India, where the copper use rate is surprisingly low given the country's large population.

Results for the same parameter (annual rates of copper use) on a regional basis are shown on the world map in Figure 4b. These rates of use, as with those of the individual countries, reflect both domestic production and product imports. Asia's rate is the highest, but it is not far above those of Europe and North America. The rates for all other regions are less than 10% of those of the top three.

Regional data for other parameters of the copper cycle are shown in Figure 5. Note first (Figure 5a) the dominance for extraction of the countries that are well-known major sources of virgin copper: Latin America and the Caribbean and North America. However, five other regions extract moderate amounts of copper, each with 7−14% of the world total. The exceptions are Antarctica and the Middle East. Less appreciated is the nutrient ratio (scrap to virgin) of copper provided for processing (Figure 5b). This is highest in Europe, which combines an extensive industrial structure with good collection of discards. Asia's rate is less than one-half as much, and others are lower still (though all rates would doubtless be enhanced by more complete scrap accounting). Rates of loss of copper in tailings and slag (Figure 5c) follow that of the extraction and refining flows.

With the exception of North America, the regions that produce copper in abundance are not necessarily the biggest fabricators, because copper semi-products from refineries are readily shipped elsewhere if economic factors are favorable. The regions with the highest rates of fabrication are Asia, Europe, and North America (Figure 5d). Asia, Europe, and the Middle East are the only net importers of copper in all forms except for Antarctica's tiny amount (Figure 5e). Additions to in-use stock (Figure 5f) are generally about two-thirds of the rate of copper use.

Discard flows (Figure 5g) do not follow earlier life stage rates very well; they seem to reflect a combination of wealth and stage of development. North America's is highest, followed by Asia and Europe. Rates are small for other regions. The portions of the copper discards that are recycled (Figure 5h) vary widely, from 100% in Antarctica to 34% in Africa. These numbers are not well documented, especially in the developing world; we suspect they are higher than we are able to determine from the available data sources because of a variety of informal, unquantified markets.

Loss to landfills (Figure 5i) is the difference between the copper discard rates and the copper recycling rates. We calculate that North America landfills the most copper, followed by Asia and Europe.

We offer the same cautionary note for the regional-level cycles as for the country-level cycles: the copper cycle is evolving, and these data are a ca. 1994 snapshot of one phase of that evolution. In particular, we anticipate that the copper cycle for Asia will change dramatically over the next few decades as a consequence of regional infrastructure growth.

Global-Level Copper Cycle

The global-level copper cycle is shown in Figure 6. This cycle is produced by aggregating the cycles for all the regions and then making minor adjustments in some of the flows so that closure around each of the reservoirs is achieved. (The detailed procedures are discussed in the Supporting Information.) A number of features of this global cycle are of interest. We comment on them below, by reservoir.

(1) Global copper inputs to production in 1994 were about 83% ore, 11% old scrap, 4% new scrap, and 2% reworked tailings. Informal scrap flows not captured in existing data probably exist as well.

(2) About two-thirds of the copper that entered use in 1994 was added to in-use stock—between 7 and 8 Tg worth. This material, in products with lifetimes of 10−60 years (*7*) can thus be expected to become available for reuse during the period 2004−2054, with peak flow for this material in about 2024.

(3) Nearly 11 Tg of copper was extracted from the lithosphere, and slightly more than 3 Tg was discarded into various long-term repositories. Thus, nearly 30% of copper mining occurred merely to replace copper that was discarded. The difference between these two flows represents changes in stocks: a slight decrease in production inventory stock and a very large increase to stock in use.

