Metal spectra as indicators of development

T. E. Graedel[1] **and J. Cao**

Center for Industrial Ecology, Yale University, 195 Prospect Street, New Haven, CT 06511

Edited by William C. Clark, Harvard University, Cambridge, MA, and approved October 20, 2010 (received for review July 30, 2010)

We have assembled extensive information on the cycles of seven industrial metals in 49 countries, territories, or groups of countries, drawn from a database of some 200,000 material flows, and have devised analytical approaches to treat the suite of metals as composing an approach to a national "materials metabolism." We demonstrate that in some of the more developed countries, per capita metal use is more than 10 times the global average. Additionally, countries that use more than the per capita world average of any metal do so for all metals, and vice versa, and countries that are above global average rates of use are very likely to be above global average rates at all stages of metal life cycles from fabrication onward. We show that all countries are strongly dependent on international trade to supply the spectrum of nonrenewable resources that modern technology requires, regardless of their level of development. We also find that the rate of use of the spectrum of metals stock is highly correlated to per capita gross domestic product, as well as to the Human Development Index and the Global Competitiveness Innovation Index. The implication is that as wealth and technology increase in developing countries, strong demand will be created not for a few key resources, but across the entire spectrum of the industrial metals. Long-term metal demand can be estimated given gross domestic product projections; the results suggest overall metal flow into use in 2050 of 5–10 times today's level should supplies permit.

industrial ecology | material flow analysis | metal cycles

It is without any doubt that modern society is only possible because of the use of metals. Metals possess properties of high utility (high melting points, structural stiffness, electrical conductivity, etc.) difficult or impossible to duplicate by other materials. As a consequence, the use of metals exploded in the twentieth century, especially after 1950. The result is a panoply of products that now appear essential to modern lives—furnaces, medical diagnostic machines, computers, cellular telephones, and on and on.

Metals are seldom deposited one at a time in nature (1, 2), nor do they tend to be employed one by one (3). Rather, they see use as components of alloys or in composite structures, or as components of complex assembled products (4, 5). Analytical studies of metal cycles generally address only individual metals, however (e.g., refs. 6–8), largely because detailed information on combinations of metals is seldom available.

In the material flow analysis approach, a metal cycle is often expressed through four principal processes: production, fabrication and manufacturing, use, and waste management and recycling. The cycle can be illustrated as shown in Fig. 1. It is characterized by processes that are linked through markets (9), each market indicating trade with other regions at the respective life stages. The scrap market plays a central role in that it connects manufacturing and the waste management and recycling stage with production and fabrication. The cycle is surrounded by entities lying outside of the system boundary: trade partners (other regions), Earth's crust from which ore extraction takes place, and repositories for metals in production waste deposits and landfills.

Production includes mining/milling, smelting, and refining: Mined ore is "milled" to remove waste rock and form "concentrate." The concentrated ore is smelted and then refined into metal, metal alloys, and a variety of chemicals. Losses to the environment consist of metal in tailings and slag, the byproducts of milling and smelting.

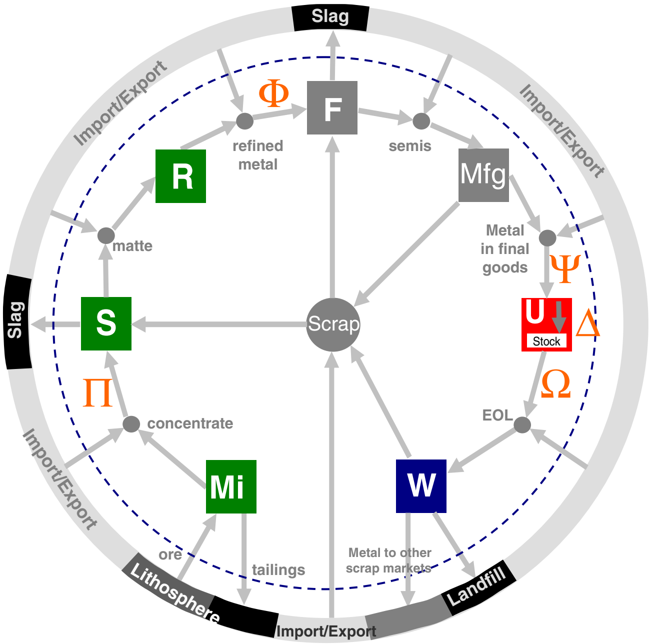

Fig. 1. The generic circular diagram for the technological cycle of a metal, including the processes of production [mining/milling (Mi), smelting (S), and refining (R)], fabrication (F), manufacturing (Mfg), use (U), and waste management & recycling (W). The processes are connected through markets [M_i]. EOL, end-of-life; IW, industrial wastes. The greek letters indicate flows from which metal utilization ratios (see text) are computed.

