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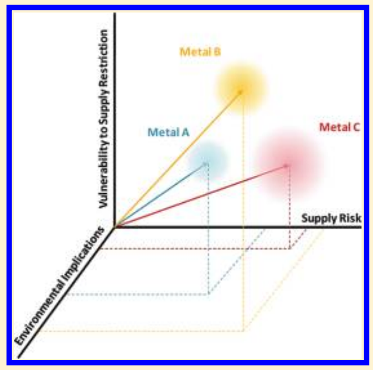
Methodology of Metal Criticality Determination

T. E. Graedel, Rachel Barr, Chelsea Chandler, Thomas Chase, Joanne Choi, Lee Christoffersen, Elizabeth Friedlander, Claire Henly, Christine Jun, Nedal T. Nassar,* Daniel Schechner, Simon Warren, Man-yu Yang, and Charles Zhu

Center for Industrial Ecology, School of Forestry and Environmental Studies, Yale University, 195 Prospect Street, New Haven, Connecticut 06511, United States

Supporting Information

ABSTRACT: A comprehensive methodology has been created to quantify the degree of criticality of the metals of the periodic table. In this paper, we present and discuss the methodology, which is comprised of three dimensions: supply risk, environmental implications, and vulnerability to supply restriction. Supply risk differs with the time scale (medium or long), and at its more complex involves several components, themselves composed of a number of distinct indicators drawn from readily available peer-reviewed indexes and public information. Vulnerability to supply restriction differs with the organizational level (i.e., global, national, and corporate). The criticality methodology, an enhancement of a United States National Research Council template, is designed to help corporate, national, and global stakeholders conduct risk evaluation and to inform resource utilization and strategic decision-making. Although we believe our methodological choices lead to the most robust results, the framework has been constructed to permit flexibility by the user. Specific indicators can be deleted or added as desired and weighted as the user deems appropriate. The value of each indicator will evolve over time, and our future research will focus on this evolution. The methodology has proven to be sufficiently robust as to make it applicable across the entire spectrum of metals and organizational levels and provides a structural approach that reflects the multifaceted factors influencing the availability of metals in the 21st century.



INTRODUCTION

Metals are vital to modern society. Indeed, it is difficult to think of a facet of human society that does not incorporate metals in one form or another. Human reliance on metals is not a new phenomenon, of course. What is new is the rate at which humans are extracting, processing, and using metals. The growth of materials use during the 20th century is such that overall global metal mobilization increased nearly 19-fold from 1900 to 2005, with aluminum increasing over 1000-fold.[1] Not only has the quantity of metals utilized by human societies increased, but so too have the number and variety of metals. In the 1980s, for example, computer chip manufacturing required the use of 12 elements. Today that number has increased to around 60—a sizable fraction of the naturally occurring elements.[2]

The exponential increase of metal utilization witnessed over the past century has led to a marked shift of metal stocks. Historically, all available stocks have been in Earth's crust. Now a significant portion resides above ground in the anthroposphere. This shift, coupled with ever-decreasing ore grades,[3] raises important questions such as whether we should be concerned about the long-term availability of metals and whether it is possible to recycle our way to sustainability.

In 2006, the United States National Research Council (NRC) undertook a study to address the lack of understanding and of data on nonfuel minerals important to the American economy. The report, titled *Minerals, Critical Minerals, and the U.S. Economy*,[2] defined the criticality of minerals as a function of two variables, importance of uses and availability, effectively communicated by a graphical representation referred to hereafter as the criticality matrix in which the vertical axis reflects importance in use and the horizontal axis is a measure of availability (for more details, see the Supporting Information).

The NRC committee carried out preliminary criticality analyses for several metals. Of those surveyed, a number fell within the region of danger—rhodium, platinum, manganese, niobium, indium, and the rare earths. Copper was considered not critical, not because of a lack of importance of use (termed "impact of supply restriction" by the committee) but because supply risk was judged to be low. A number of other elements were located between these extremes. The evaluations were regarded as very preliminary, but served to point out the potentially great differences in criticality among a number of the metals.

