Criticality of metals and metalloids

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Imbalances between metal supply and demand, real or anticipated, have inspired the concept of metal criticality. We here characterize the criticality of 62 metals and metalloids in a 3D "criticality space" consisting of supply risk, environmental implications, and vulnerability to supply restriction. Contributing factors that lead to extreme values include high geopolitical concentration of primary production, lack of available suitable substitutes, and political instability. The results show that the limitations for many metals important in emerging electronics (e.g., gallium and selenium) are largely those related to supply risk; those of platinum group metals, gold, and mercury, to environmental implications; and steel alloying elements (e.g., chromium and niobium) as well as elements used in high-temperature alloys (e.g., tungsten and molybdenum), to vulnerability to supply restriction. The metals of most concern tend to be those available largely or entirely as byproducts, used in small quantities for highly specialized applications, and possessing no effective substitutes.

economic geology | materials science | substitution | supply risk | sustainability

Modern technology relies on virtually all of the stable elements of the periodic table. Fig. 1, which pictures the concentrations of elements on a printed circuit board, provides an illustration of that fact. The concentrations of copper and iron are obviously the highest, and others such as cesium are much lower, but concentration clearly does not reflect elemental importance: all of the elements are required to maintain the functions for which the board was designed. However, some elements may not be routinely available well into the future. How is this risk of availability, or "elemental criticality," to be determined?

Some perspective on elemental origins and availability is useful in discussing criticality. As is now well established, the elements of the periodic table, which together create and define the composition of our planet, were created over the eons in the centers of exploding stars (1, 2). Their relative abundances in the universe are not duplicated in Earth's crust, however, because of the differentiating processes of material accretion, geological segregation, and tectonic evolution (3). A feature of Earth's ore-forming processes is their creation of large spatial disparities in elemental abundance, with some locales hosting rich stores of mineable resources, others almost none. It is these resources, rich or not, dispersed or not, that enable modern technology and hence modern society.

Until the second half of the 20th century, only a modest fraction of the elements was used in technology to any significant degree, and limits to those resources were not thought to be matters for useful discussion. The situation began to change with the publication of the "Paley Report" in 1952 (4), which suggested that resource limitations were, in fact, possible. A decade later, a civil war in the Democratic Republic of the Congo caused a significant, if temporary, decrease in the supply of cobalt (5), indicating that the Paley Report's concerns might indeed have merit. More recently, a decrease in exports of rare earth elements by China resulted in a variety of technological disruptions (5, 6). The result has been numerous calls in recent years (e.g., refs. 7–9) to better assess elemental resources and to determine which of them are "critical," the aim being to minimize further disruptions to global and national technologies and economies.

Despite one's intuition that it should be straightforward to designate one element as critical and another as not, determining criticality turns out to be very challenging indeed. This is because criticality depends not only on geological abundance, but on a host of other factors such as the potential for substitution, the degree to which ore deposits are geopolitically concentrated, the state of mining technology, the amount of regulatory oversight, geopolitical initiatives, governmental instability, and economic policy (10). As various organizations (e.g., refs. 11–13) have attempted to determine resource criticality in recent years, a variety of metrics and methodological approaches have been chosen. The predictable result has been that criticality designations have differed widely (14), thus offering relatively little guidance to industrial users of the resources or to governments concerned about the resilience of their supplies.

In an effort to bring enhanced rigor and transparency to the evaluation of resource criticality, we have developed a quite comprehensive methodology. It is applicable to users of different organizational types (e.g., corporations, national governments, global-level analysts) and is purposely flexible so as to allow user control over aspects of the methodology such as the relative weighting of variables. As with any evaluation using an aggregation of indicators, the choice of those indicators is, in part, an exercise in judgment (15), but alternative choices have been evaluated over several years and we believe all of our final choices to be defendable in detail.