The discard flow in Figure 6 is actually made up of seven distinct waste streams: municipal solid waste (MSW), construction and demolition debris (C&D), industrial waste (IW), hazardous waste (HW), waste from electrical and electronic equipment (WEEE), end-of-life vehicles (ELV), and sewage sludge (SS). We compare information on the seven global waste streams in Figure 7. In the top panel, IW is seen to have, by far, the largest total flow; those of MSW and C&D are high as well. Their copper concentrations are all quite low, however, while those of WEEE and ELV are quite high (*18*) (center panel). Multiplying the total flows by the copper concentrations in the flows gives the copper flows shown in the bottom panel. The result is that WEEE and ELV, with about 4% of the total discard flow, contain about 70% of the discarded copper. In addition, the lifetimes of these uses

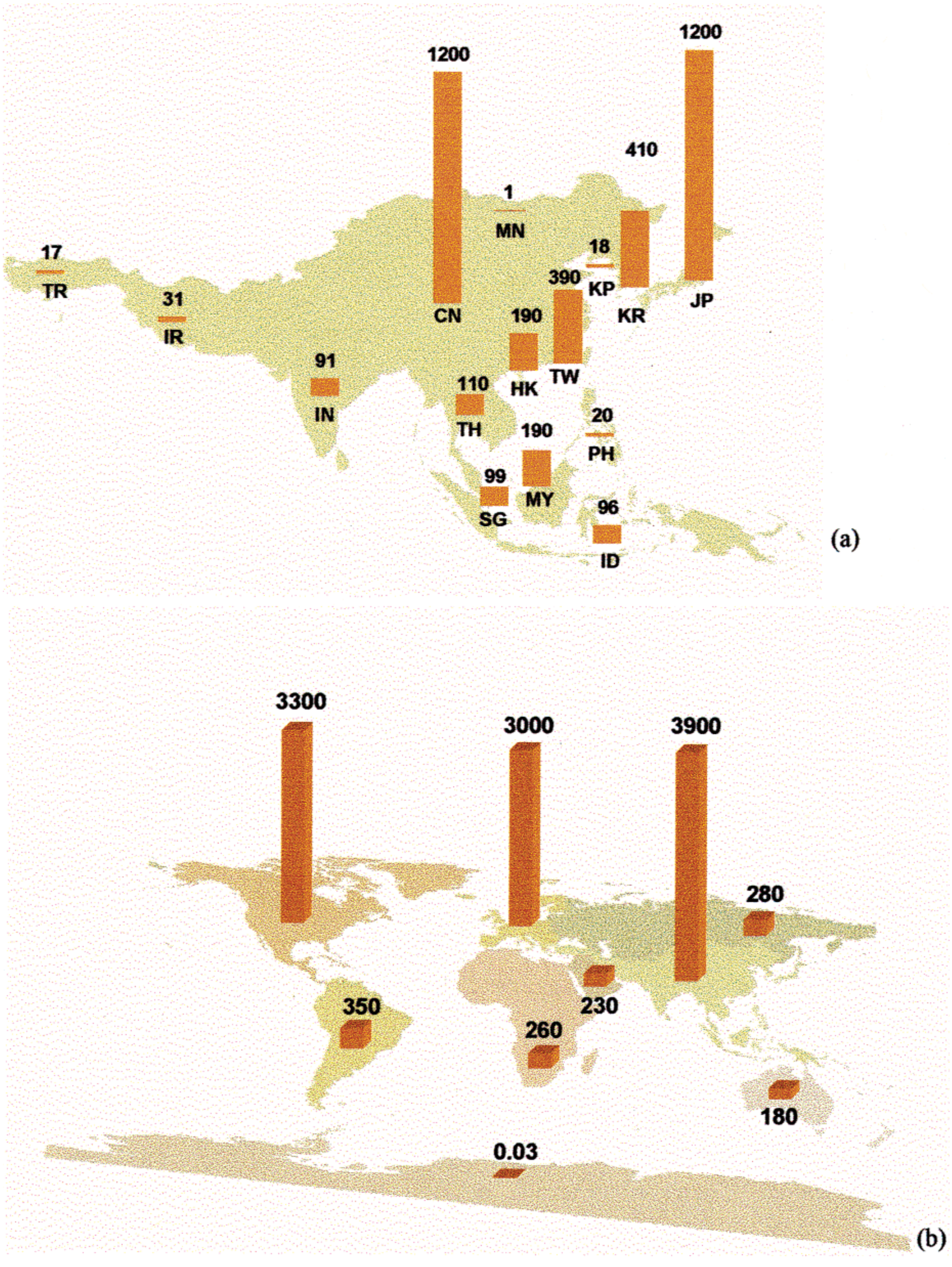

FIGURE 4. (a) Annual rates of copper entering use in Asian countries. (b) Regional rates of copper entering use in the nine world regions. The year is ca. 1994; units are Gg Cu/year.

