Environmental Science & Technology

Critical Review

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Anthropogenic Cycles of the Elements: A Critical Review

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Ⓢ *Supporting Information*

A cycle is the quantitative characterization of the flows of a specific material into, within, and from a given system. An anthropogenic elemental cycle can be static (for a point in time) or dynamic (over a time interval). The about 350 publications collected for this review contain a total of 1074 individual cycle determinations, 989 static and 85 dynamic, for 59 elements; more than 90% of the publications have appeared since 2000. The cycles are of varying quality and completeness, with about 80% at country- or territory-level, addressing 45 elements, and 5% at global-level, addressing 30 elements. Despite their limitations, cycles have often been successful in revealing otherwise unknown information. Most of the elements for which no cycles exist are radioactively unstable or are used rarely and in small amounts. For a variety of reasons, the anthropogenic cycles of only perhaps a dozen elements are well characterized. For all the others, with cycles limited or nonexistent, our knowledge of types of uses, lifetimes in those uses, international trade, losses to the environment, and rates of recycling is quite limited, thereby making attempts to evaluate resource sustainability particularly problematic.

1. INTRODUCTION

As is now well-known, the human combustion of fossil fuels and the clearing of forest lands inject carbon dioxide into the atmosphere. Some 55% of that flow is taken up by land plants or dissolved in the oceans, while the remainder is added to the atmosphere. Scientists know this ratio largely because of the quantification of the carbon cycle,[1] and the subsequent investigations that preliminary carbon cycles inspired.

A cycle is the quantitative characterization of the flows of a specific material into, within, and from a given system. The global biogeochemical cycle for carbon is probably the most widely known, but scientists have also devoted considerable effort to the biogeochemical cycles of nitrogen, phosphorus, and sulfur.[1−4] It is only within the past decade or so that these efforts have been expanded in a comprehensive way into other parts of the periodic table, and to elements for which human activity is the dominant driving force rather than a perturbation on an existing system. As with carbon, nitrogen, phosphorus, and sulfur in nature, those wholly anthropogenic cycles reveal a number of characteristics of the flows of human-dominated elements. Among the aspects of interest for both science and policy are rates of extraction of materials from geological reservoirs, rates and types of uses, pathways from one life stage to others, balances of international trade, and rates of loss, recycling, and storage.

The utility of cycles of the elements, some wholly natural, some wholly anthropogenic, some combined,[5] makes it important to know for which elements and for which geographic entities have cycles been completed, as well as what those completed cycles demonstrate. Accordingly, in this paper we review the extant information on anthropogenic cycles, namely cycles focused mainly on the anthroposphere. Thus, we exclude those biogeochemical cycles directed largely or completely at natural stocks and flows,[2] as well as those that are said to be anthropogenic cycles but actually only treat exchanges between the anthroposphere and the natural environment. As to the elements concerned, we exclude the inert gases (whose cycles are not of major interest, except helium), the alkalis (except lithium and cesium) and the halogens (except fluorine and chlorine because natural processes dominate the flows of these water-soluble substances), technetium and promethium (which have no stable isotopes), and five elements found only in nuclear facilities or research laboratories (polonium, astatine, francium, actinium, and protactinium). This leaves 75 of the first 92 elements as possible subjects for the review (Table 1). Iron cycles may include a few percent of common steel constituents; the publications are not always clear on this point. We also include stainless steel alloy cycles, which demonstrate how cycles of technological combination of elements can be linked to the individual metal cycles.

2. MATERIALS AND METHODS

2.1. Cycle Construction. There are many ways to construct an anthropogenic materials cycle, but the general form shown in Figure 1 (a) is the most common, especially for metals. It follows a solid material from its extraction reservoir (ore, mineral sands, air, etc.) into the production stage (where the extracted material is transformed into elemental or related

Received: March 15, 2012
Revised: June 13, 2012
Accepted: July 17, 2012
Published: July 17, 2012

Table 1. Elements with Different Number of Anthropogenic Cycles

no. of cycles	elements	no. of elements
≥5	N, Al, P, Cl, Cr, Mn, Fe, Co, Ni, Cu, Zn, Pd, Ag, Cd, In, Sn, Sb, W, Pt, Hg, Pb	21
4	V, As, Mo, Rh, Au	5
3	Li, Ti, Ga, Ge, Nb, Ta	6
2	Be, Mg, Se, Zr, Cs, Dy, Hf, Bi	8
1	B, C, F, Si, S, Sr, Y, Te, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Re, Tl, U	19
0	H, He, O, Ca, Sc, Ru, Ba, Ho, Er, Tm, Yb, Lu, Os, Ir, Ra, Th	16
excluded	Ne, Na, Ar, K, Br, Kr, Rb, Tc, I, Xe, *Pm*, Po, At, Rn, Fr, Ac, Pa	17

forms), to fabrication and manufacturing (F&M, where the material is employed in fashioning utilitarian products), to use, and finally to discard into the waste management and recycling (WM&R) system. Return flows occur at several of these stages, as do losses to the environment in a number of different forms. Unless the cycle is done for the planet as a whole, transfers can occur across the system boundary (e.g., the import and export flows). The challenge for the analyst is to generate self-consistent quantitative flow numbers for all the arrows on the diagram.

At each stage in the cycle, conservation of mass must be observed, that is, the output flows must equal the input flows after adjustment for any material added to or subtracted from the storage reservoir (stockpile, in-use stock, etc.) for that life stage. Failure to achieve conservation of mass is an indication that a deficiency exists in the description of the cycle or in the quantification; this could be because a source or sink flow may not have been identified or a flow may not be quantitatively understood, or for some other reason. It is common for such discrepancies to occur, because data must be drawn from a wide variety of sources (mining rates, processing loss estimates, import/export records, recycling statistics, corrosion losses, etc.) and then harmonized. As a result, a high degree of accuracy is not anticipated. Nonetheless, as will be shown below, even cycles that are not very well quantified can provide significant amounts of useful information.