We have applied the methodology to 62 metals and metalloids (hereafter termed "metals" for simplicity of exposition)—essentially all elements except highly soluble alkalis and halogens, the noble gases, nature's "grand nutrients" (carbon, nitrogen, oxygen, phosphorus, sulfur), and radioactive elements such as radium and francium that are of little technological use. Detailed results for individual groups of elements have been published separately (16–21). Here we report on the patterns and dependencies

Significance

In the past decade, sporadic shortages of metals and metalloids crucial to modern technology have inspired attempts to determine the relative "criticality" of various materials as a guide to materials scientists and product designers. The variety of methodologies that have been used for this purpose have (predictably) resulted in widely varying results, which are therefore of little use. In the present study, we develop a comprehensive, flexible, and transparent approach that we apply to 62 metals and metalloids. We find that the metals of most concern tend to be those with three characteristics: they are available largely or entirely as byproducts, they are used in small quantities for highly specialized applications, and they possess no effective substitutes.

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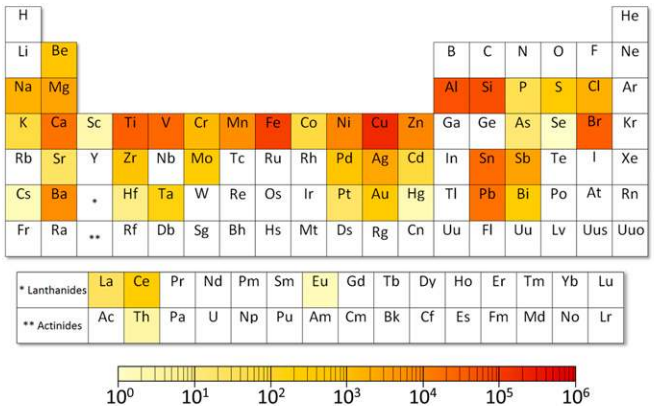

Fig. 1. The concentrations (parts per million) of 44 elements found on printed circuit boards (33).

of the entire suite of studies (thus, for some two-thirds of the periodic table), present both general results and exceptions of particular interest, and discuss the implications of the results for modern technology now and in the future.

Our methodology locates individual metals in a 3D "criticality space," the axes being supply risk, environmental implications, and vulnerability to supply restriction. Evaluations of each axis involve a number of criticality-related indicators, each measured on a 0–100 scale and weighted equally (*SI Appendix*, sections 1–3). Related methodologies address global, national, and corporate levels. We illustrate the methodology at the national level in Fig. 2, and at the global level in *SI Appendix*, section 4, Fig. S1. A full uncertainty analysis is performed as part of focused metal analyses, as described in *SI Appendix*, section 5. The methodology responds to recommendations of others (5, 10, 14) for optimum criticality assessment. Extensive details are given in previous publications (18, 22–24) and in *SI Appendix*.

Our methodology is best regarded as appropriate for moderate (5–10 y) or longer (10–50 y) time scales; that is, we do not attempt to capture such short-term features as economic fluctuations, natural disasters, rapid changes in production, or the like. Formally, the results that follow are for a "snapshot in time": the year 2008, largely because much of the necessary data are reported with long time delays. We are now in the process of updating our database to 2012, the most recent year with satisfactory data availability. Our initial review of this information indicates only modest revisions in the determinations, so we regard the results that we present here as fully applicable over the medium and longer time scales we have aimed to capture.

Metal Criticality

By making use of the global-level methodology described in previous paragraphs and with additional details provided in *SI Appendix*, sections 6–10, we have evaluated each of the criticality-related indicators for the 62 metals of our analysis. In Fig. 3 the indicator results at both global and national (US) levels are shown on a common color scale. These determinations permit us to investigate the degree of independence of the indicators in our criticality methodology. As is illustrated and discussed in *SI Appendix*, section 11, there is little to no correlation among any of the indicators. The determinations of Fig. 3 form the basis for our analyses of overall criticality, as described below for the global level and in *SI Appendix*, section 12 for the United States.