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Table 1. Relevant Material-Related Characteristics for Different Organizational Levels

		using corporation	using nation	global
1	focus	relevance to that firm's product line	relevance to national industry and population	all uses of a material, wherever they happen
2	time scale	1–5 years	5–10 years	10–100 years
3	supply potential	crucial	very important	very important
4	technological change	very important	worth consideration	impossible to predict
5	geopolitical factors	crucial	important	unimportant
6	social factors	moderately important	very important	unimportant
7	environmental implications	important	important	moderately important
8	intensity of competition	crucial	depends on national industry composition	unimportant

There has been significant interest in initial criticality work,[2,4−12] enough to warrant the development of a more rigorous and quantitative methodology for assessing criticality. Our extension of the NRC concept involves three key dimensions, each of which comprises one axis of "criticality space"—supply risk (SR), environmental implications (EI), and vulnerability to supply restriction (VSR; termed "impact of supply restriction" by the National Research Council). Utilizing this methodology is an exercise in both data acquisition and expert judgment. For many of the geologically scarcer "specialty" metals, data are in short supply. In developing the methodology, a balance has been sought between analytical rigor and data availability to evaluate the criticality of as many metals as possible and to draw attention to cases for which data are simply not adequate. After all, a lack of information can be a risk in itself. Additionally, efforts to explore the criticality of metals generally consider only the global level, but organizational differences make a uniform analytical approach for all organizational levels impractical. Our methodology was thus developed at three organizational levels (corporate, national, and global).

A suitably comprehensive assessment of criticality involves incorporating information from widely disparate specialties and data sources, from geology, technology, economics, human behavior, expert assessment, and many more. Some useful data sets are quantitative, while some are qualitative; some are well-defined, others less so. In response to this complexity, we present our work in a highly transparent fashion and invite users to redefine aspects of the work as may be most useful to them. In general, however, our resultant methodology has been extensively tested, and we believe it to be robust, reliable, and defendable.

■ MATERIALS AND METHODS

Temporal Perspective. A detailed discussion of the temporal complexities that emerge when evaluating criticality is presented in the Supporting Information. In brief, no single approach is suitable for all time scales or all interested parties, as suggested in Table 1. What we describe in the present work is a methodology to prescribe criticality as a snapshot in time, with plans to develop metal supply and demand scenarios in future work to better evaluate the temporal aspects of metal criticality.

Supply Risk. Because the different temporal perspectives suggest that no methodology focused on a single time scale can adequately serve the complete spectrum of interested parties, we have created a methodology for SR for the medium term (5–10 years) and another for the longer term (a few decades). The former is likely to be most appropriate for corporations and for governments, while the latter will perhaps best serve long-range planners, futurists, and the community of scholars dealing with sustainability.

Because our medium-term methodology is of particular relevance to corporations and nations that utilize materials rather than, or in addition to, supplying them, our focus in this work is on *using* entities rather than *sourcing* entities (i.e., manufacturing firms rather than mining firms). The methodology evaluates SR for using entities on the basis of three components: (1) geological, technological, and economic, (2) social and regulatory, and (3) geopolitical (Figure 1). The first of these components aims at measuring the potential