A variation of the generic cycle of Figure 1 (a) is the "clock diagram" devised by Reck and colleagues[6] and shown in Figure 1 (b). This approach emphasizes the transfer of the resource across the system boundary through market exchanges between life cycle stages, as well as the potential for the resource in question to see multiple uses as a consequence of return flows via the scrap market. While essentially equivalent to the original linear diagram, the clock diagram may be intellectually better related to today's emphasis on "loop closing" and sustainability thinking, and is probably the better choice.

In practice, cycles are often much more complicated than Figure 1 suggests. First, each life stage may have to deal with several substages, depending on the level of detail derived. For example, the production stage (Figure 1 (a)) of some metals can be divided into mining, smelting, and refining (Figure 1 (b)), while the waste management and recycling stage can be divided into collecting, dismantling, cleaning, and remelting.[7−9] The production chains for nonmetal elements are even more complicated because they are generated by chemical processes which are usually longer and more complex than metallurgical processes.[10−13] Second, it is common to divide a flow into several subflows. For example, flows of metals from fabrication into manufacturing are usually divided into several different semiproducts, such as forgings, extrusions, sheet, etc.,[14,15] while those into use are commonly divided by major industrial sector—buildings and construction, transportation, consumer durables, etc.[15−17] In addition, an analysis of export and import flows may require trade statistics for more than one hundred different industrial product groups. Choosing how to combine or divide these flows is one of the places where different studies diverge substantially. For example, some treat the import and export of the element in question only so long as it is in elemental form (including ore, concentrate, refined metal, scrap, and semiproducts[18,19]), whereas others treat flows of the element as it is embodied in common industrial products.[15,17,20,21] As a consequence of these approaches, the information available from many analyses is quite detailed, but more daunting to construct than would be inferred from Figure 1.

A paucity of relevant data constrains the quantitative characterization of many element cycles. The situation for the "major metals" (those used widely, such as copper or zinc) is reasonably satisfactory, with data on production and international trade widely available from producers and metal exchanges. This circumstance does not generally obtain for the "minor metals" that move from life stage to life stage in private transactions. In all cases, however, the industrial sectors in which the elements are finally used can generally be deduced.

Trade data for elements in pure, alloy, chemical compound, and final product forms are compiled and reported by the United Nations[22] and others.[23] This is, however, usually not so for the elemental content in products, which for some countries can be quite significant. Losses during processing, losses to the environment, and rates of recycling are reported sporadically, if at all. The data that are available typically appear a few years after the subject year, so few cycles could be regarded as really timely. Together, these limitations render cycle characterization a bit of a detective activity in which information of varying quality is assembled from a variety of sources and then harmonized. The result, which we will show below to be often quite useful, is inherently limited in accuracy, and updatable only with significant additional effort.

Cycles can be static (that is, referring to a "snapshot" of flows at a specific point in time), or dynamic (characterizing anthropogenic stocks and flows of an element over a time interval). The latter is much to be preferred, because it can provide information on reservoir stocks and on the evolution of stocks and flows over time. Dynamic cycle construction is very challenging, however, because of its extensive data requirements. As a consequence, few dynamic cycles exist even though they are regarded as more useful than the static versions.

2.2. Scope and System Boundaries. Because of the many variations in the analysis of elemental stocks and flows, it is necessary to establish what is to be included in our review and what is not. In addition to excluding those directed solely at biogeochemical cycles, as mentioned above,[2] our basic rule is that all stages of the life cycle in the anthroposphere must be addressed if a study is to be incorporated into this analysis as a static cycle, while for dynamic cycles, at least the use stage and its input and output flows should be considered, and in-use stocks are (or can be) deduced. Thus, we exclude papers addressed primarily or completely to only one stage,[24] to emissions,[25] or to trade.[21] We also exclude papers reporting only on stocks but not flows.[26−28] While these distinctions