tend to be short and recovery of the copper relatively straightforward. This predominance of discarded copper in two short turnover waste streams, previously noted for Europe (*18*), appears to hold for all nine regions. However, some waste streams are problematic, so we cannot definitively state that this result holds for all regions.

Overall, worldwide discard copper in 1994 worldwide amounted to about 40% of the amount acquired from virgin repositories. A little more than one-half of that material was reused with the remainder discarded. If a larger proportion of the discards was recaptured [and much of it is in easily collectable electronics and vehicle discards (*18*)], virgin ore extraction requirements would decrease significantly. Overall, including tailings and slag, nearly one-third of the amount of copper that was mined in 1994 was returned to the soil (but not necessarily in the same location: copper was mostly

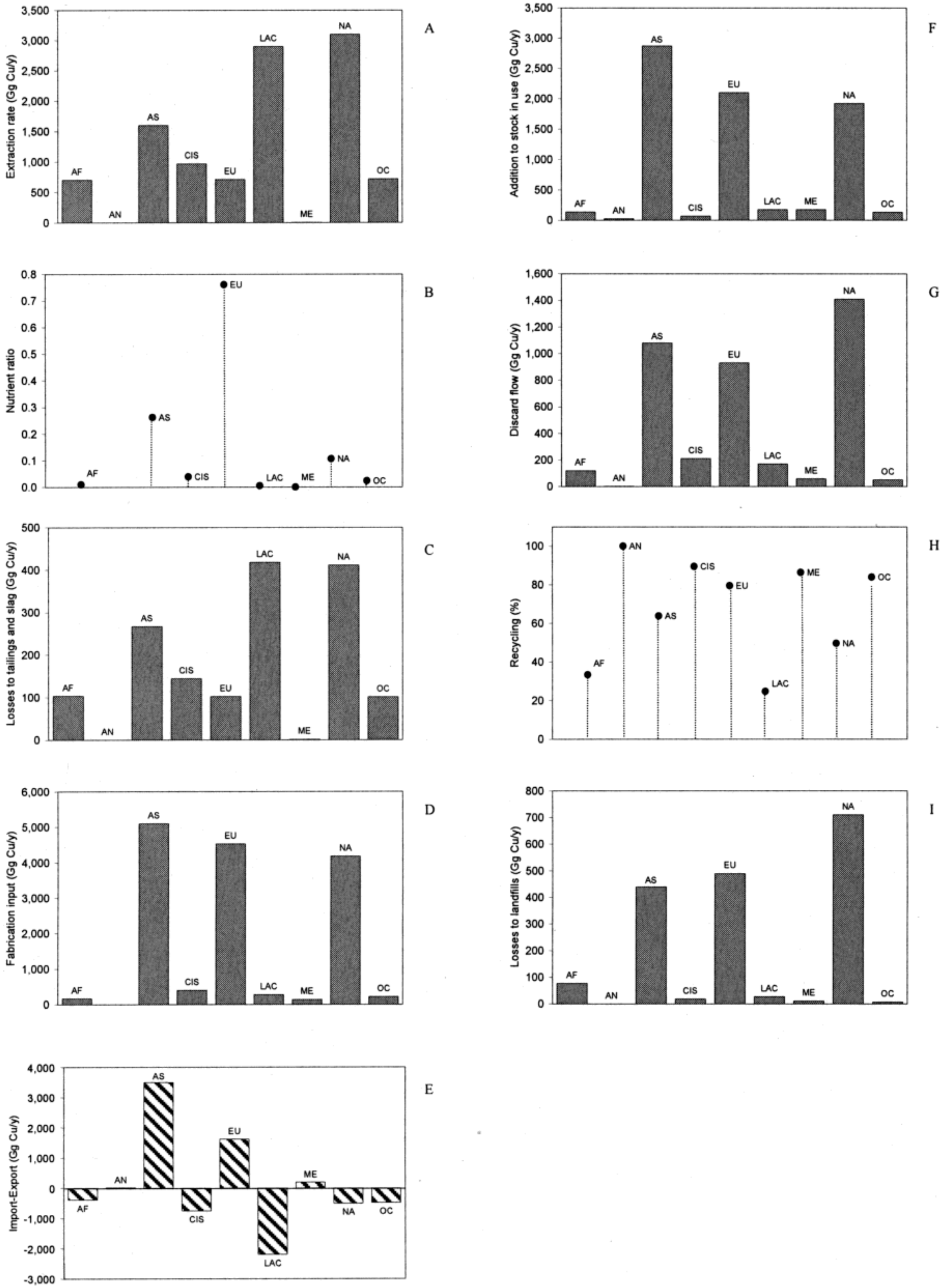