An overview of the 62 metal criticality results is provided by plotting the three-axes results for each metal in criticality space (Fig. 4*A*). A number of metals of quite different criticality properties are concentrated at the middle of the diagram; they may rank moderately high on one or two of the axes, but not extremely high. Another group of metals is concentrated toward the lower left front corner. For those metals, criticality concerns are relatively low on all three axes. A third group is located toward the right side of the diagram. For those metals, the concern is largely related to supply risk. Only platinum and gold appear toward the upper left back corner. Gold has large geological reserves and a low companion fraction, so supply risk is low, but its high cradle-to-gate environmental impacts per kilogram of metal (related to extraction and processing from ore deposits) and its high vulnerability to supply restriction (related to its near-universal use in electronics, jewelry, and investments and its lack of available suitable substitutes) render it of special interest. Platinum has similar energy and environmental challenges and, in addition, its deposits are geopolitically highly concentrated. It

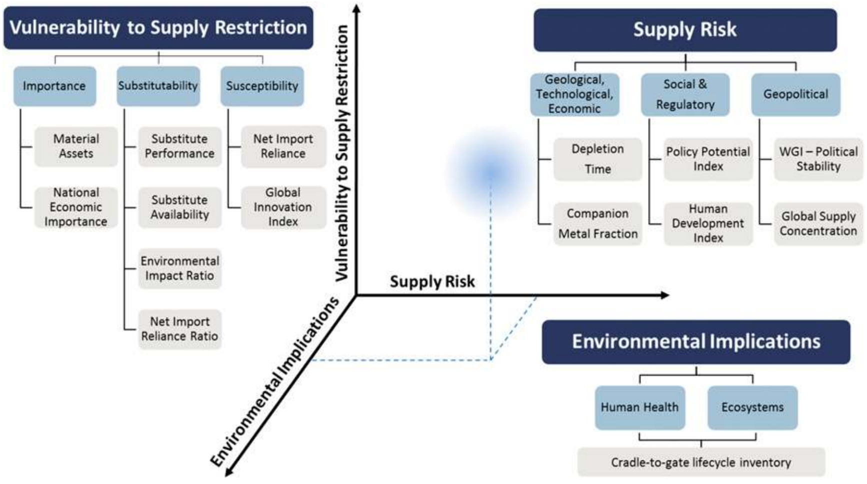

Fig. 2. The methodology of criticality at the national level. The axes in criticality space are supply risk, environmental implications, and vulnerability to supply restriction. Several indicators on each axis are aggregated to arrive at a criticality assessment, as indicated in the diagram. WGI, World Governance Institute. Data sources for the assessment are metal in-use stock determinations, metal material flow analysis, metal substitution potential, country-level information, and environmental life cycle assessment results (comparison on the basis of 1 kg of each element at the factory gate). The global methodology is similar, but omits social and regulatory and geopolitical components on the supply risk axis and the susceptibility component and net import reliance ratio and national economic importance from the vulnerability to supply restriction axis.