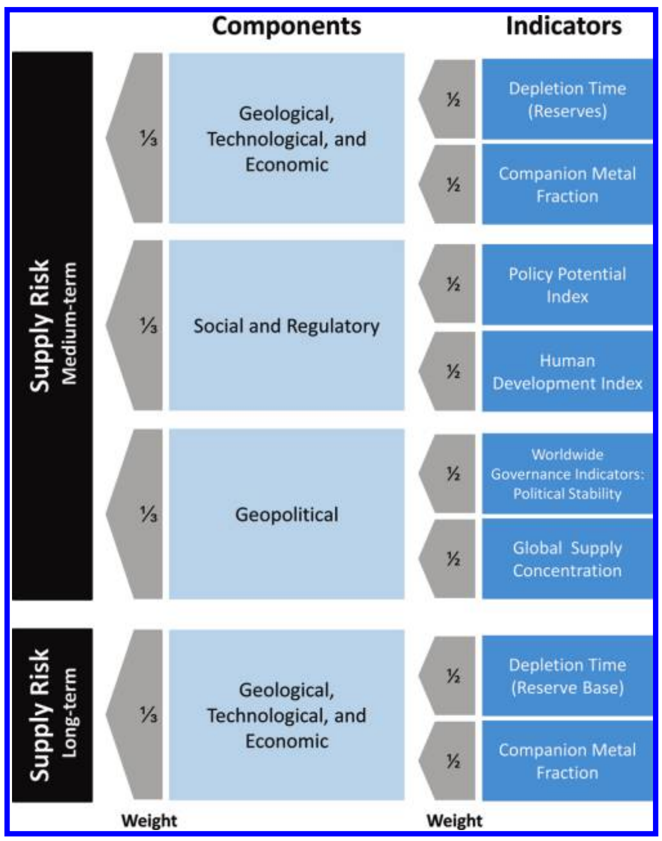

Figure 1. Diagram of the supply risk axis, its components, and its constituent indicators, for the medium-term perspective, used mainly in conjunction with the corporate- and national-level assessments and, for the long-term perspective, used mainly in conjunction with the global-level assessment.

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availability of a metal's supply, including both primary and secondary (recycled) sources, while the latter two address the degree to which the availability of that supply might be constrained. Each component is evaluated on the basis of two indicators, as shown in Figure 1. All indicators are scored on a common 0−100 scale, with higher values suggesting a higher level of risk. When aggregated, the scores of these components yield a metal's overall SR score.

Geological, Technological, and Economic Component. The geological, technological, and economic component is comprised of two equally weighted indicators: one that examines the relative abundance of the metal (termed "depletion time") and a second defined as the percentage of the metal mined as a companion (i.e., recovered as a trace constituent in the ore of a "host metal" rather than being mined principally for itself; termed "companion metal fraction").

The most obvious questions related to a metal's availability in the ground are how much there is, whether it is technologically feasible to obtain, and whether it is economically practical to do so. It is generally surprising to the nongeologist that these simple questions are very challenging to answer in any useful way.

The U.S. Geological Survey (USGS) and others have for many years surveyed companies and governments around the world and compiled the results of the mineral wealth estimates. The USGS classifies its information on the basis of several relevant metrics and organizes it into several categories on the basis of increasing levels of economic and geological certainty. The category that most closely resembles the amount of an element that has the potential to be extracted within the next few years is that of reserves. The USGS defines reserves as "that part of the reserve base which could be economically extracted or produced at the time of determination".[13]

To estimate the relative availability of the metal, we determine the amount of supply being met by recycling and then calculate the amount of time it would take to deplete the geological reserves at the current rate of demand. Details regarding how this depletion time (DT) (and other indicators; see below) is calculated and employed in the overall SR evaluation appear in the Supporting Information. One should not regard the result as how long it will be until we run out, but rather as a useful relative indicator of the contemporary balance between supply and demand for the metal in question. For the long-term perspective, used in conjunction with global-level assessments, the reserve base ("that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices" [13]) is substituted for reserves. Note that, for the long-term perspective, the geological, technological, and economic component is the only component considered (see Figure 1).

The metals that have been in common use for millennia are those that can be found in relatively high concentration (a few weight percent) in good-sized deposits. Generally speaking, these are also elements whose abundances in the continental crust are relatively high. In contrast, where the crustal concentration of a metal is less than about 0.1%, it will seldom form usable deposits of its own, but occurs interstitially in the ores of metals with similar physical and chemical properties.[14] Such metals, if recovered, are termed "companion metals" and the principal metals in the deposits "host metals" (Figure S4, Supporting Information). The availability of the companions therefore depends not only on whether they are recovered but also on the magnitude of the mining of the relevant host metal.

To express the potential for SR related to the host−companion relationship, the percentage of a target metal that is extracted as a companion is used as the relevant metric. A score of 100 thus represents a metal with all (100%) of its production resulting from mines in which it is mined as a companion metal.

Social and Regulatory Component. Regulations and social attitudes are influences that can either impede or expedite the development of mineral resources. Often, objections to mining developments stem from the perception of negative environmental and socioeconomic effects on surrounding communities and ecosystems. Communities are aware of the potential for environmental damage from tailings ponds, for example, and may resist the development of a new mine. The reliability of mineral resources supply can therefore be significantly curtailed in jurisdictions that have rigid regulations or unreceptive social attitudes. From a mining company's perspective, social and regulatory availability can be viewed as an aspect of its right to operate in a specific jurisdiction.[2]