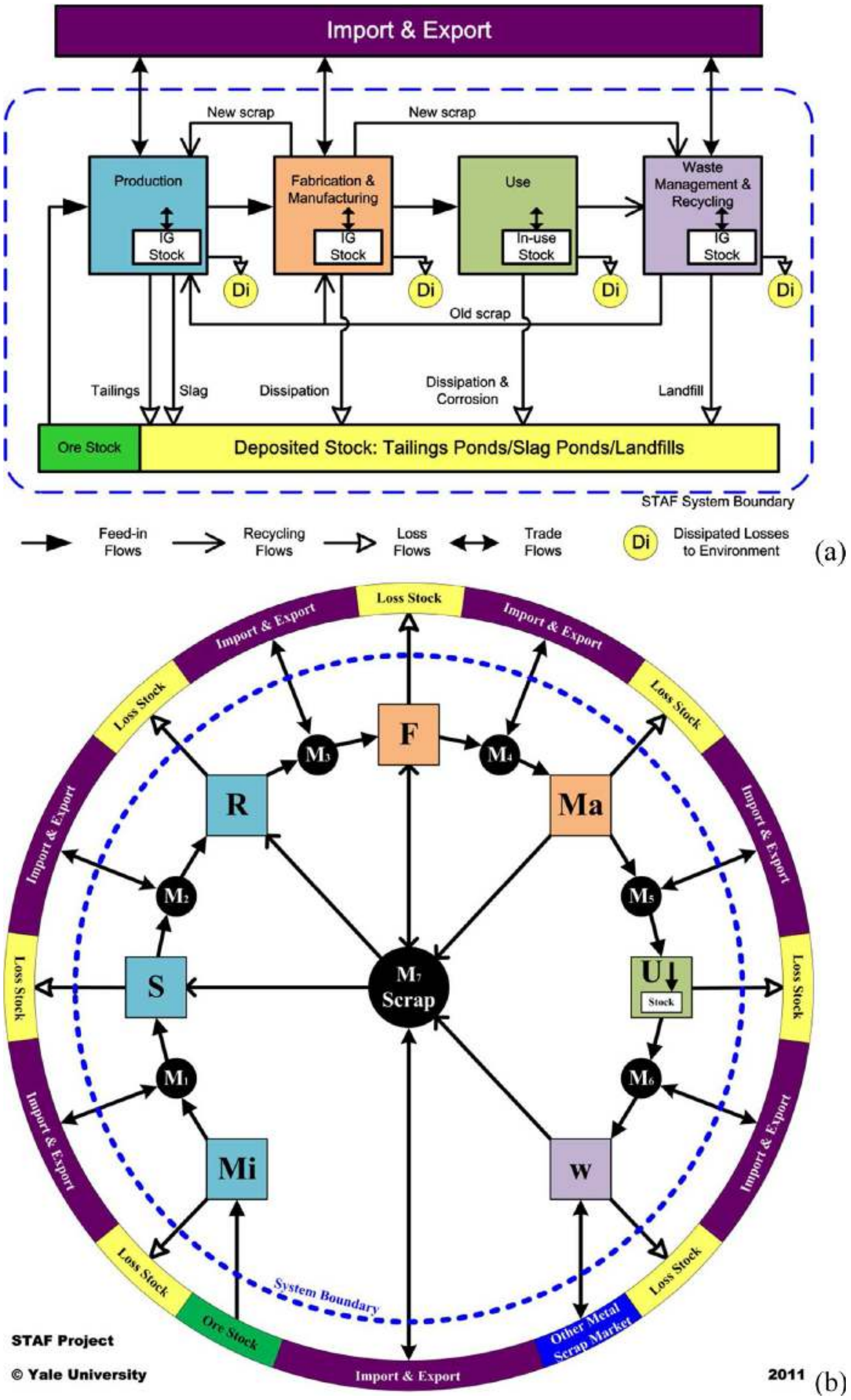

Figure 1. Schematic diagrams of generic elemental cycle with life processes depicted (a) from left to right,[17] and (b) in a circle.[6] IG Stock = industrial, commercial, and governmental stock, Mi = mining, *S* = smelting, *R* = refining, *F* = fabrication of semiproducts (sheets, rolls, etc.), Ma = manufacturing, *U* = use, *W* = waste management and recycling, M_{1-7} = international or national market for trade of the elements or element-containing products. Cycles for elements not derived from ores, such as carbon, will vary somewhat from this general framework.

appear to be clear, the heterogeneity among cycle construction invariably introduces some degree of arbitrariness into our choices, particularly as regards the failure of some cycles to include loss, trade, or recycling flows included by others.

Other selection criteria are that if a study is published in more than one language, the most widely used (often English) is that studied by us and cited in the references. Also, peer-reviewed publications are preferred to online reports, project reports, and other "gray literature" unless the latter contains additional useful information. In general, the references we have collected are reported as studies on anthropogenic cycles, mass/material flow analysis (MFA), substance flow analysis (SFA), stocks and flows analysis, industrial metabolism, or material budgets/balances.

2.3. Sources of Cycles. Under the criteria outlined above, the earliest English reference (released in 1992) characterizing an anthropogenic cycle is for zinc in the United States,[29] although we are aware that some European countries may have started national substance flow analysis in the late 1970s or 1980s.[30] The U.S. zinc study treated the extraction and processing life stages in reasonable detail, but was sketchy concerning other life stage flows. A European effort two years later[31] added more structure to the methodology. By 2002,[9,14] the treatment of all life stages and the flows between them was expressed in essentially the conception and level of detail that is common today.

A large number of cycles have been constructed in the past few years, but most of them have come from a rather small number of research groups (see Supporting Information (SI)). These groups are located in four geographical areas, although their studies often extend to other regions. The United States[14,29,32−41] and Europe[30,31,42−51] have been quite active since the mid-1990s. Japan has been a significant contributor as well,[52−59] though almost all its publications date from 2005 and apply mostly to Japan. China has only recently begun to characterize its domestic cycles,[20,60−65] but is now an enthusiastic participant in elemental cycle development.

A measure of the degree to which elemental cycle research is progressing is to plot the number of publications by year for the past two decades, as shown in Figure 2. The rapid increase since about 2000 is obvious, with more than thirty individual publications appearing in each of the last several years. Publications before 2000 originated only in the U.S. or Europe. More and more publications come from Japan and China after 2005, indicating the degree to which these two countries pay increased attention to materials cycles, especially for promoting the development of the "circular economy". Not all the publications are of equal scope: sometimes a paper[17] or a report[66] provides many cycles, while sometimes a book having more than 200 pages may describe a single cycle, albeit in great detail.[67]

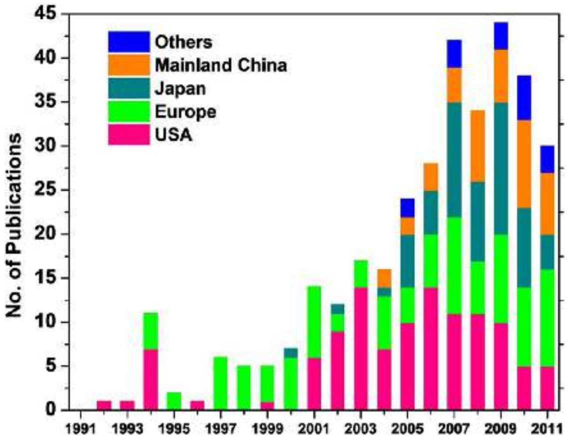

Figure 2. Number of publications of anthropogenic cycles of the elements as a function of time. The total number of publications is more than those cited in the SI because all publications related to anthropogenic cycles are included here, but many are excluded from the tabular listings in the SI according to the criteria as described in Section 2.2.