In fabrication, primary and secondary (i.e., recycled) metal is used for the production of intermediate products (such as wire), which are then used in the manufacturing of final products. In- and outflows at the fabrication and manufacturing stage and the use stage can be further differentiated into product categories, generally, building and infrastructure, transportation, industrial machinery, household appliances and electronics, and metal goods.

Data for the fabrication and manufacturing life stage are generated from the literature, and a model is developed to quantify the use and generation of scrap in fabrication (10). A combination of the two provides the inflow into manufacturing. Metal traded in the form of intermediate and final products is determined by multiplying the mass flows of the relevant commodities from trade statistics with the estimated metal content.

Because of conservation of mass, the inflow of metal to the use life stage must equal the outflow from fabrication and manufacturing, with adjustments for the trade of final goods. The outflow

---

Author contributions: T.E.G. designed research; J.C. performed research; T.E.G. and J.C. analyzed data; and T.E.G. and J.C. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

[1] To whom correspondence should be addressed. E-mail: thomas.graedel@yale.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1011019107/-/DCSupplemental.

from use is based on two simplified models: outflows from transportation and industrial machinery through a lifetime model, and outflows from other in-use stocks through an inflow/outflow model (for details, see ref. 10). The difference between flows into and from use is the net addition of metal to in-use stock.

Waste management includes the collection, separation, treatment, recycling (mostly as scrap), and deposition (mostly as landfilling) of waste. The domestic metal scrap market is fed through waste management and recycling (postconsumer scrap), fabrication and manufacturing (preconsumer scrap), and from other regions. Three flows leave the scrap market: exports, scrap used for the fabrication of intermediate goods, and scrap used in production in smelting and refining.

In this paper we treat a selection of major industrial metals as an ensemble, rather than individually. We do so by drawing upon very extensive datasets developed to characterize the multilevel cycles of copper (11), zinc (12), silver (13), chromium (14), iron (15), nickel (10), and lead (16), for reference year 2000. Together, the use of these metals constituted more than 85% of total global metal flow in 2000 (17). It would be useful as well to include aluminum, which has not yet been fully addressed in our work, but the thrust of our conclusions is unlikely to be affected in any significant way by this limitation.

Drawing upon and unifying this information, we quantify all the flows pictured in Fig. 1 for the seven different metals and for 46 countries, 1 territory (Taiwan), 1 region (the Commonwealth of Independent States; i.e., the former Soviet Union), and Belgium-Luxembourg. (The three "special" geographical units reflect data availability; for simplicity hereafter all geographical units are termed "countries"). In a few cases, flows were unavailable for some countries from our previous work. Those flows were estimated by fitting available data to gross domestic product, purchasing product parity [GDP (PPP)] curves and deriving missing data from the fitted line, when a regression model is appropriate (e.g., all countries use metals but not all produce them). In all cases, the correlation values exceeded 0.8. The complete dataset appears in Tables S1–S7.

In our analysis, we focus on the five main flows identified by the greek letters in Fig. 1. Global average per capita rates are given in Table 1. For perspective, we have also included in Table 1 some values for aluminum, as well, based on ref. 18. As a metal more commonly used in high-technology applications than iron or copper, we suspect aluminum indices will follow those of chromium and nickel (high-value constituents of stainless steel), but multilevel cycle analysis for aluminum remains to be done.

To investigate the metals as a group rather than individually, it is necessary to normalize the flows appropriately because some metals are employed in industry in much larger quantities than others. We do so by taking the ratios of the per capita flows for each country to the global average per capita flows. For example, for flow into use, which we designate by $\psi_{j,k}$:

$$\psi_{j,k} = \frac{f_{j,k}/P_j}{f_{g,k}/P_g}, \qquad [1]$$

where f is the flow in country j or the world g for metal k, normalized by the respective populations P.

Other metal utilization indices from the generic diagram can be formulated in the same way, using the appropriate flows designated in Fig. 1. We designate and calculate four additional indices as $\pi_{j,k}$, the production index for metal k in country j; $\phi_{j,k}$, the fabrication index for metal k in country j; $\delta_{j,k}$, the addition to stock index for metal k in country j; and $\omega_{j,k}$, the discard index for metal k in country j. We refrain from calculating a recycling index because of methodological differences across the metal cycles from which our information is derived.