Two indicators—the policy potential index (PPI)[15] and the human development index (HDI)[16]—are employed to quantify the social and regulatory component of the SR evaluation. Detailed information about each may be found in the Supporting Information. Each index is comprised of multiple variables that are aggregated into a single score for individual nations and, in some cases, for subnational jurisdictions. The final PPI and HDI metal indicator scores are obtained by weight-averaging each jurisdiction's transformed index score by its annual production for the metal being studied, with the transformations discussed in the Supporting Information. For the HDI, the production quantity used in the weighting should be the metal's mining, smelting, or refining production, whichever yields the highest risk score. The rationale for this approach is to emphasize the highest risk in the supply chain, as the process step that has the highest risk is the "bottleneck" most likely to cause the supply constraint. This selection of the highest risk production weighting is not used for the PPI, because the PPI is inherently based on mining factors and should thus only be based on mining considerations. For companion metals, it is often the case that no mining production data are available. In such cases, the mining production of the host metal is used in the calculation.

Geopolitical Component. Governmental policies, actions, and stability can significantly affect one's ability to obtain mineral resources. Two indicators, one of the worldwide governance indicators (WGI)[17] and the global supply concentration (GSC) implemented with the Herfindahl−Hirschman index (HHI),[18] are adapted to quantify this effect and form the geopolitical component of our methodology.

Nations that are politically unstable pose a higher risk of mineral supply restriction than those that are not. The WGI is utilized to quantify this risk and has been used in previous criticality assessments (e.g., European Commission[6] and Rosenau-Tornow et al.[19]). The index encompasses national social, economic, and political factors that are associated with underlying vulnerability and economic distress. A number of specific criticisms of WGI have been answered by the WGI researchers.[20] We recognize these challenges, but nonetheless feel that the WGI is a satisfactory indicator for our purposes on the basis of its use in previous criticality assessments.

In the WGI methodology, six different indexes are included, each based on a number of different data sources.[17] In each index, the data are standardized and a percentile ranking is given for each country. A margin of error is also provided to reflect the inherent imprecision involved in such an operation. For the purposes of our analysis, we utilized the political stability and absence of violence/terrorism index (WGI-PV). Scoring details may be found in the Supporting Information. Like the HDI, the final WGI-PV score for a particular metal is obtained by weight-averaging each country's transformed WGI-PV score by its annual mining, smelting, or refining production—whichever yields the highest risk score.

Mineral deposits are not equally or randomly distributed on Earth. Some minerals are predominantly found in only a few countries, while others have more widely dispersed ore deposits. In general, the more concentrated the mineral deposits, the higher the risk of supply restriction.

HHI is a metric commonly used to measure market concentration.[18] Its first noted use for the purpose of evaluating the availability of mineral resources is in a recent paper by Rosenau-Tornow et al.,[19] where it is used to measure the concentration of mining production at both the national and corporate levels. (It is also used by the European Commission to weigh SR[6]). HHI is utilized in this study to quantify the risk of having "all of your eggs in one basket" by examining the degree of production concentration. It is used to calculate GSC, with details found in the Supporting Information.

Each component score is the average of its indicators's scores, and the final SR score, calculated by averaging the three component scores, locates the metal under study on the SR axis in criticality space. A user of the methodology may, however, wish to alter this evaluation by introducing a weighting scheme (or by taking the geometric or harmonic average) that better matches his or her needs, as discussed in more detail in the Supporting Information. Our approach to weighting factors, as well as presentation of an alternate weighting scheme (and its effect upon the results) is presented in a companion paper that evaluates the criticality of several metals belonging to the geological copper family.[21]

Environmental Implications. Metals can often have a significant environmental impact as a result of their toxicity, the use of energy and water in processing, or emissions to air, water, or land. We designate an axis on the criticality diagram to depict the environmental burden of the various metals, thus moving from a criticality matrix to a criticality space.

The EI evaluation included in our methodology is not intended to be viewed as the regulatory measures that may restrict one's ability to obtain mineral resources; that issue is addressed in the social and regulatory component of SR. Rather, it should be viewed as indicating to designers, governmental officials, and nongovernmental agencies the potential environmental implications of utilizing a particular metal. For this evaluation, the inventory data from the ecoinvent database are utilized because of the breadth and depth of that database.[22] From the ecoinvent inventory data, the damage categories human health and ecosystems are calculated according to the ReCiPe end point method,[23] with "world" normalization and "hierarchist" weighting. The third damage category according to this method, resource availability, is not incorporated into the EI evaluation because it is addressed in the SR methodology. The summation and subsequent scaling of the two damage category evaluations provide a single score on a common 0−100 scale for a cradle-to-gate (from the unmined ore to the manufacturing front gate) environmental impact assessment.