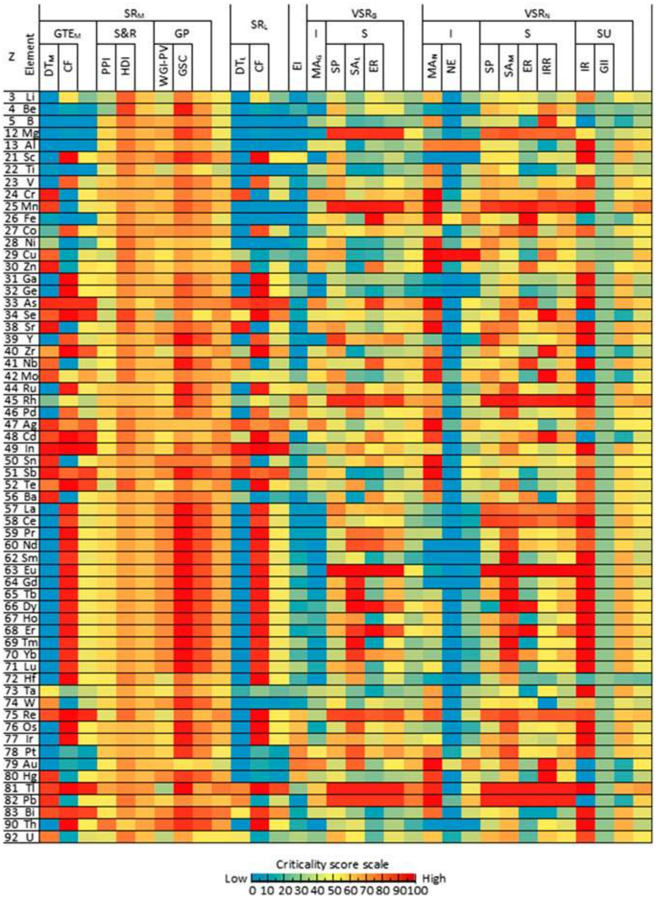

Fig. 3. Evaluation of criticality indicators, components, and axes, global and US levels, 2008 epoch. The abbreviations are defined in *SI Appendix*, section 1.

is notable that the rare earth elements (dark blue) form a pattern of medium supply risk but of sequentially increasing environmental implications; this reflects the allocation of environmental impacts on the basis of economic contribution (25).

Several of the regions of criticality space can be provided with labels that suggest their significance. The lower left front corner is a region of opportunity for users. That is, a metal falling into that region can be used with little concern that its availability will be constrained in any way. Conversely the lower right front corner represents a region of opportunity for suppliers. Suppliers with assets of metals falling into that region have a commodity whose high supply risk limits the number of competitors, and cradle-to-gate environmental issues are not as significant. The upper left back corner represents a region of danger for suppliers. Metals in this region have significant environmental issues (when compared on a per-kilogram basis as done in this study) but low supply risk, so competitors are likely and constraints on use are possible. (No metals fall firmly into that region, but as noted above, platinum and gold are not far removed.) Finally, in the upper right back corner would be metals that represent a region of danger for users. Fortunately, we do not find that any of the metals reside in this problematic location, although rhodium, silver, and thallium are closest to that problematic region.

An alternative perspective on the criticality space results is provided by a hierarchical cluster analysis, based on Euclidean distance and Ward's method (26), and set to five principal clusters (a choice justified by an analysis given in *SI Appendix*, section 13). The result appears as a dendrogram in Fig. 4*B*. Comparison with Fig. 4*A* demonstrates that cluster 5 tends to group toward the top right (a region of significant criticality from supply risk and vulnerability to supply restriction perspectives) and cluster 2 groups to the center back top (a region of significant criticality from environmental implications and vulnerability to supply restriction perspectives). The other clusters are less distinctive from a criticality standpoint.

As was pointed out in the Introduction, some exercise in judgment was required in selecting the criticality indicators. It is therefore reasonable to ask whether these choices might introduce uncertainty in the clustering results of Fig. 4*A*. In this regard, we note that the cluster analysis is based on the indicator choices discussed above and, as with our other results, are potentially subject to uncertainties in the data. We note, however, that (as discussed below) the clusters form metal groupings with generally common physical and chemical characteristics. Therefore, we regard the cluster analysis as generating both reliable and useful results.

Further relationships among the metals can be examined by looking at 2D plots in criticality space. That for supply risk and vulnerability to supply restriction is shown in Fig. 5*A*. (This approach to display criticality was devised originally by the US National Research Council) (11). As in Fig. 4*B*, we group the metals into five hierarchical clusters (the dendrogram appears in *SI Appendix*, section 13). We see that the full range of supply risk is occupied, whereas somewhat less of the vulnerability to supply restriction range contains entries. The loci of the five clusters are widely distributed across Fig. 5*A*. Cluster 1 consists of iron, manganese, gold, and platinum, and has high vulnerability to supply restriction because of the extensive and important uses of these metals, but the supply risks are very low. Midrange values on both axes are characteristic of the metals in cluster 5, an assorted group that includes rhodium, lead, tin, and tellurium. Most of the rare earths are located in cluster 3. Perhaps the most interesting group is cluster 4, composed largely of metals generally used in small quantities in very specific technological applications. These metals, a group that includes indium, antimony, and selenium, have high supply risk and some have quite high vulnerability to supply restriction scores as well.