Table 1. Global average per capita rates for seven industrial metals for year 2000, listed in order of total global rate of use (ref. 17, except ref. 18 for aluminum)

Metal	Processing, Π_j	Fabrication, Φ_j	Use, Ψ_j	Addition, Δ_j	Discard, Ω_j
Iron, kg/cap	159	175	162	112	50
Aluminum, kg/cap	4.88	9.77	2.93	1.70	1.14
Copper, kg/cap	3.04	3.95	2.93	2.55	0.38
Zinc, kg/cap	2.23	1.88	1.81	1.13	0.68
Lead, kg/cap	0.78	1.36	1.29	0.32	0.98
Chromium, kg/cap	1.13	0.80	0.71	0.56	0.16
Nickel, kg/cap	0.24	0.24	0.32	0.19	0.13
Silver, g/cap	4.35	7.35	6.30	3.20	3.10

Results

Metal use index ($\psi_{j,k}$) values were derived for all the metals and countries in our dataset. The results are shown graphically in Fig. 2, with the country order arranged by the magnitude of iron use (iron and its steel alloys are the backbone of the modern technological society). Several features of the display are readily apparent. First, inhabitants of a number of countries use very little of any of the metals. (The actual situation is even more extreme, because we lack data on many relatively undeveloped countries.) In contrast, inhabitants of some other countries use substantial amounts of all the metals relative to the global average ($\psi_{j,k} = 1$). Second, in some countries and for some metals, per capita rates of use are from several times to more than 10 times the global average. Third, the indices do not behave uniformly across the different metals, suggesting that the relative patterns of use may be important to study. Fourth, these intriguing results imply that analyses of the metal indices other than $\psi_{j,k}$ may yield useful information.

To construct what we term "metal use spectra," use ratios have been computed for all seven metals for all countries, and their logarithmic values then viewed side by side. An example is illustrated in Fig. 3*A* for Turkey. It can readily be seen that per capita metal use in Turkey is near the world average for all seven metals. The only feature of any note is the somewhat lower rates of chromium and nickel use.

In Fig. 3*B*, we present a selection of the 49 country-level metal use spectra. Many of the results are not qualitatively surprising in an individual sense, but their quantification and grouping

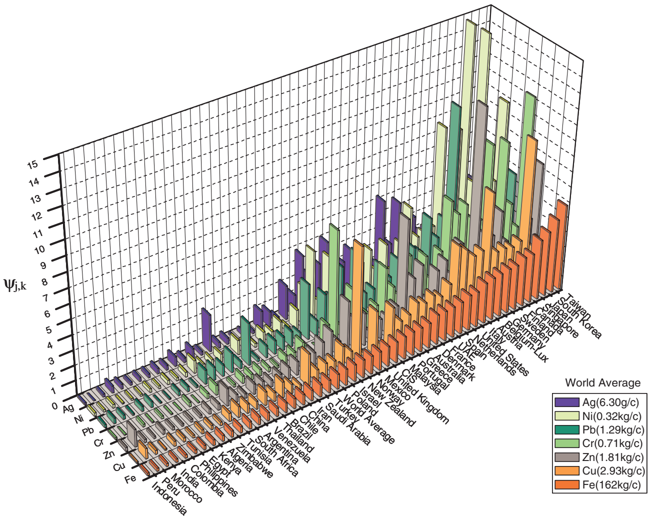

Fig. 2. Metal use indices (i.e., metal use per capita compared to world averages) for all metals and countries in this study, with countries arranged by iron index magnitude. A country using exactly the world per capita average of metal k would have $\Psi_k = 1$.