Vulnerability to Supply Restriction. No single approach is appropriate for evaluating VSR at each of three organizational levels (corporate, national, and global). For example, we recognize that a particular metal may be crucial to the product line or operations of some corporations, but of little or no import to others. Similarly, countries with a strong industrial base will value certain metals more than may technologically depauperate countries. In the present work, we approach the design of a methodology for measuring VSR with the realization that there will be some indicators in common among the various organizational levels but that other indicators may be specific to only one or two. As a consequence, we have developed three distinct, yet often overlapping, methodologies for the three organizational levels. The methodologies utilize indicators adjusted to a common 0−100 scale. In several of the cases, in which a qualitative assessment is thought to be the most desirable approach, we provide a scoring rubric in which the 0−100 range is divided into four equal "bins". Each bin has a range of 25 points to represent the level of uncertainty in the assessment, and the middle score for each bin is utilized as the default score for those cases in which specifying an exact number proves too great a challenge.

A complication in assessing the VSR is that, unlike assessing the level of SR, it is important to evaluate each significant end-use application of a metal separately. This is because the degree of importance and the substitutability of the metal in question generally vary from one end-use application to another.[2,24]

Corporate Level. The VSR is dependent on the importance of the metal in question and the ability to find adequate substitutes if the metal is unavailable. Quantifying the VSR is thus conducted by evaluating two components, importance and substitutability, using several indicators assessed independently for each end-use application of the metal. The corporate-level assessment is directed to a corporation's current and anticipated product line, with special emphasis paid to economic considerations. A third component, ability to innovate, is included at this organizational level because of our belief that more innovative corporations are likely to be able to adapt more quickly to supply restrictions. The result of these considerations is the evaluation structure shown schematically in Figure 2.

Each component is, in turn, comprised of indicators. The importance component is comprised of the percentage of revenue impacted, ability to pass through cost increases, and importance to corporate strategy. The substitutability component is comprised of substitute performance, substitute availability, the environmental impact ratio, and the price ratio. The task of evaluating substitutability consists of several steps: identifying the principal end uses of the metal under study, determining the fraction of the metal utilized by each end use, determining the most likely substitute material for each end use should the subject metal come under supply restriction, and evaluating the properties of the substitute (see the Supporting Information). Each of these steps can be a research project in itself, especially for the lesser used metals. The ability to innovate component is comprised solely of an indicator termed "corporate innovation".

Combining all eight indicators included in VSR generates the matrix illustrated in Table 2. The corporate-level VSR is then given by eq 1, in which equal weighting is given to each component and each indicator within a component. This calculation should be completed for each end use and then weighted by the fraction of the metal utilized by each end use (termed end-use fraction) to obtain a final score.

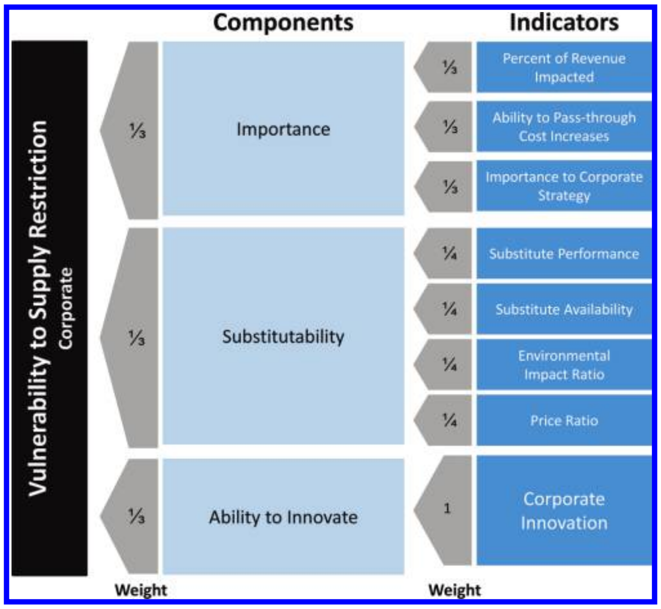

Figure 2. Components of the valuation methodology for the vulnerability to supply restriction, corporate level.