On the analogous environmental implications-supply risk plot (Fig. 5*B*), most of the elements fall into the low-to-moderate environmental implications range (per kilogram comparison), with the platinum-group metals, gold, scandium, and mercury being higher. The vulnerability to supply restriction-environmental implications plot (Fig. 5*C*) emphasizes that for some metals (especially those in cluster 1 having relatively high vulnerability to supply restriction scores, such as rhodium, palladium, gold, and rhenium) both vulnerability to supply restriction and environmental issues can be substantial.

A final perspective on global-level criticality is provided by displaying the values of the three criticality space axis variables on the periodic table, as shown in Fig. 6. Fig. 6*A* illustrates that the highest values for supply risk are concentrated in groups 13–16/periods 4–5. The figure demonstrates that the metals so important for high-tech applications, such as electronics and thin-film solar cells, are most crucial from a supply risk perspective. For environmental implications (Fig. 6*B*) the highest values are in groups 8–11/periods 5–6. In the case of vulnerability to supply restriction (Fig. 6*C*), the highest values include thallium, lead, arsenic, rhodium, and manganese.

We have performed a similar criticality assessment for the United States (*SI Appendix*, section 12). Note that the global and national criticality results cannot be strictly compared, because the methodology used to assess criticality at the global level differs from that used at the national level. That said, general comments may be made about how a metal's criticality differs at the two levels. The trend of the results is similar, and most of the elements that are more critical at the global level are also more critical at the US level.

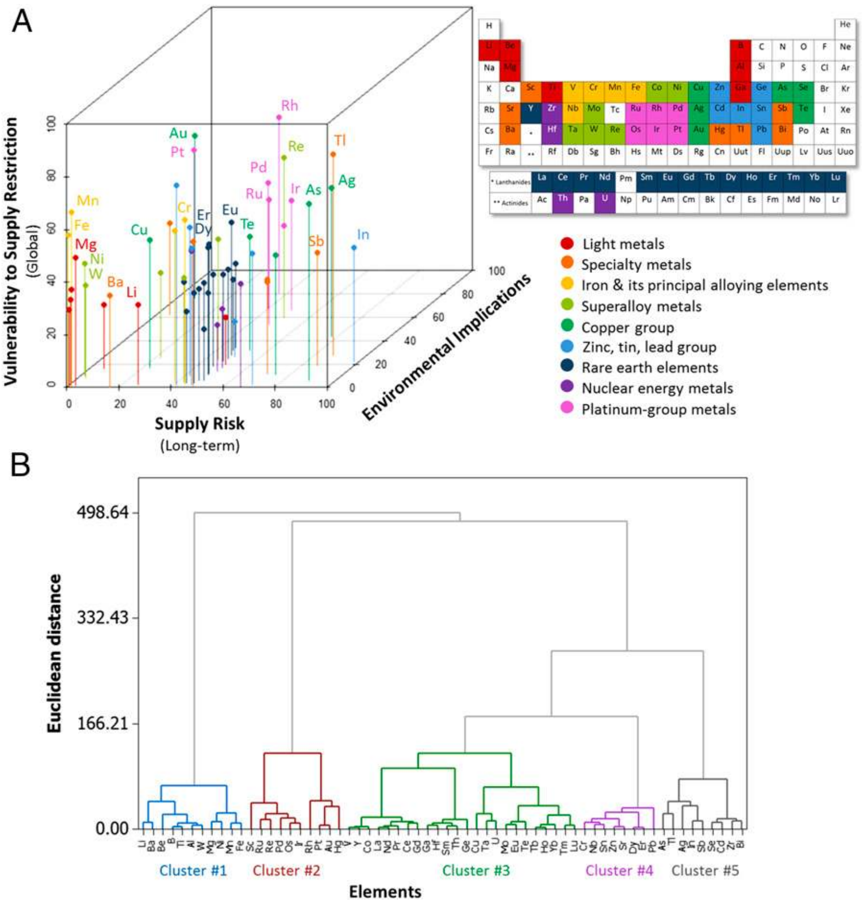

Fig. 4. (*A*) The global assessment for 62 metals, 2008 epoch, global level, in criticality space. The highest level of criticality is at 100, 100, 100 (*Back Right Top*). The metals assigned to the several groupings are indicated in color on the periodic table. (*B*) Hierarchical cluster analysis dendrogram of the results shown in *A*.