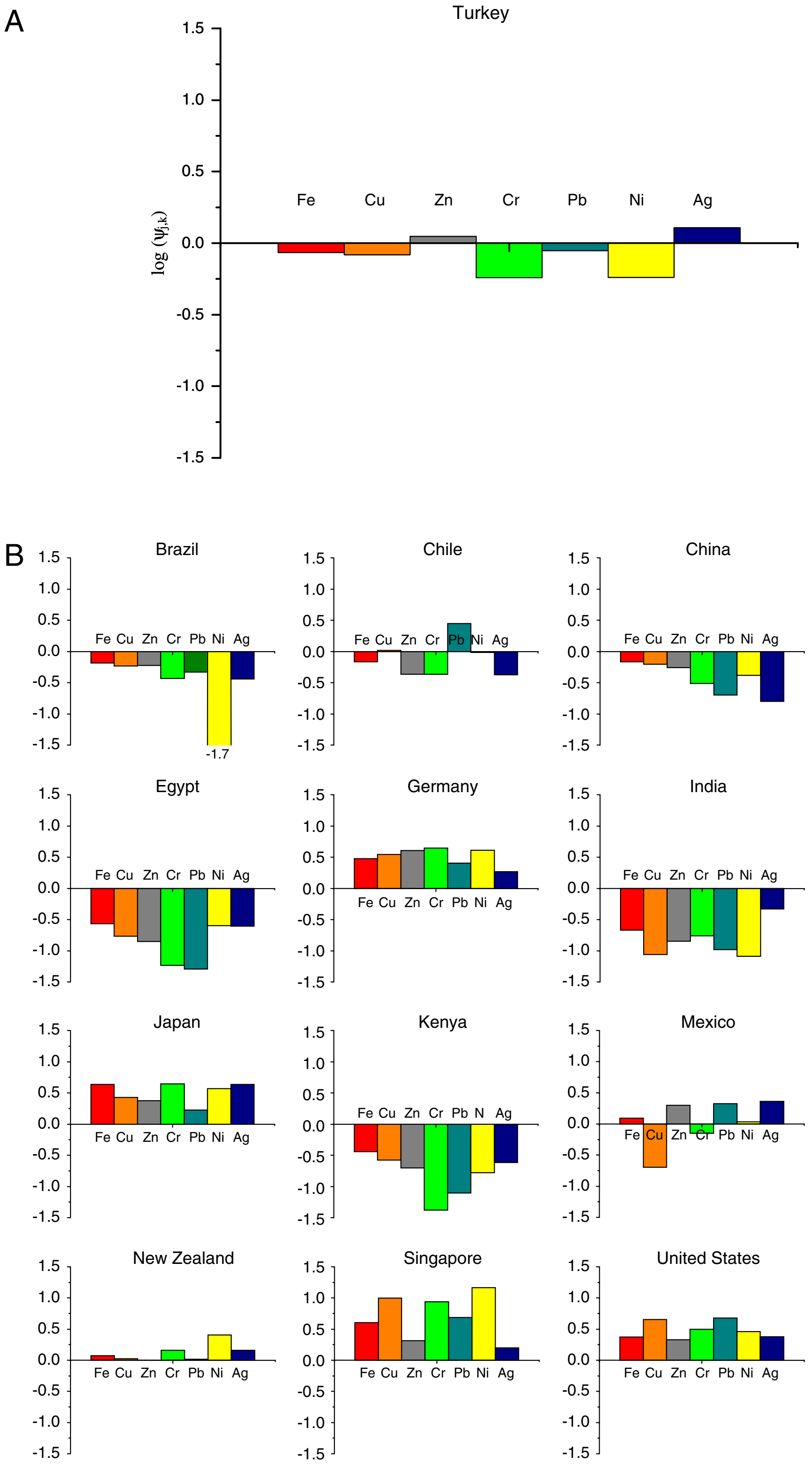

Fig. 3. (*A*) The metal use spectrum for Turkey. (*B*) Metal use spectra for a selection of countries around the world. The dimensionless units are logarithms of per capita flow into use (log $\Psi_{j,k}$) for each metal relative to the world average.

contains information of value. The obvious observation that can be made is that in most cases countries that rank above the global average in per capita use of any one metal are very likely to be above the global average for all seven, and those below the global average for one are very likely to be below the global average for all. We see no strong evidence that the metal signatures reflected in products used in any one developed country are markedly different from those in another. In general, the use rates in countries such as Germany and Japan are two to four times the global average. Developing country patterns also tend to be similar to one another, with most use rates for countries such as India and Egypt being three to ten times below the global average.

To explore this issue more fully, Table 2 presents correlation coefficients for all possible metal pairs. With the exception of sil-

Table 2. Correlation coefficients for metal use indices

	Cr	Ag	Cu	Pb	Zn	Fe	Ni
Cr	1.00						
Ag	0.38	1.00					
Cu	0.70	0.48	1.00				
Pb	0.60	0.43	0.73	1.00			
Zn	0.67	0.35	0.59	0.80	1.00		
Fe	0.79	0.52	0.60	0.63	0.65	1.00	
Ni	0.86	0.32	0.73	0.61	0.67	0.75	1.00

ver (which is more of a "specialty" metal than an industrial metal), all the coefficients are near or above $r^2 = 0.6$. Nickel, chromium, and iron are more highly correlated, however, as are zinc and lead. Nickel and chromium are the two crucial ingredients in high-performance stainless steel, so their mutual correlation, as well as that with iron, appear reasonable. Zinc and lead are not normally used together, so their correlation is probably a more general measure of level of technology development.