3. RESULTS

3.1. Number and Level of Elemental Cycles. The application of the criteria results in a total of 1074 cycles from about 350 publications, as summarized in Table 2. Most of these are static cycles, but a few are dynamic and thus contain many subcycles within them. All are for a calendar year as opposed to any other time interval, the predominant year being 2000 or later. With the exception of several cycles for the U.S. in the mid-1990s, the historical cycle record is sparse indeed, at least partly because the necessary data sets from earlier periods are generally not extant.

Table 2. Number of Cycles at Different Geographical Levels[a]

spatial level	global	continent	country or territory	city	river basin	total
static	47	105	791	28	18	989
dynamic	9	7	60	9	0	85
total	56	112	851	37	18	1074

[a] More detailed information is available in the SI.

A "periodic table of global-level elemental cycles" identified by our review is shown in Figure 3. Such cycles exist for 30 elements representing 47 static cycles and 9 dynamic cycles. Most of these are major metals such as iron, aluminum, copper, and zinc, as well as nutrient elements such as nitrogen and phosphorus, although a recent study[68,69] presents global cycles for nine of the rare earths. Obvious omissions include the platinum group metals (except platinum itself), the metalloids, nonmetal elements, and a number of the metals widely used to improve the performance of iron or to form superalloys (niobium, molybdenum, tungsten, and rhenium). Dynamic cycles exist only for aluminum,[70] silicon,[71] phosphorus,[72] vanadium,[73] iron,[57] cobalt,[41] tin,[74] platinum,[75] and lead.[76] Some static global-level cycles are aggregates of lower level cycles for regions or countries/territories, whereas others characterize the global cycle directly. A similar situation obtains for cycles at the continent level. Except for some of those from the Yale Center for Industrial Ecology, all continent-level cycles describe cycles in Europe.

Cycles are more numerous at the country or territory level, as shown in the periodic table of Figure 4, which has entries for 45 different elements representing 791 static cycles and 60 dynamic cycles. Japan has characterized cycles for the most elements (42, in 97 static cycles and 26 dynamic cycles). The U.S. is next, with cycles for 31 elements (57 static cycles and 8 dynamic cycles). European countries are third (20 elements in 223 static cycles and 12 dynamic cycles). For the rest of the world, except mainland China,[63] Taiwan area,[77] South Korea,[78] Australia,[79] Brazil,[80] and Turkey,[81] cycles at the country or territory level are only available for the seven metals (chromium, iron, nickel, copper, zinc, silver, and lead) for which cycles have been characterized by the Yale Center for Industrial Ecology.[6,17,38,82−86] Dynamic cycles exist for only 18 elements, mostly for major metals including iron, aluminum, and copper, but also for nitrogen,[87−89] phosphorus,[88−90] cobalt,[91] lead,[92−94] chromium,[95,96] nickel,[95,97] zinc,[98] the platinum group metals,[99] cadmium,[100] indium,[59] antimony,[101] dysprosium,[102] and tungsten.[41]

Cycles at the city- or river-basin- levels were first reported in a seminal book on industrial metabolism,[103,104] and are basically available for two groups of elements: (1) nitrogen

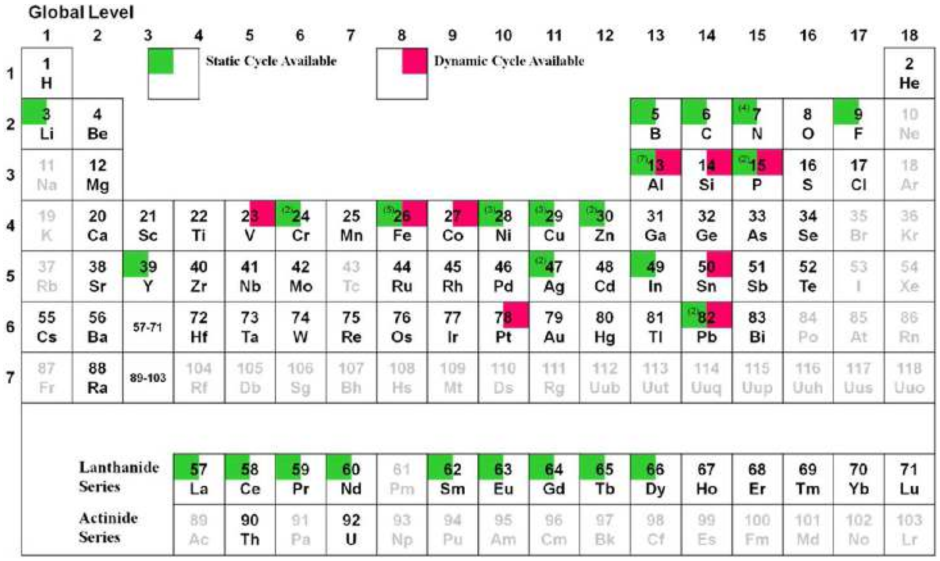

Figure 3. Elements for which global-level cycles have been derived.