Discussion

It is useful not only to examine the results of this research at the aggregate level (i.e., supply risk, environmental implications, and vulnerability to supply restriction), but also at the disaggregated level. Such an analysis is presented largely in Fig. 3 and *SI Appendix*, sections 6–10, but some particularly interesting results worth discussing here emerge from that effort.

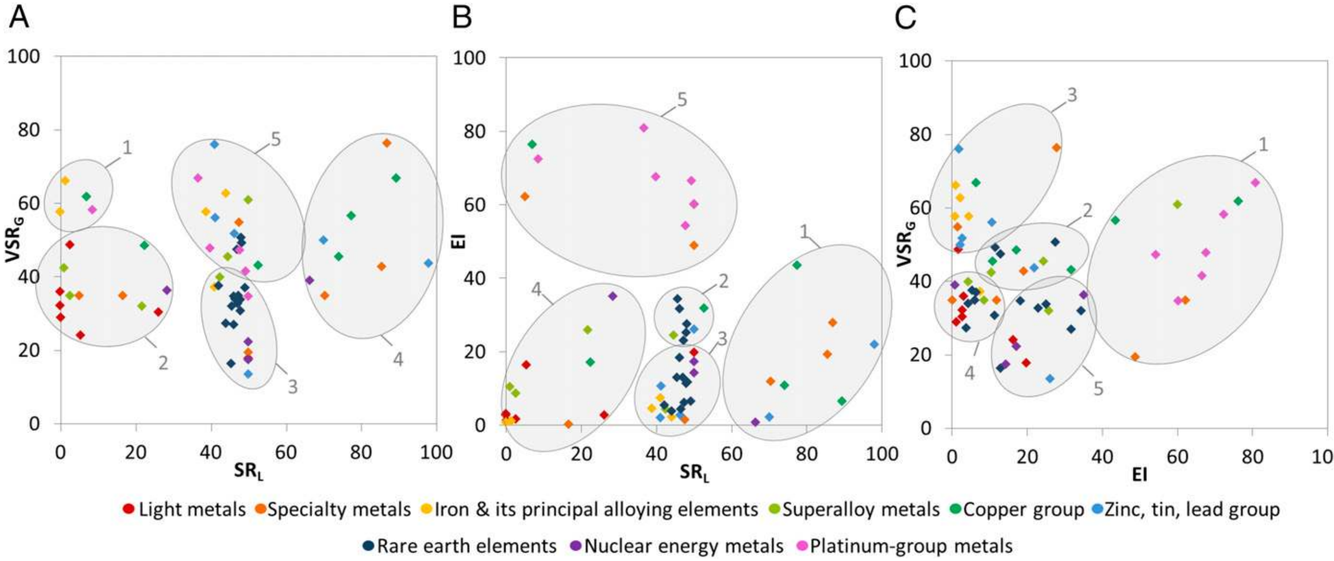

Fig. 5. Two-axes criticality plots for 62 metals, 2008 epoch, global level, with hierarchical clustering of elements identified. (*A*) Supply risk versus vulnerability to supply restriction, (*B*) environmental implications versus vulnerability to supply restriction, and (*C*) supply risk versus environmental implications. Dendrograms for these displays are given in *SI Appendix*.