$$\mathrm{VSR}_{\mathrm{corporate}} = \sum_i \Phi_i \frac{\frac{\mathrm{RI}_i + \mathrm{PT}_i + \mathrm{CS}_i}{3} + \frac{\mathrm{SP}_i + \mathrm{SA}_i + \mathrm{PR}_i + \mathrm{ER}_i}{4} + \mathrm{CI}}{3} \tag{1}$$

For each end use i, Φ_i is the end-use fraction, RI_i is the percentage of revenue impacted, PT_i is the ability to pass through cost increases, CS_i is the importance to corporate strategy, SP_i is substitute performance, SA_i is substitute availability, PR_i is the price ratio, ER_i is the environmental impact ratio, and CI is corporate innovation (which would likely, but not necessarily, be scored equally across all end uses).

National Level. Assessing the VSR on a national level differs from the corporate assessment in several ways. The importance of the element in question is again a central component, but one in which the indicators relate to domestic industries and the country's population. Importance and substitutability are retained, but are evaluated somewhat differently. Importance here is composed of two indicators—national economic importance and percentage of population utilizing. National-level substitutability is identical to that described for the corporate-level assessment, except that it substitutes the net import reliance ratio for the price ratio. The ability to innovate is renamed "susceptibility" and is comprised of net import reliance and a measure of innovation, provided by INSEAD's country-level global innovation index.[25] Additional details are given in the Supporting Information, and the evaluation structure is shown schematically in Figure 3. (The details of sourcing-nation evaluations differ somewhat from those of using nations; this methodology is currently under development.)

Combining all eight indicators under the three components of importance, substitutability, and susceptibility into a single diagram yields the matrix presented in Table 3. The national-level VSR, again with equal weightings, is given by the following equation:

$$\mathrm{VSR}_{\mathrm{national}} = \sum_i \Phi_i \frac{\frac{\mathrm{NE} + \mathrm{PPU}}{2} + \frac{\mathrm{SP}_i + \mathrm{SA}_i + \mathrm{IRR}_i + \mathrm{ER}_i}{4} + \frac{\mathrm{GII} + \mathrm{IR}}{2}}{3} \tag{2}$$

where, for end use i, Φ_i is the end-use fraction, NE is national economic importance, PPU is the percentage of population utilizing, IRR_i is the net import reliance ratio, GII is the global innovation index, IR is net import reliance, and the other terms are as in eq 1. The evaluation is completed for each end use and then weighted by each end-use fraction to obtain a final metal score. Indicators lacking a subscript are calculated for the metal overall, with the same score applying to each end use. The PPU indicator may, however, be calculated for individual end uses if such data are available.

Global Level. At the global level, shorter term considerations recede and the emphasis is on the intrinsic value of a metal to society and the degree to which substitution is feasible. Importance is comprised of a percentage of population utilizing indicator, whereas substitutability is comprised of three indicators—substitute performance, substitute availability, and

Table 2. Corporate-Level Vulnerability to Supply Restriction Matrix[a]

Component		Importance			Substitutability				Ability to Innovate
Indicator		Percentage of Revenue Impacted	Ability to Pass-through Cost Increases	Importance to Corporate Strategy	Substitute Performance	Substitute Availability	Environmental Impact Ratio	Price Ratio	Corporate Innovation
Score	**87.5** (75-100)	> 5%	Practically impossible	Essential	Poor	Supply Risk score of substitute	See equation in SI	See equation in SI	Poor
	62.5 (50-75)	>2.5-5%	Difficult	Very important	Adequate				Adequate
	37.5 (25-50)	0.5-2.5%	Possible	Moderately important	Good				Good
	12.5 (0-25)	< 0.5%	Relatively easy	Less important	Exemplary				Exemplary

[a]The scores in bold are the default values attributed to each indicator, and the range delineated below these values represents the range that is utilized in the uncertainty analysis when the methodology is applied. SI refers to Supporting Information.