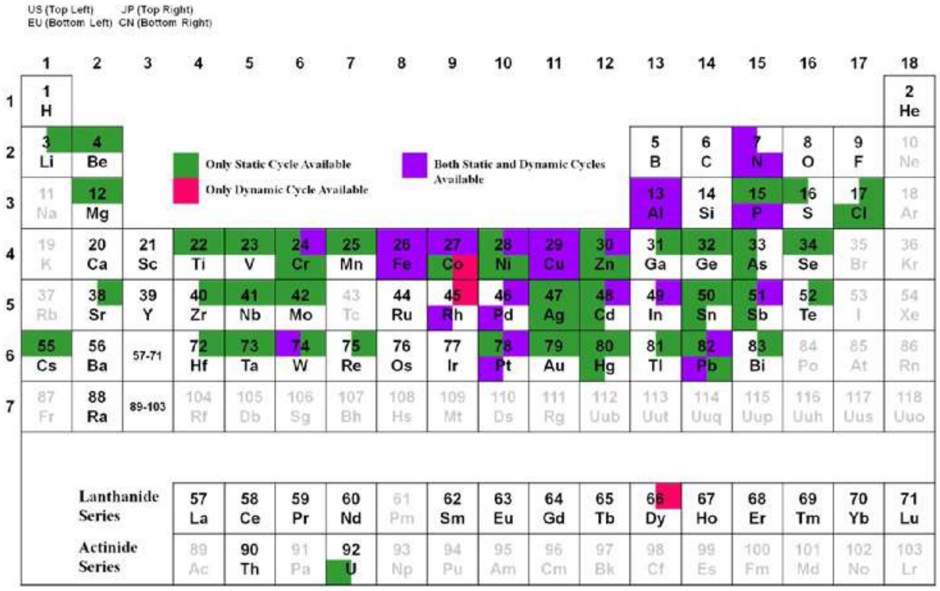

Figure 4. Elements for which country- or territory-level cycles have been derived. The four corners of each elemental area refer to the country or territory from which the study originated; this is often the country or region of the cycle as well, but not always, and a single study may treat many different countries or territories.

and phosphorus because of food production and water eutrophication concerns,[103,105−107] and (2) heavy metals because of the emission and toxicity concerns.[104,108−111] Most of the city-level cycles for heavy metals are from a program sponsored by the Swedish Environmental Protection Agency, and are directed toward in-use stock, inputs, and emissions of heavy metals in Stockholm.[108−110] At the river basin level, one paper reported cycles of seven heavy metals for the Seine River basin.[111]

Of the 92 elements, anthropogenic cycles are unavailable for 33. Only one cycle exists for 19 elements, and two for 8 elements, as listed in Table 1. It is interesting to see that for carbon, of which the biogeochemical cycles and anthropogenic emissions have been analyzed extensively, we found only one that could be roughly regarded as a cycle inside the anthroposphere.[112] In contrast, 21 elements have five or more cycles each (Figure 5). Iron has been the most widely analyzed, with more than 200 cycles available, and nickel, copper, lead, zinc, silver, and chromium each have more than 70 cycles. Phosphorus and nitrogen are the next well characterized, and are usually addressed together in the characterization of cycles of the so-called nutrients.[89,113−115] Iron, aluminum, and copper cycles have been characterized dynamically to the highest degree, probably because of their importance and the greater availability of data.

3.2. Features of Elemental Cycles.

The information contained in these cycles is substantial, as demonstrated by the results shown in Figures 6 and 7. In the case of the static nickel cycle on the global level (Figure 6), several features are immediately apparent:[116] (1) flows of nickel from the mine through to the use phase are large; (2) losses from ore processing and smelting are relatively small by comparison; (3) the nickel flow exiting use is less than half of that entering, indicating that nickel stock in use was accumulating; (4) about

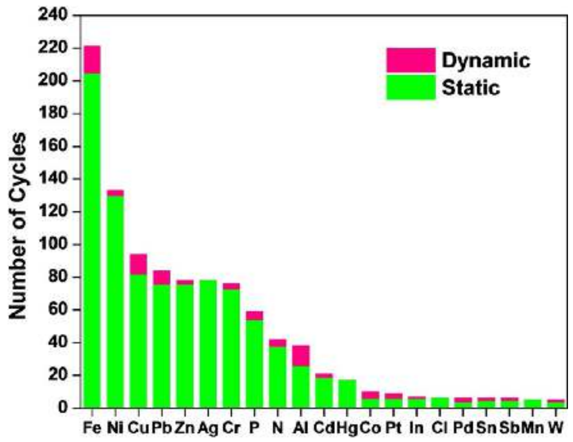

Figure 5. Number of derived cycles for the elements most frequently the subject of such analyses.

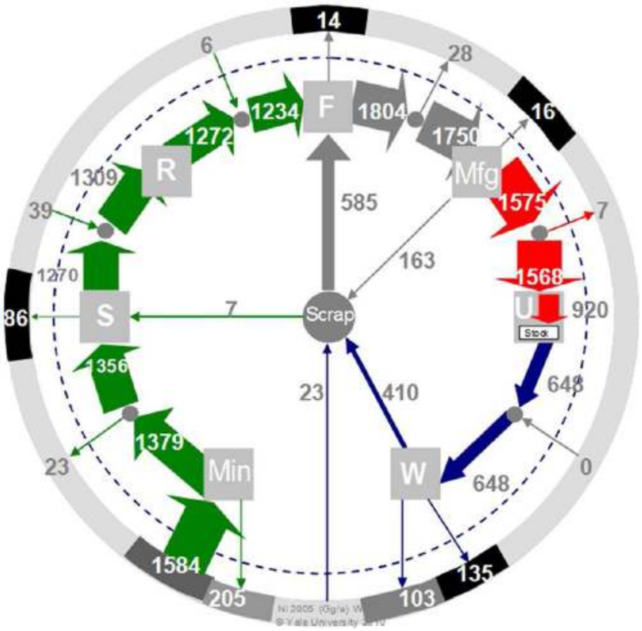

Figure 6. An example of static elemental cycle: the global nickel cycle for year 2005[116] with flow values in Gigagram (thousand metric tons).

a third of the nickel being fabricated into products is from scrap recycled from preconsumer and postconsumer life stages, and (5) almost half of the nickel exiting use is lost to landfills or to incorporation into general carbon steel scrap.