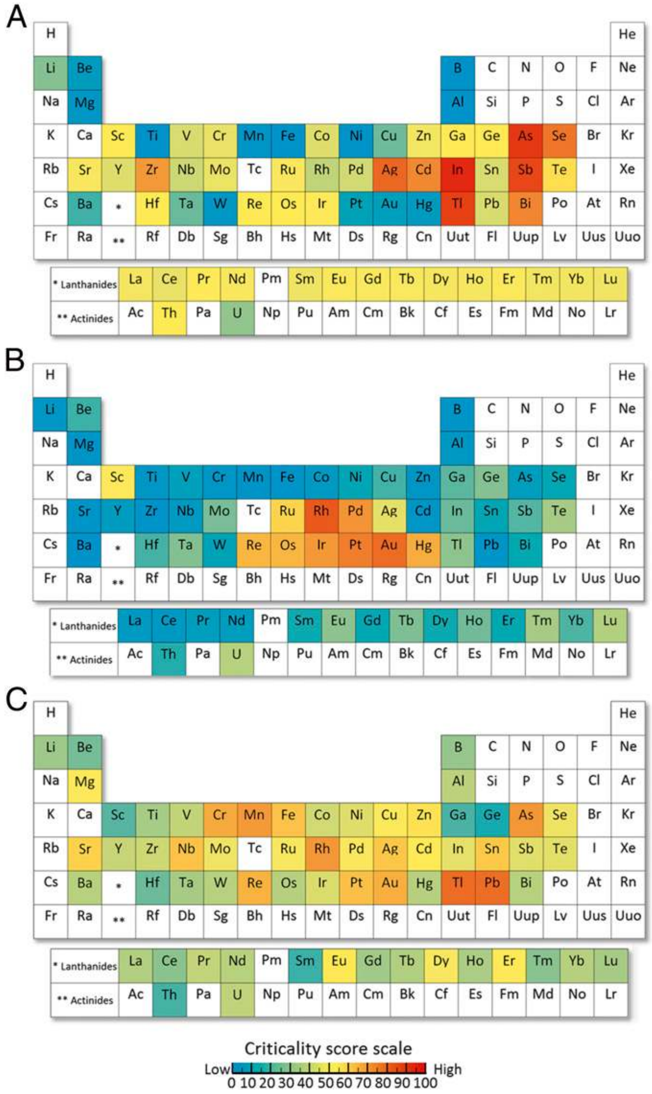

Fig. 6. Periodic tables of criticality for 62 metals, 2008 epoch, global level for (*A*) supply risk, (*B*) environmental implications, and (*C*) vulnerability to supply restriction.

There are only a few metals that have an overall high score along the supply risk dimension (i.e., the metals that have small geological resources relative to their current demands and that are mainly recovered as byproducts of other metals, with byproducts called companions in our analysis). These include indium, arsenic, thallium, antimony, silver, and selenium, metals important in modern electronics and thin-film solar cell technology.

From an environmental implications perspective, the most concern rests with precious metals (gold and the platinum group metals, in particular), because of environmental impacts related to extraction and processing. On the vulnerability to supply restriction dimension, the degree to which suitable substitutes are unavailable is a signal of concern. That parameter singles out magnesium, chromium, manganese, rhodium, yttrium, and several rare earths for attention. All of the elements mentioned above should thus be targeted for special consideration in any general effort to minimize the use of metals that are the more problematic from various criticality perspectives.

In stating these results, we recognize that a significant degree of uncertainty exists in this analysis. For a variety of reasons related to data limitations and data consistency, this uncertainty cannot be rigorously determined. However, our Monte Carlo approach to quantifying uncertainty, and the generation and display of uncertainty clouds for the results (*SI Appendix*, section 5) is a significant step in that direction.

Reductions in uncertainty will likely occur over time as a result of improved information on geological resources estimates, more accurate production figures for companion metals, updated life cycle assessment information related to mining and processing, and improved characterization of the identification and performance of substitutes.

A seemingly obvious thing to do is to compare the results of this exercise with those from other criticality determinations, but doing so turns out to be quite difficult. The results from the US National Research Council (11) were described in that report as preliminary and treated a very limited number of elements. Determinations from the British Geological Survey (12) cover only supply risk, not vulnerability. The EU report (13) was developed specifically for European economic vulnerability. Further, the methodologies are all rather different, often not well described, and only the present study treated all of the rare earth elements and platinum group metals on an individual basis. About all that can be said in a comparative sense is that the more recent studies appear to agree in finding that elements that are less widely used are generally more critical.