FIGURE 5. Comparative copper statistics for the nine world regions: Africa, Antarctica, Asia, Commonwealth of Independent States, Europe, Latin America and the Caribbean, Middle East, North America, and Oceania. Bar graphs are used where the parameter being plotted is a magnitude, lolliplots (*35*) where the parameter is a ratio or percentage and where bars signifying "everything from the bottom to the top of the bar" would be inappropriate: (a) Copper extraction rate; (b) Nutrient ratio [ratio of scrap copper to virgin copper provided for processing]; (c) Rate of copper loss in tailings and slag; (d) Copper fabrication rate; (e) Copper [import−export] rate; (f) Rate of copper additions to in-use stock; (g) Copper discard rate; (h) Percentage of discarded material that was recycled; (i) Copper landfill rate. All statistics are ca. 1994.

mined far from concentrations of population and landfilled near urban areas).

If all copper import and export flows were accurately quantified, import and export would be expected to cancel

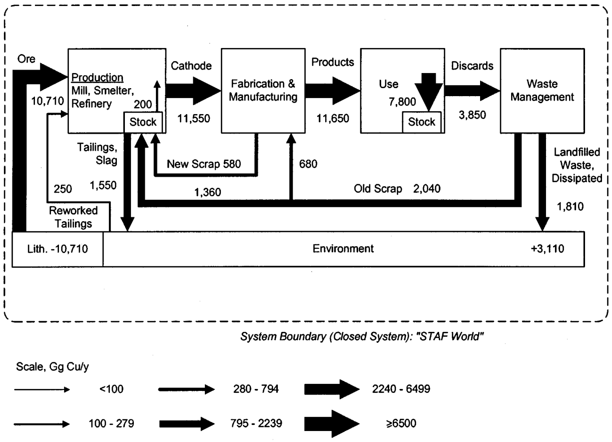

FIGURE 6. Global “best estimate” anthropogenic copper cycle for ca. 1994.