The Fig. 2 results suggest that a composite parameter of metal use indices might have utility. To derive such a parameter, we define a comprehensive metal use index (or simply "use index") as $\Psi_j = \log(\Sigma_k[\psi_{j,k}]/7)$, where equal weight is given to each of the metals. Similarly, we define the production index $\Pi_j = \log(\Sigma_k[\pi_{j,k}]/7)$, the fabrication index $\Phi_j = \log(\Sigma_k[\phi_{j,k}]/7)$, the addition to stock index $\Delta_j = \log(\Sigma_k[\delta_{j,k}]/7)$, and the discard index $\Omega_j = \log(\Sigma_k[\omega_{j,k}]/7)$. When these indices are computed for each country, and the units then arranged by per capita GDP (a choice based on the results of ref. 19), the results are as shown in Fig. 4, where each index forms one row of the diagram, and the countries form the columns.

The top row of the diagram in Fig. 4 is the index for the processing stage, which is closely related to the rate of natural resource extraction. Especially notable are countries with rich resources, such as Zimbabwe, Peru, and Chile, as well as those with few to none, such as Egypt and Singapore. Fabricating countries (Fig. 4, row 2) tend to be those with high per capita GDP, especially the Organisation for Economic Co-Operation and Development countries plus South Korea and Taiwan. The rates of use and addition to stock (Zimbabwe is omitted because of the lack of data) appear closely related to GDP per capita.

The Fig. 4 diagram, which is constructed for the composite indices, demonstrates that most developed countries have active involvement with the metals throughout all their life stages from fabrication onward. Conversely, developing countries may or may not be involved in mining and processing, but are only rarely involved in any significant way in later life stages.

For a country with sufficient wealth, the presence of substantial domestic manufacturing is not a prerequisite for a high level of use (as in the United Arab Emirates or Denmark, for example). Similarly, domestic resource stocks are not a prerequisite for a high level of manufacturing (as in Germany or Japan, for example). We can examine the influence of imports and exports on the countries in our study by defining and calculating a comprehensive metal "trade index" T_j (i.e., the difference between imports and exports, summed across all metals and for all stages of the life cycle), as described in *Methods*.

In the Fig. 5 "waterfall diagram," we show the T_j value for all the countries in our study. For nearly two-thirds of them, $T_j > 0$, that is, the country is a net importer of the suite of seven metals. A strongly negative T_j occurs for countries that are major global net suppliers of virgin or minimally processed ore, as is the case, for example, with Chile (copper), Zimbabwe (chromium), and Brazil (iron).

Resource use is a response to the demand for increased services. Resource use should therefore be related to driving factors, such as wealth, and reveal itself in improved quality of life. We explored these suppositions by computing the correlations between Ψ, the composite metal use index, and a variety of potential relational parameters. Fig. S1 demonstrates that Ψ is strongly correlated ($r^2 = 0.75$) to wealth [per capita GDP

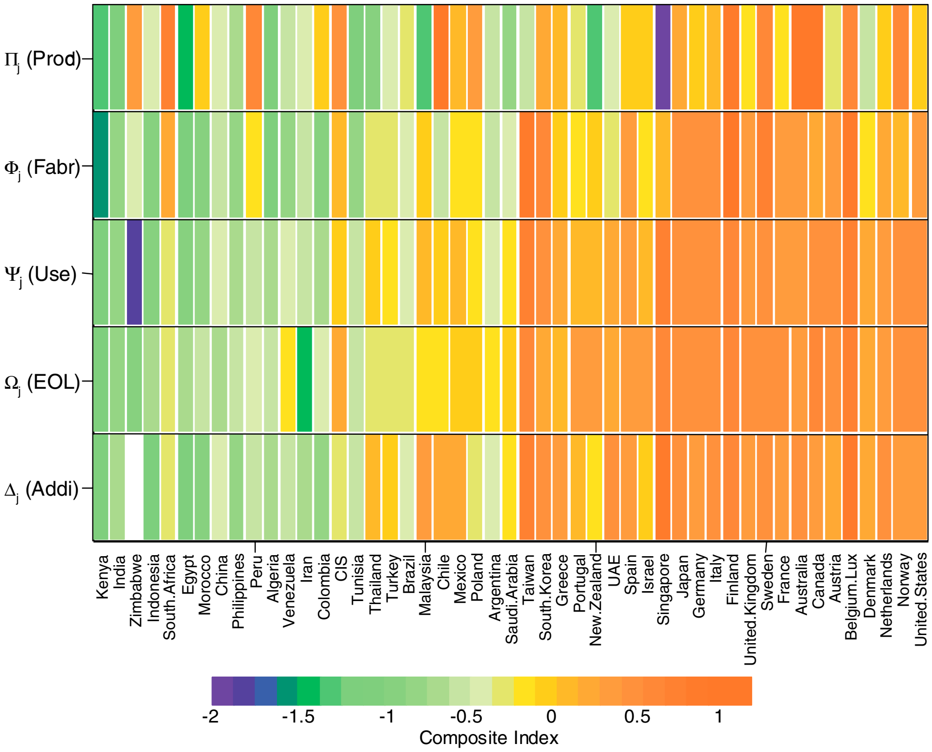

Fig. 4. A rainbow diagram for five metal indices for the 49 countries included in this study. Each index is the aggregate of normalized flows for the seven metals analyzed in this study. The countries are ordered by the year 2000 per capita GDP.