An example of the results of a dynamic cycle is shown in Figure 7, for aluminum in the United States.[15] This display of results is cumulative, for the period 1900–2009. On the "Sankey" diagram in Figure 7 (a), the widths of the arrows approximate the flows of aluminum from one life stage to another. It is clear that over the century-long period imports to the United States of bauxite (aluminum-containing ore), alumina, and unwrought aluminum were all substantial, and that little of the total raw material input was domestic. It is also clear that recycled aluminum constituted only about a quarter of the flows to metal fabricators. The diagram shows the distribution of material into different fabrication processes, into the "semi-fabricated" products (e.g., sheet and plate, foil) that were generated, and into the industrial sectors in which the final products were employed. The quantities and fractional distribution of discards from in-use stock are also depicted, as are a number of different discards to the natural environment.

The features of a dynamic cycle can be made more obvious by looking at specific flows and stocks over a period of time, as shown in Figure 7 (b), (c), and (d), again for the U.S. aluminum cycle.[15] In Figure 7 (b), the aluminum flows into different end-use sectors are shown for the entire period of the analysis. The rise of aluminum in the packaging industry is seen to have originated in the 1960s and to have increased thereafter, and the dramatic increase in aluminum use in aircraft and automobiles (the transportation sector) to have arisen also in the 1960s but to have increased rapidly in the 1990s. Aluminum flows into use are seen to be very sensitive in the short term to world events, with sharp decreases in all uses as an economic consequence of the three energy crises, the September 11 attack, and the 2008 financial crisis. Scrap generation by sector in Figure 7 (c) is modeled by the top-down method[117] using historical data from Figure 7 (b). Per-capita in-use stocks by sector in Figure 7 (d) are then deduced by the cumulative differences between input into and output from use, together with the pattern of change in the U.S. population. It is interesting to see that the per-capita in-use stock pattern in different sectors varies significantly.[15]

Not all cycles are as well characterized as those of Figure 6 and Figure 7, but most of those that have been published (all of which are listed and their features described in the SI) contain useful information about the life cycles of the elements involved. For example, a cycle for antimony in the U.S. in 2000,[118] which looks much more simplified than some of its parallel cycles (such as those for aluminum,[119] copper,[120] and other metals[121−123]) as a result of ignoring trade, loss, and dynamic modeling, still provides very useful information for identifying the main source of recycled antimony, for calculating the ratio of new scrap to old scrap, for estimating old scrap recovery efficiency, and for gaining perspective on the composition of the U.S. antimony supply.

3.3. Heterogeneity of Elemental Cycles.

The cycles are heterogeneous in many respects. In the case of static cycles, it is common to find that one stage or several substages of the life cycle, or some relevant flows, are omitted or inadequately characterized. Trade flows of final goods are totally ignored in most cycles, and the loss flows are seldom captured completely because of the difficulties in data collection. For example, a platinum cycle for Germany in 2001 quantifies recycling flows and loss flows by sectors, but does not cover all life stages and ignores trade flows;[67] another for the U.S. in 1998 basically covers the whole life cycle but does not provide information on flows by sectors or trade in final goods.[124] Others for Japan totally omit information on loss flows, including only a diagram for each cycle, although the whole life cycle is covered and the estimation on trade flows is careful.[66]

Dynamic cycles differ widely in the years covered and in the detail provided. Although some dynamic cycles quantify all stocks and flows along the whole life cycle,[15,20,39,74] most only estimate in-use stocks, as well as associated flows in stages or substages of F&M and of WM&R.[55,57,125−127] From the perspective of time scale, dynamic cycles can be roughly divided into two categories: those tracking stocks and flows in the past,[15,20,39,74,98,127−129] and those conducting scenario predictions for future stocks and flows under the concept of "stocks drive flows".[57,75,126,130] Another heterogeneity often observed is that although most cycles cover all end-use sectors, others, we