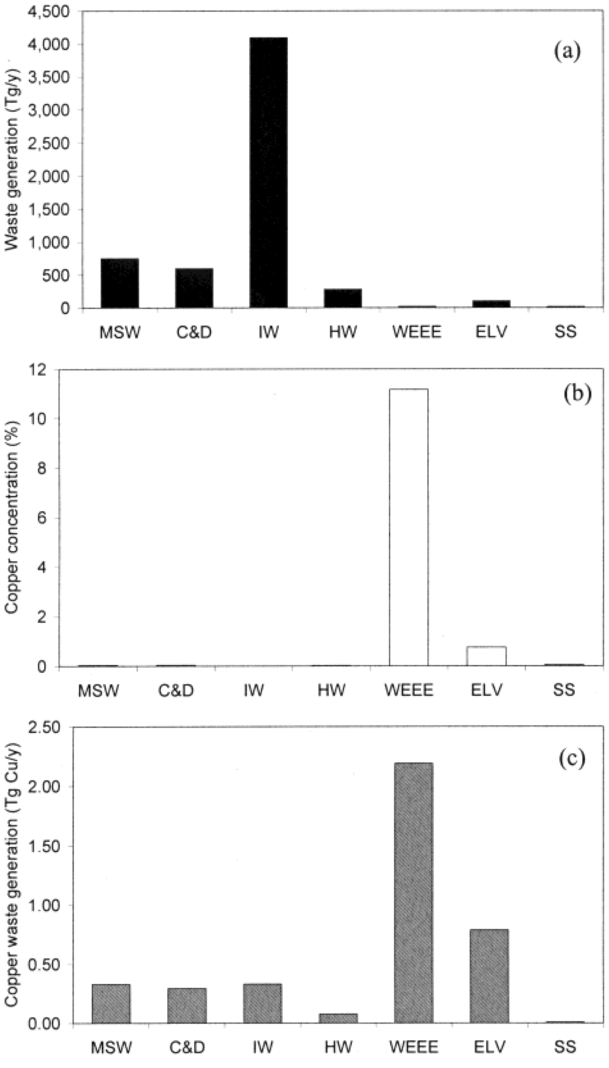

FIGURE 7. Rates of global copper discards in different types of waste streams: (top) total waste streamflow; (center) average copper concentration in waste stream; (bottom) copper flow. The abbreviations are defined in the text.

in the global cycle. Our initial review of the data suggested that import/export flow data might not sum to zero, however, so we resolved to capture at least 80% of each of the flows. We thus conceded from the start that we would be unable to account for every copper atom mobilized and used throughout the world. Nonetheless, we note that the flow amount required to achieve closure is of order 5−10% of the flows between the major reservoirs. Overall, we regard the flow magnitudes of Figure 6 (import/export excepted) to be accurate to between one and two significant digits.

Note on Uncertainty

As is the case with all other material flow analysis, our cycles of copper will never be completely correct nor entirely complete, due of data limitations. Nonetheless, it is appropriate to evaluate the uncertainty in our results, a process made challenging by the widely differing reliabilities of the information that we used. One way to examine this issue is to look at closure—the degree to which inputs and outputs in a cycle achieve mass balance. At the country level, closure is achieved for each reservoir by adding or subtracting the required amount, indicated on the diagram as a virtual input or output. We have no independent data for inputs and outputs to the four stages of the anthropogenic copper cycle; we regard the lithospheric extraction data to be generally of high accuracy (because it follows international metal markets data), import/export data to be of moderate accuracy (because copper content in many of the data flows is not well-known), and loss to the environment to be of low accuracy (because many portions are not routinely monitored and can only be quantified by representative information).

At the regional level, the cycle is established by aggregating the country-level flows (with the exception of the landfill flow in the waste management stage) but not the closure deficits. As a result, closure is not automatically achieved for each reservoir, and the same degree of uncertainty holds for lithospheric, import/export, and environmental flows as for the country-level cycles.

The landfill flows for all nine regions were calculated by difference between discard and recycling flows (*18*). Scrap data published by the World Bureau of Metal Statistics (*4*) and by the International Copper Study Group (*21*) were used for all regions, except for Asia, Latin America and the Caribbean, and the Middle East, in which cases data uncertainty made it necessary to use recycling ratios to determine scrap data (*27*, *28*); in these cases, the scrap amounts thought to be recycled are represented in dashed-line boxes on the diagrams. At a regional level, trade in waste streams destined for disposal (e.g., MSW, HW) was not considered, due to the fact that these numbers are very small (*18*). However, at a county level, waste trade for disposal becomes an important consideration. Due to data limitations and uncertainties, “waste trade for disposal” on a country level could not be explicitly considered. Further, we assume low reliability of the published waste for recycling trade data. To achieve an estimate for the amount of waste landfilled, without using “waste trade for disposal” data, a landfill ratio was determined for each region and applied to the countries in that region, with the major assumption that countries in the same region have similar waste management practices. The only exception to this analysis was Asia, where countries were grouped into developing and developed categories. In the waste management stage, on a country level, dashed-line boxes thus may include waste trade.