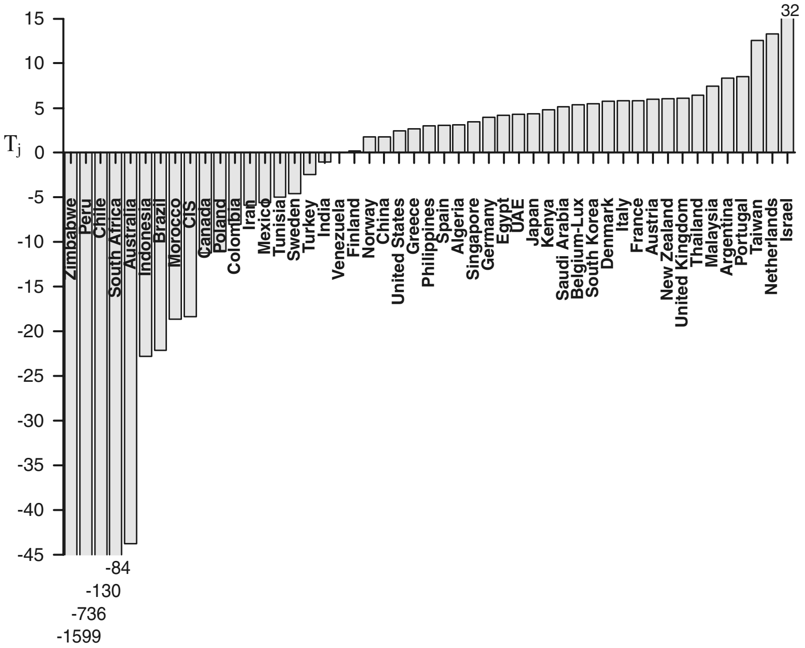

Fig. 5. Comprehensive metal trade indices T_j (i.e., the difference between imports and exports, summed across all metals and for all stages of the life cycle) for all 49 countries included in this study. T_j is a dimensionless parameter.

(PPP)]. [The very few cases in which we derived flows for low-use countries using GDP (PPP) scaling are far too few to have generated this result.] Thus, the per capita saturation of iron in the United States, as noted by Müller et al. (9), does not appear to influence the composite parameter Ψ to any significant degree. The composite parameter Ψ is also well correlated with the United Nations Human Development Index (HDI, year 2000; ref. 20), with $r^2 = 0.80$. Interestingly, a high use index is also reasonably well correlated ($r^2 = 0.67$) with the Global Competitiveness Index (21), suggesting that per capita use of metals is related to how productively a country uses available resources and to the set of institutions, policies, and factors that set the sustainable levels of economic prosperity.

Table 3 lists the correlations between all pairs of composite indices as well as between them and GDP or HDI. Fabrication (Φ), use (Ψ), discard (Ω), and addition to stock (Δ) are seen to be highly correlated to each other and to GDP and HDI, whereas processing (Π) is not, as is expected.

Discussion

Other than fossil fuels, the industrial metals present the most obvious and important examples of nonrenewable resources. Because the functions they perform enable contemporary technology and are thus vital to modern life, it is important that the cycles of the metals, individually and as a whole, are well understood. Much of that understanding for the most widely used industrial metals has been summarized above and in the references cited herein. The implications of that information deserve attention as well. Perhaps the most obvious but highly significant result is that a country with a per capita use higher than the world average for any particular industrial metal is very likely to be above the world average for all metals. Another way of expressing this result is to say that this typical national "materials metabolism" tends to reflect a balanced use of the spectrum of metals rather than an unbalanced one. This synergy in demand is a natural result of modern technological development. A modern building, for example, is very likely to employ a zinc-coated iron frame, use copper wire to provide power, and utilize stainless steel (containing iron, nickel, and chromium) in many highly visible applications. A reasonable extension of this realization is that a realistic development scenario for the planet implies increasing use of the entire suite of the industrial and specialty metals; i.e., virtually the entire periodic table.