Unlike many research results in the physical sciences, a criticality of metals assessment should not be regarded as static, but as a result that will evolve over time as new ore deposits are located, political circumstances change, and technologies undergo transformation. This dynamic characteristic of metal criticality requires that evaluations such as that done in the present work be periodically updated. However, data revisions are not frequent, and major transformations in technology and society often occur slowly (27). We thus regard criticality reassessments on perhaps 5-y intervals as both practical and perfectly adequate for most uses.

We view the results of this work as not purely of academic interest, but also of significant value to industrial product designers and to national policy makers. Designers are already advised to choose materials so as to minimize embodied energy and energy consumption during use (28). The present study adds an additional dimension to materials choice: that of minimizing criticality in material choices. For designers, the criticality designations are surely relevant to efforts that seek to minimize corporate exposure to problematic metals in product design, especially for products expected to have long service lives. Perhaps more important to designers than the aggregate assessments, however, are those for individual indicators, because manufacturers may be able to minimize or avoid some risks if those risks are recognized (29), especially if current designs involve metals in or near problematic regions of criticality space. For example, efforts can be made to find secure sources of supply, to increase material utilization in manufacturing, to reduce the use of critical metals, or to increase critical metal recycling (30). Cross-metal analyses of specific criticality indicators can also reveal properties of individual metals or metal groups, as we have shown in the cases of potential substitutability (23) and environmental implications (25). Considerations such as these extend the product designer's remit from a sole focus on materials science to consideration of corporate metal management as well. In the case of supplier nations or user nations, recognizing the regions of opportunity and of danger in connection with their own resources and industries can minimize risk going forward.

A final point of discussion relates to the relevance of the present work to national and global resources policy. Whether or not individual products or corporate product portfolios are designed with metal criticality in mind, it is indisputable that the world's modern technology is completely dependent on the routine availability of the full spectrum of metals, now and in the future. Tomorrow's technology cannot be predicted with much confidence, especially in the longer term, but it would be quite short sighted were one or more metals to be depleted to the extent that their use in new technologies could not be confidently assumed. Such occurrences would be less likely to happen if metal criticality were routinely considered by industries and governments. In any case, metal availability in perpetuity should not be taken for granted.

Conclusions

We have presented in this work what we believe to be the first comprehensive study of the criticality of metals. The uncertainties that exist in the underlying information limit the precision of the analysis, but do not appear to call the principal conclusions into question. In this regard, and using our detailed and transparent methodology, we identify at the global level the most critical metals as those with constraints resulting from the degree to which they are mined as companions, high geopolitical concentrations of mineable ore deposits, environmental impacts during ore processing, and lack of available suitable substitutes.

Although we support the view that abundance limitations are ultimately likely so far as the geological resources of specific metals are concerned, we do not view these limitations as of immediate concern. Given the anticipated global rise in per capita wealth (31) and the indication that the magnitude of metal use increases with per capita income (32), however, one can anticipate increased pressure on metal supplies over the next few decades. Criticality constraints are thus multifaceted, and evolving.

It is important to repeat the caution that criticality is too complex, and the users of the information too diverse, for metals to simply be designated as “critical” or “not critical.” Corporations, national governments, and resource sustainability experts have different goals, different perspectives, and different time scales. Universal criticality designations can be informative and useful, but can never be prescriptive.

Notwithstanding these considerations, we believe that our results provide a useful starting point for discussions and decisions related to the future availability and use of the metals of the periodic table. They can serve as a guide to the need for specific materials-related policies by corporations and governments, or the need for development of transformative technologies to avoid extensive use of high-criticality materials. Such approaches can help to ensure a more sustainable future for a human society that has become reliant on the diverse and ubiquitous products of modern technology that are made possible by Earth’s metal resources.

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