The global cycle was produced by aggregating all regions and making minor adjustments to achieve closure of the four life-stage reservoirs, as discussed in the Supporting Information. Overall, the required closure amounts requiring adjustment tend to be of order 5−10% of total flows to or from each of the four reservoirs.

Several alternative approaches to uncertainty assessment exist for calculations in which numbers whose accuracy cannot be precisely established are added or otherwise propagated. Hedbrant and Sörme (*30*) recommend dividing data into five categories of uncertainty, though with different ranges from those of Moss and Schnieder (*29*). Bayesian statistical approaches (e.g., 31) have also been investigated for use here. Neither approach appears particularly appropriate for the copper cycle data, in which a number of the flows are based on information of uncertain accuracy while others are calculated using reasonable assumptions and informed estimates. Overall, we regard our use of confidence limits we set for the flows on the regional and global diagrams as the best current method to evaluate and express the uncertainty in our results. These copper cycles, while possessing more uncertainty then desirable, are almost certainly better characterized than the early-stage atmospheric cycles [such as that for methane (*32*)] that have nonetheless formed the basis for much valuable subsequent research. Clearly there is much work left to do to improve the accuracy of the cycles. Equally clearly, characterizing copper cycles to the level of accuracy we have been able to achieve provides much information of value.

Discussion

To our knowledge, these results comprise the first multilevel cycle for any of the elements dominated by human activity. Among the most interesting and significant results are the following: (1) Transformation rates and recycling rates in apparently similar national economies differ by factors of two or more. (2) The discard flows that have the greatest potential for copper recycling are those with low magnitude flows but high copper concentrations—electronics, electrical equipment, and vehicles. (3) Worldwide, about 53% of the copper that was discarded in various forms was recovered and reused or recycled. (4) The highest rate of transfer of discarded copper to repositories is into landfills, but the annual amount of copper deposited in mine tailings is also substantial. (5) Nearly 30% of copper mining occurred merely to replace copper that was discarded.

The copper cycle is not in steady state at any of the three organizational levels (country, region, world) we have studied. This situation arises largely from the trend to increased use of copper and from the fact that many copper in-use lifetimes are several decades long. As a result, material now in stock will revert to the waste management stage over a period of time (*33*). At present, resource recovery following discard is relatively underdeveloped. We judge that there may be the potential to significantly increase the recycling percentage if collection and scrap management approaches are enhanced.

Another aspect of this copper cycle study—a statistical analysis of the information contained in the material flow cycles—is given in a companion paper appearing in this issue of the journal (*34*).

Although the multilevel cycles are significant in themselves, their broader utility lies in the associated analyses and activities that the cycles enable. These include (1) studies of resource availability, now and in the future, as suggested by rates of recycling and by the amount and type of copper in in-use stock; (2) analysis of the energy use implications of the copper cycle, both overall and in its various stages; (3) characterization of the environmental implications of copper use and loss; and (4) considerations of potential governmental and industrial initiatives related to the stocks and flows of copper. Each of these areas can be addressed at different organizational levels or for specific countries, specific regions, or the planet. Also, as for cycles such as that for carbon that have been established in some detail, we anticipate that others will devise uses for these data not now evident to the authors.

We recognize that this work has many limitations, and we invite our colleagues around the world to join us in resolving them and in improving the accuracy of the copper cycles at each level. At the same time, we have demonstrated a number of useful results as a consequence of our research. We anticipate that many new insights will result as cycles dominated by human activities are increasingly better characterized over the next few years.

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Supporting Information Available

The Supporting Information for this paper consists of two sections as follows: Copper cycles for the mid-1990s for all 54 countries and 2 country groups included in the analysis; Characterization of the global copper cycle of the mid-1990s. This material is available free of charge via the Internet at http://pubs.acs.org.

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