Table 3. Correlation among composite indices

	Processing, Π	Fabrication, Φ	Use, Ψ	Addition, Ω	Discard, Δ	Log (GDP)	HDI
Π	1.00						
Φ	0.51	1.00					
Ψ	0.28	0.86	1.00				
Ω	0.35	0.84	0.91	1.00			
Δ	0.35	0.88	0.98	0.86	1.00		
Log (GDP)	0.31	0.79	0.89	0.91	0.85	1.00	
HDI	0.37	0.78	0.86	0.86	0.78	0.91	1.00

Additionally, Fig. 5 demonstrates that substantial dependence upon international trade is an inescapable adjunct to modern development. No country is blessed with deposits even approaching the entire suite of virgin resources, and most have only a handful. Development therefore requires the import of a very large variety of materials in the form of processed ore, finished metal, and/or metal-containing products. This situation is perhaps even more relevant for metals present only in low abundances in Earth's crust, and generally produced only as byproducts of the major metals. Their availability is essential to modern technology but often has the potential to be restricted for a variety of reasons (22).

Are these results, based on the year 2000 as a consequence of the slow pace of data availability and subsequent analysis, relevant to the current situation? Certainly there are year-to-year changes in metal use, perhaps most notably for China (23). Nonetheless, we regard our conclusions as having considerable applicability throughout the 2000–2010 period because they are largely relative rather than absolute, e.g., use of one metal is related to the suite of metals, metal use correlates with wealth, and because the use of all metals is so highly interconnected in modern technology.

We have seen that composite metal use is directly related to per capita wealth, as did Binder et al. (19) for copper and zinc. As both average wealth and technology increased over the past century, global production rates of materials increased by large fractions as well (24, 25). Modern economies have thus "materialized" at a rapid pace, and continue to do so. Given a prediction as to the evolution of GDP in developing regions, our data can be used to indicate future metal needs (at least approximately) and thus can aid in planning by industrialists, economists, and governments. If we employ development scenario A1 from the Intergovernmental Panel on Climate Change (26) as a reasonable projection of population and gross global product in 2050, together with the relationship derived in Fig. 5 for flow into use as a function of per capita wealth, the calculation indicates that the overall flow into use of the group of metals will need to be between 5 and 10 times today's rate in order to maintain the relationship between wealth and metal use.

Issues of sustainability now raise their heads, because the balance between demand and ultimate supply must be considered. Unlike fossil fuels, metals are not destroyed by use, though they may be dispersed or otherwise rendered unfit for reuse. Sustainability of supply is thus related both to mineable virgin ore deposits and to the eventual recyclability of metals. At present, few analyses of sufficient rigor and scope allow for confident assessments of metal sustainability, although Gordon et al. (27) state that providing today's developed world technological services for the world's population "would appear to require essentially complete extraction of copper ores and essentially complete recycling of copper exiting use." They suggest that the same could be true of zinc and the platinum group metals. Information is badly needed on the potentially mineable deposits of the remaining metals (estimates of "reserves" and "reserve bases" are insufficiently vetted and insufficiently expansive to be generally useful in this regard). Statistics on discard, recycling, and reuse are also strongly limited, but recent estimates suggest that recycling rates for many metals are low to insignificant (28). Were enhanced research and monitoring of the stocks and flows of metals carried out so that their ultimate sustainability might be more rigorously assessed, as advocated by the Committee on Critical Material Impacts (3), the results of the present work could then be extended in breadth and over time, thereby forming a much fuller picture of metal extraction, use, loss, and long-run sustainability.

Methods

The trade index upon which Fig. 5 is based is defined as

$$\tau_{j,k} = \left(\sum_m I_{j,k,m} - \sum_m E_{j,k,m}\right)/f_{j,k}, \tag{2}$$

where $I_{j,k,m}$ are the rates of import of metal k in country j for import flow m (i.e., in ore, concentrate, semiproducts, or final products), $E_{j,k,m}$ are the similar rates of export, and $f_{g,k}$ is as in Eq. **1**. From Fig. 1, we note that imports and exports occur throughout the life cycle. Therefore, $\tau_{j,k}$ is properly regarded as the trade fraction of a country's overall economic activity related to metal k. For the suite of metals in this study, the composite metal surplus or deficiency for a country; i.e., the comprehensive metal trade index, can be simply computed as

$$T_j = \sum_k \tau_{j,k}. \tag{3}$$

ACKNOWLEDGMENTS. This research is based on extensive metal statistics generated over the past 10 y by nearly 70 researchers, all of whom we thank for their diligence and rigor. We thank M. Eckelman, D. Lang, R. Lifset, J. Rauch, and B. Reck for helpful discussions. Sponsors have included the US National Science Foundation, the Nickel Institute, the Grainger Foundation, the International Stainless Steel Forum, the International Copper Association, Team Stainless, the International Iron and Steel Institute, the International Aluminium Institute, and Natural Resources Canada. We thank the US Geological Survey and many others for providing data.