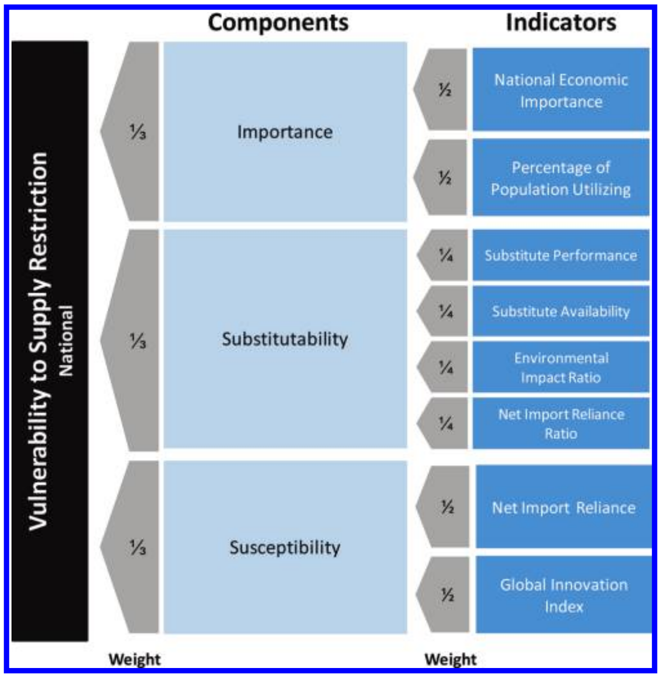

Figure 3. Components of the valuation methodology for the vulnerability to supply restriction, national level.

the environmental impact ratio (Figure 4). Further details about the indicators are provided in the Supporting Information.

Combining the indicators under importance and substitutability generates the matrix illustrated in Table 4. The final global-level VSR, again with equal weightings, is given by the following equation:

$$\mathrm{VSR}_{\mathrm{global}} = \sum_i \Phi_i \frac{\mathrm{PPU} + \frac{\mathrm{SP}_i + \mathrm{SA}_i + \mathrm{ER}_i}{3}}{2} \tag{3}$$

where the terms are the same as those in eq 2.

Overall Criticality. For some organizations it may be useful to have a single value on which to compare the various metals

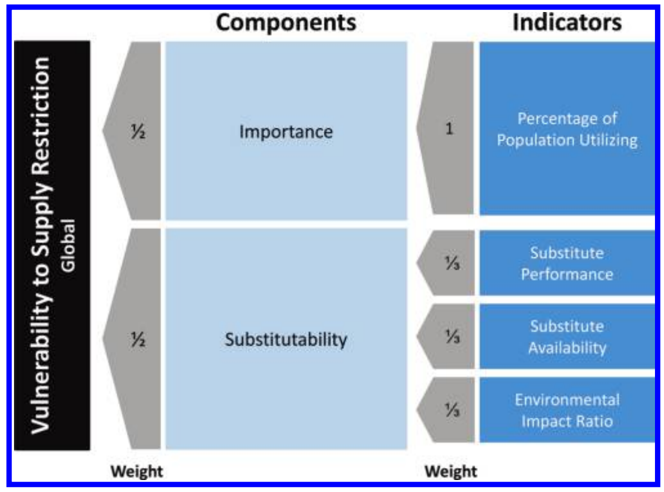

Figure 4. Components of the valuation methodology for the vulnerability to supply restriction, global level.

of interest. A measure of overall criticality may be derived by calculating the distance from the origin to a metal's location in criticality space. Normalizing this distance to obtain a value within the common 0−100 scale yields the "criticality vector magnitude" $\|C\|$:

$$\| C \| = \frac{\sqrt{\mathrm{SR}^2 + \mathrm{EI}^2 + \mathrm{VSR}^2}}{\sqrt{3}} \tag{4}$$

■ RESULTS AND DISCUSSION

We have indicated in this paper and in ref 21 how metal criticality can be evaluated using three core dimensions: SR, EI, and VSR. We concede that any methodology that involves choices among composite indicators and ordinal scales is less than precise. There is some degree of overlap among some of the indicators, a number of indicators with a claim to consideration have not been included, and evaluation approaches to the indicators that were chosen could be debated. Nonetheless, the indicators that have been incorporated are measures that have near-universal applicability and are

Table 3. National-Level Vulnerability to Supply Restriction Matrix[a]

Component		Importance		Substitutability				Susceptibility	
Indicator		National Economic Importance	Percentage of Population Utilizing	Substitute Performance	Substitute Availability	Environmental Impact Ratio	Net Import Reliance Ratio	Global Innovation Index	Net Import Reliance
Score	87.5 (75-100)	See equation in SI	Score for Percentage of Population Utilizing	Poor	Supply Risk score of substitute	See equation in SI	See equation in SI	See equation in SI	See equation in SI
	62.5 (50-75)			Adequate					
	37.5 (25-50)			Good					
	12.5 (0-25)			Exemplary					

[a]The scores in bold are the default values attributed to each indicator, and the range delineated below these values represents the range that is utilized in the uncertainty analysis when the methodology is applied. SI refers to Supporting Information.