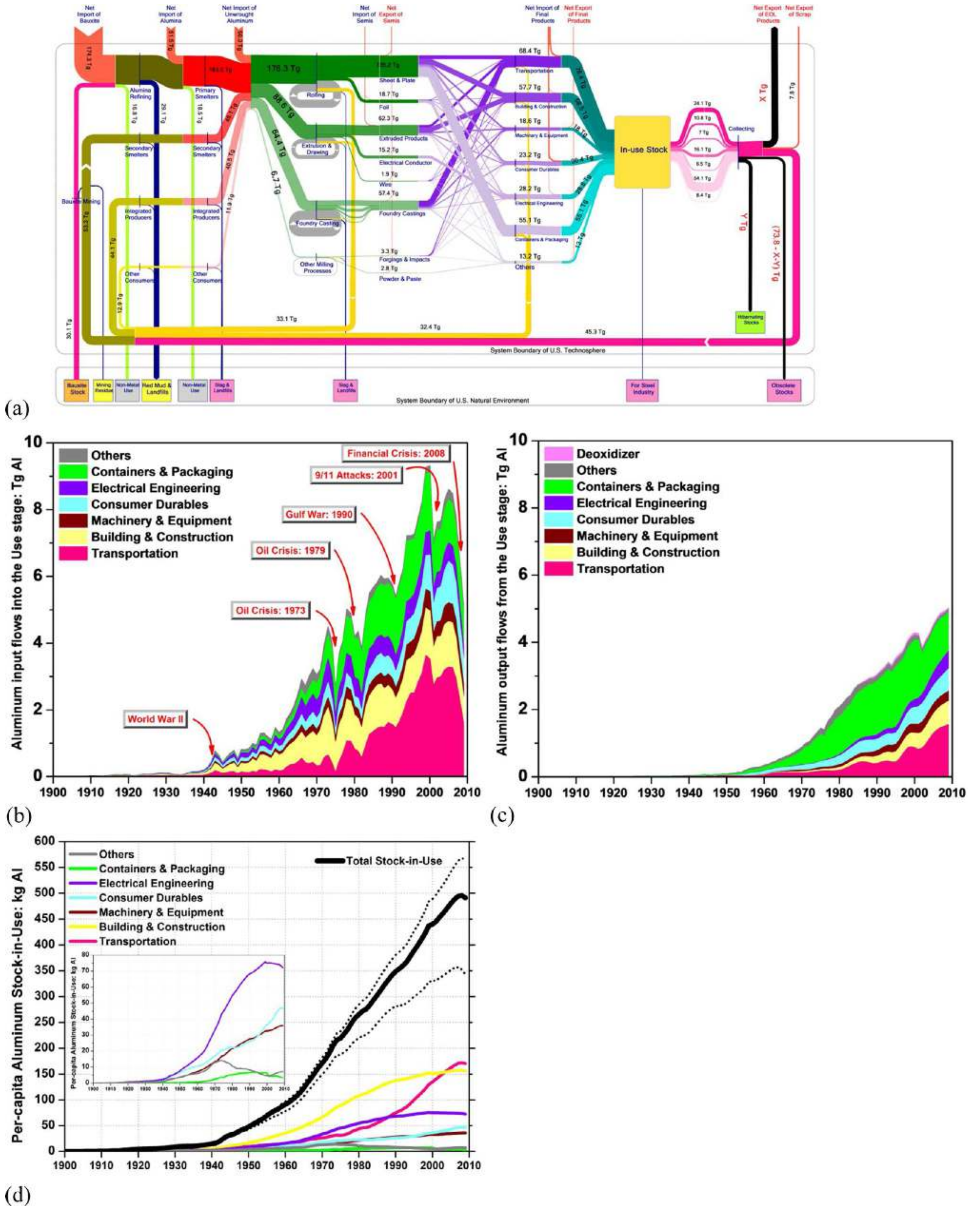

Figure 7. An example of dynamic elemental cycle: (a) the cumulative aluminum cycle for the United States, 1900–2009,[15] with flow values in Teragram (million metric tons); the widths of the arrows roughly correspond to the relative magnitudes of the flows; (b) flows of aluminum entering the Use stage; (c) flows of aluminum leaving the Use stage modeled by the top-down method; and (d) per-capita in-use stocks of aluminum by sector.

deem worth including, characterize element cycles for only a particular final product[56] or end-use sector.[131]

Finally, although most cycles are depicted by frameworks that look the same as or similar to either (a) or (b) of Figure 1, especially for metals,[6,17,20,38,62,106] it is usual to find cycles that are shown totally different from those in Figure 1, especially for nonmetal elements.[11,12,15,40,51,132] There are two reasons for this heterogeneity in representing cycles: (1) some cycles may only have numbers,[11,12] whereas others may use widths of arrows to roughly[17,82] or accurately[15,40,62,63] indicate the relative values of flows; in addition, some cycles are depicted by Sankey diagrams;[15,40,133,134] (2) besides omitting or integrating one or several stages or substages, some cycles may in contrast describe a certain stage or substage in great detail, making the whole cycle appear to be dominated by that stage or substage. For example, although the framework for the chlorine cycle for China[62] looks similar to Figure 1 (a), another one at the European level[11] appears much more complicated as a result of analyzing chlorine-containing products and the production stage in more detail.

4. DISCUSSION

The most important perspective to be gained from elemental cycles is precisely their potential cyclic nature, that elements in technological use are eventually dissipated, discarded, and lost if no diligent effort is made to recover them. Nature has evolved to recycle the elements it uses, while humanity has done so less well. The cycles demonstrate opportunity, and degree of failure and process in recovery and reuse.

An important outcome of this review is the realization that elemental cycles have yielded important information not otherwise appreciated. For example, a pioneer SFA paper published in 1994 revealed that European policy on cadmium, including end-of-the-pipe measures, a phase-out of certain applications, and recycling of batteries and certain other products, did not appear to offer a sustainable solution to the cadmium problem without attention to the zinc industry because cadmium is mainly a byproduct of zinc production.[31] In an analysis carried out in Japan, it was shown that the quantity of phosphorus in iron- and steel-making slag is almost equivalent to that in imported phosphate ore in terms of both amount and concentration, therefore identifying the iron and steel industry as a potential phosphorus source for Japan.[135] Another Japanese study demonstrated that only about 2% of the scarce metal indium extracted from mines actually enters use in products, whereas the rest is recovered from process waste or lost.[59] A dramatic recent result is that per capita iron use appears to saturate rather than continuously increase in many developed countries.[26,39] Finally, a simultaneous analysis of the cycles of seven metals indicates that countries that use more than the per capita world average of any metal tend to do so for all metals, and vice versa.[136]

Quantified elemental cycles have particular resonance because of their policy implications, both for businesses and governments. In this regard, elemental cycles provide a perspective on and quantification of trade of an element among countries and regions. There is obvious financial relevance here, but there is also the realization that international trade permits countries to import materials for which they do not have domestic resources,[21] or to lose material in export instead of using domestic recycling to provide secondary resources.[137] Analysis and comparison of the trade of material (and sometimes of embodied energy and emissions as well [138]) among countries or regions help to identify the different roles regions play in the global trade network,[6,17,82,139] as well as to geographically locate the final sinks of materials.[140] When linked to discussions on public policies (e.g., tariffs or national resources strategies), trade analyses can also provide insights into policy options to promote supply security and sustainable development of resources.[141]

Elemental cycles provide a perspective on and quantification of rates of recovery or recycling, both preconsumer and postconsumer. Elemental cycles have helped in recent years to make recycling data increasingly clear, defining and quantifying recovery efficiency, system recovery rates of discarded elements, and the ratio of new scrap to old scrap.[142−145] By estimating and comparing these rates at different levels, across areas, and over time, policy makers can more accurately assess options for promoting sustainable materials cycling.