1. Verhoef EV, Dijkema GPJ, Reuter MA (2004) Process knowledge, system dynamics, and metal ecology. *J Ind Ecol* 8(1–2):23–43.
2. Nakamura S, Murakami S, Nakajima K, Nagasaka T (2008) Hybrid input-output approach to metal production and its application to the introduction of lead-free solders. *Environ Sci Technol* 42:3843–3848.
3. National Research Council (2008) *Minerals, Critical Minerals, and the US Economy* (Natl Acad Press, Washington, DC).
4. Smith WF (1981) *Structure and Properties of Engineering Alloys* (McGraw–Hill, New York).
5. van Schaik A, Reuter MA, Heiskanen K (2004) The influence of particle size reduction and liberation on the recycling rate of end-of-life vehicles. *Miner Eng* 17:331–347.
6. Zeltner C, Bader H-P, Scheidegger R, Baccini P (1999) Sustainable metal management exemplified by copper in the USA. *Reg Environ Change* 1:31–46.
7. Hawkins TR, Matthews HS, Hendrickson C (2006) Closing the loop on cadmium: An assessment of the material cycle of cadmium in the US. *Int J Life Cycle Ass* 11:38–48.
8. Xueyi G, Yu S (2008) Substance flow analysis of copper in China. *Resour Conserv Recy* 52:874–882.
9. Müller DB, Wang T, Duval B, Graedel TE (2006) Exploring the engine of anthropogenic iron cycles. *Proc Natl Acad Sci USA* 103:16111–16116.
10. Reck BK, Müller DB, Rostkowski K, Graedel TE (2008) The anthropogenic nickel cycle: Insights into use, trade, and recycling. *Environ Sci Technol* 42:3394–3400.
11. Graedel TE, et al. (2004) The multilevel cycle of anthropogenic copper. *Environ Sci Technol* 38:1242–1252.
12. Graedel TE, et al. (2005) The multilevel cycle of anthropogenic zinc. *J Ind Ecol* 9(3):67–90.
13. Johnson J, et al. (2005) The multilevel cycle of anthropogenic silver. *Environ Sci Technol* 39:4655–4665.
14. Johnson J, Schewel L, Graedel TE (2006) The contemporary anthropogenic chromium cycle. *Environ Sci Technol* 40:7060–7069.
15. Wang T, Müller DB, Graedel TE (2007) Forging the anthropogenic iron cycle. *Environ Sci Technol* 41:5120–5129.
16. Mao JS, Dong J, Graedel TE (2008) The multilevel cycle of anthropogenic lead. II. Results and discussion. *Resour Conserv Recy* 52:1050–1057.
17. US Geological Survey (2001) *Mineral Yearbook* (US Geological Survey, Reston, VA).
18. International Aluminium Institute (2006) *Global Aluminium Recycling: A Cornerstone of Sustainable Development* (Int Aluminium Inst, Brussels).
19. Binder C, Graedel TE, Reck B (2006) Drivers for per capita stocks and flows of copper and zinc: A comparative statistical analysis. *J Ind Ecol* 10(1–2):111–132.
20. United Nations Statistical Office (2008) Fighting climate change: Human solidarity in a divided world. *Human Development Report 2007–2008* (United Nations, New York).
21. Porter M, et al. (2000) *The Global Competitiveness Report 2000* (Oxford Univ Press, New York).
22. Enterprise and Industry Directorate General (2010) *Critical Raw Materials for the EU* (European Union, Brussels).
23. Reck BK, Chambon M, Hashimoto S, Graedel TE (2010) Global stainless steel cycle exemplifies China's rise to metal dominance. *Environ Sci Technol* 44:3940–3946.
24. Rogich DG, Matos GR (2008) The global flows of metals and minerals. *US Geological Survey Open-File Report 2008-1355* Available only online at http://pubs.usgs.gov/of/2008/1355/.
25. Mudd GM (2007) An analysis of historic production trends in Australian base metal mining. *Ore Geol Rev* 32:227–261.
26. Nakićenović N, et al. (2000) *Special Report on Emission Scenarios* (Cambridge Univ Press, Cambridge, UK).
27. Gordon RB, Bertram M, Graedel TE (2006) Metal stocks and sustainability. *Proc Natl Acad Sci USA* 103:1209–1214.
28. Graedel TE, et al. (2010) Recycling rates of metals: A status report. *J Ind Ecol*, in press.