Table 4. Global-Level Vulnerability to Supply Restriction Matrix[a]

Component		Importance	Substitutability		
Indicator		Percentage of Population Utilizing	Substitute Performance	Substitute Availability	Environmental Impact Ratio
Score	**87.5** (75-100)	Score for Percentage of Population Utilizing	Poor	Supply Risk score of substitute	See equation in SI
	62.5 (50-75)		Adequate		
	37.5 (25-50)		Good		
	12.5 (0-25)		Exemplary		

[a]The scores in bold are the default values attributed to each indicator, and the range delineated below these values represents the range that is utilized in the uncertainty analysis when the methodology is applied. SI refers to Supporting Information.

either generally available or readily derivable by technical experts and public and private executives. The fact that criticality is being evaluated with multiple indicators tends to compensate for inadequacies in a few of the choices.[26,27] In addition, we have developed an approach to assessing the level of uncertainty, which is discussed in detail in the Supporting Information.

Although there are significant similarities in the methodology for the three levels, corporate, national, and global, there is an implicit temporal dimension worth recalling. The corporate evaluation is very much a shorter term effort—a snapshot in time, as it were. On the national level, some of the indicators (e.g., net import reliance) are shorter term in principle, but in practice tend to change rather slowly, so the national methodology is perhaps intermediate in time. The global-level assessment addresses the longer term, with none of the indicators having a significant short-term characteristic.

Corporations, governments, and other organizations need a current evaluation of criticality and some idea about how that evaluation might evolve over time. In the present paper we seek to identify the indicators that are central to assessing criticality and to describe each in a detailed and transparent way. In every case, time-appropriate data are to be used for each indicator wherever available. The value for each indicator will therefore evolve over time, and we are now developing a set of varied scenarios that will be used to examine how they may evolve under different development alternatives.

Another aspect not addressed in this methodology is that many elements are predominantly used in combinations in which physical and chemical properties differ from those of the constituents—alloys, composites, and the like. This topic is potentially quite important for elements for which such uses predominate and will also be the subject of future work.

Although we believe our methodological choices to be the most robust on an elemental basis, the framework has been constructed to permit flexibility by the user in its application. Specific indicators can be deleted as desired and weighted as the user deems appropriate. An example of doing so is given in ref 21. Also, the indicators may be adjusted or reformulated if desired. For example, the price ratio is performed on a mass basis, but this could be changed to a functional unit basis (i.e., considering how many units of the substitute would be required to perform the same function as one unit of the metal being evaluated) or a total cost difference basis instead. We anticipate that this flexibility will be particularly useful to corporations, which often have specific issues that no general framework can ever fully accommodate.

We acknowledge that linear summation has inherent challenges. For example, a metal with a ready substitute may have a high criticality score based on the other indicators, but yet not be viewed as critical due to the substitute. A potential approach that circumvents this issue is a threshold-based assessment of criticality determined by whether one or more indicators reach (or fail to reach) a certain threshold. However, it is our judgment that none of these mechanisms would be as defendable as the transparent method presented. In the companion paper,[21] we provide each individual indicator score, so that it is clear exactly which are the most critical indicators, and we are transparent about the weightings and summations utilized to calculate the final scores.

It is obvious to wonder what results are produced when this methodology is applied to specific situations. We address this in the companion paper,[21] in which we treat the cases of the copper geological family of metals, demonstrating therein that the methodology is successful in distinguishing among the criticality situation of the various metals and making transparent the indicators that separate one metal in this group from another. The consistent application of this approach to questions related to metal criticality is demonstrated therein to be applicable and useful at the corporate, country, and global levels and to serve as a most useful tool for studies of resource sustainability in the 21st century.

ASSOCIATED CONTENT

Supporting Information

Detailed information about the three key dimensions used to assess criticality: supply risk, environmental implications, and vulnerability to supply restriction. This material is available free of charge via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

Corresponding Author

*Phone: (607) 379-0572; fax: (203) 432-5556; e-mail: nedal.nassar@yale.edu.

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