Elemental cycles aid in understanding pathways, magnitudes, and impacts of losses to the environment. A comprehensive life cycle will provide estimates of loss at each life stage, thereby identifying pathways and magnitudes of loss and reducing loss, as well as the potential for recovery. For elements that have significant toxicity, losses will not only result in depletion from the anthroposphere but can also lead to health risks and ecosystem degradation. Therefore, scientists (especially those from European countries) have attempted to characterize the loss of heavy metals from emissions into air, water, and soil,[25,146] as well as to develop indictors such as emission rates, environmental accumulation, and environmental concentrations so as to inform possible policies to decrease the negative impacts of emissions.[31,46,49,93,108,147]

Elemental cycles also identify and quantify the location, magnitude, and existing forms of in-use stock, and help explore patterns of resource use from both flows and stocks perspectives. Some studies[116,136] analyze the per-capita use or intensity of use of metals as shown in data on flows into the Use stage (considering secondary production and adjustment of trade of final products) rather than just flows of primary metals into fabrication or manufacturing.[148] Information on historical in-use stocks of metals modeled by the top-down method[117] provides another way of evaluating patterns of materials use in societal evolution[15,26,39] (unlike other studies which are from the perspective of flows such as production or consumption[116,148]). When performing scenario analyses, unlike studies that assume future trends for flows directly,[149] some efforts based on in-use stocks create scenarios of future element cycles using dynamic modeling methods under the concept of "stocks drive flows".[57,75,126,130,150] Another potential application for dynamic in-use stocks modeling is that it helps to explore potentials of and approaches to urban mining,[15,151] especially when combined with bottom-up stocks estimation.[152,153]

Summarizing the implications of anthropogenic cycles of the elements, it may be possible to conclude that, for promoting sustainable resource management, a number of measures are important and feasible: (1) promoting the secure supply of elemental resources; (2) reducing the losses of resources back to the environment, especially those that are dissipative losses; (3) promoting the recycling of resources after their end-of-life in the use stage; (4) increasing the lifespans of resources in the in-use stock; (5) avoiding or reducing the toxicity of the elements along their entire life cycles; and (6) exploring potentials of urban mining from in-use stocks and landfill mining from deposited stocks, especially for metals.

Despite these benefits from elemental cycle characterization, much remains to be done. To the best of our knowledge, no quantified anthropogenic cycles exist at all for 33 of the first 92 elements of the periodic table (Table 1). It is unsurprising that no cycles exist for radioactive elements with short or intermediate half-lives, nor for hydrogen and oxygen. However, it seems odd that no cycles are extant for relatively widely used elements such as bromine, calcium, sodium, and perhaps even ruthenium and iridium. For the 19 elements for which only one cycle exists, and for those 19 elements having only 2−4 cycles, knowledge of reservoirs and flows is often scanty. Dynamic cycles exist for only a few. More often, extant knowledge is limited to a single country and/or to a single year. And, while a geographically constrained cycle may be quite useful to a city, region, or country, it says little to nothing about the long-term sustainability of an element, for which a global perspective is required.

The review indicates that there are significant differences on cycle methodology, with a number of different treatments of loss, recycling, trade, end-use sectors, and other cycle entities. These differences, as described in more detail in Section 3.3, usually result from different purposes and different data availabilities for the research. Therefore, there would be great potential value in standardization in the characterization of elemental cycles. Some combination of the most widely used methodologies would appear to be useful in that it would make cycles more consistent, element to element and country to country, and make comparisons and combinations easier and more efficient. From methodology and data perspectives, input-output analysis may provide a promising way of obtaining data[154] and constructing mathematical models[155] to derive more accurate lifetimes of elements in the anthroposphere,[156,157] to track the flows of a single element across sectors, and to determine the flows of multi elements in a specific product/sector.[155,158,159] For the moment, achieving standardization remains a task for the future, but one that would be immensely useful from a pedagogical standpoint as well as a political one.

As to the material focus of cycles, it should be noted that cycles can apply not only to elements, but also to groups of elements like alloys, or to nonelemental products such as engineering plastics.[160,161] It is also worth noting that elemental cycles, while appearing to stand alone, are in fact often closely linked. For something like half of all the elements the principal uses are in alloy form,[151] meaning that many cycles are closely associated with at least one other element, and usually with several. Some cycle studies for stainless steel and its alloy elements[83,95,162,163] demonstrate the value of going beyond single elements to explore these linkages in more detail. Another important question that has not been sufficiently addressed is that of “downcycling”. For some alloys (e.g., those of aluminum), the accumulation of alloy elements in scrap will result in quality loss (e.g., wrought aluminum alloys are often recycled as casting alloys).[164,165] The solution, sometimes a challenging one to put into practice, is to identify and segregate alloys at the point of discard, so that they may be reused more or less as originally designed.

Given the modern dynamism of metal cycles, our rudimentary knowledge of the uses and losses of these elements, and the changes in use and loss rates over time is quite startling. It is fair to say that technologists have designed an industrial system that relies on the availability of virtually all stable elements that exist, but for which knowledge of how they are employed and dissipated is totally inadequate. Modern technology will not rest on a firm foundation until cycles of all significant elements and combinations thereof are characterized on a multilevel basis, regularly updated, and widely and publicly disseminated.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Detailed description of each cycle, as well as sources and statistics of cycles of the elements at different levels are available at the Supporting Information. This information is available free of charge via the Internet at http://pubs.acs.org/.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We thank Dingjiang Chen, Minpeng Chen, Ichiro Daigo, Xiaoyue Du, Matthew Eckelman, Ayman Elshkaki, Masaaki Fuse, Kohmei Halada, Ermelinda Harper, Hiroki Hatayama, Hope Katagiri, Carsten Lassen, Reid Lifset, Yi Liu, Barbara Reck, Lei Shi, Tao Wang, Ya-Mei Yang, Zengwei Yuan, Saskia Ziemann and the three anonymous reviewers for providing relevant literature and/or for helpful comments.

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