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Criticality of the Geological Copper Family

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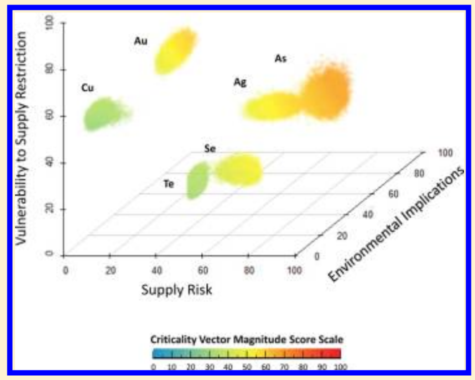
Supporting Information

ABSTRACT: Because modern technology depends on reliable supplies of a wide variety of materials, and because of increasing concern about those supplies, a comprehensive methodology has been created to quantify the degree of criticality of the metals of the periodic table. In this paper, we apply this methodology to the elements of the geological copper family: Cu, As, Se, Ag, Te, and Au. These elements are technologically important, but show a substantial variation in different factors relating to their supply risk, vulnerability to supply restriction, and environmental implications. Assessments are made on corporate, national, and global levels for year 2008. Evaluations of each of the multiple indicators are presented and the results plotted in "criticality space", together with Monte Carlo simulation-derived "uncertainty cloud" estimates for each of the aggregated evaluations. For supply risk over both the medium term and long term, As is the highest risk of the six metals, with Se and Ag nearly as high. Gold has the most severe environmental implications ranking. Vulnerability to supply restriction (VSR) at the corporate level for an invented solar cell manufacturing firm shows Se, Te, and Cu as approximately equal, Cu has the highest VSR at the national level, and Cu and Au have the highest VSRs at the global level. Criticality vector magnitudes are greatest at the global level for As (and then Au and Ag) and at the national level for As and Au; at the corporate level, Se is highest with Te and Cu lower. An extension of this work, now in progress, will provide criticality estimates for several different development scenarios for the period 2010−2050.



■ INTRODUCTION

Industrial manufacturing sectors and their host countries depend upon reliable supplies of resources. Some of those resources are more important than others; they may be the principal constituents of major products, their physical and chemical properties may be unsubstitutable, or they may be more environmentally benign than alternative materials. If these resources are not available, or are only available at unsuitably high prices, the business plan of a corporation, the strategic plan of a country, or the flexibility of technology in the future may be severely impacted.

Most metals are found in nature in combinations, rather than singly. A given mineral deposit normally has one or two elements that provide the economic basis for development (host metals), together with smaller concentrations of other elements (companion metals) whose recovery might or might not make economic sense. Because of variations in companion metal concentrations and financial considerations, companion metal production sometimes occurs, sometimes not. Data on host metals are generally available, but information on companion metal production, trade, and use is much less widely reported. As a consequence, recent assessments regarding the long-term availability of metals[1−6] have generated quite widely differing results, both because of the sparse information available and because of the different goals of the assessments themselves.

The concept of a structured assessment of the criticality of nonrenewable resources was developed by the National Research Council (NRC),[1] where the criticality of an element is defined as the risk that supplies of the element might not be routinely available together with an assessment of the impact of such a restriction on the evaluating organization. The general concept of criticality, if not the NRC framework, has been embraced by a number of organizations, but differences in methodology and perspective have produced wide differences in results.[7] To address this unsatisfactory situation, and to build upon the NRC's conceptual foundation, our research group has created a detailed methodology to generate utilitarian assessments of the criticality of metals and to display the results on a three-dimensional criticality plot.[8] We demonstrate this methodology in specific applications in this paper.

Because of the nature of metal deposits, we have chosen to analyze the criticality of metals in groups of geological families.

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In the present work, we assess the criticality of the copper family, which we define as consisting of six elements: the copper host and five companions, arsenic, selenium, silver, tellurium, and gold. We recognize that gold and silver are sometimes mined for themselves and sometimes occur as companions of metals other than copper and that trace amounts of additional metals are occasionally found in copper ores. Our family definition is thus a grouping of convenience rather than a precise reflection of geological exclusiveness.

The elements in the copper family are, of course, central to much of modern technology. Copper's widest use is to transport electricity, while gold and silver, in addition to their obvious uses as investment and jewelry metals, also play important roles in modern electronics. Selenium and tellurium are major constituents in thin-film solar cells, among other uses. Arsenic is an essential ingredient in high-speed computer chips, in the form of gallium arsenide. Restrictions to the availability of any of these elements would constrain a number of technological sectors, and an assessment of their criticality is therefore of significant interest.

■ MATERIALS AND METHODS

The methodology for evaluating criticality is the subject of a companion paper,[8] in which we describe aspects of the methodology that pertain to what we term "criticality space": supply risk (SR), environmental implications (EI), and vulnerability to supply restriction (VSR) and to corporate, national, and global organizational levels. (An index of acronyms is contained in the Supporting Information of ref 8.) The application of this methodology to the specific example of the geological copper family is discussed below. The listed order of the elements in tables is that of their atomic numbers. All data and results refer to year 2008. A unique aspect of this approach is what we believe to be the first Monte Carlo uncertainty estimate for three-dimensional aggregated variables. For each component evaluation, each indicator was varied over its assigned uncertainty range for a sequence of 10 000 iterations, each iteration being plotted to form an "uncertainty cloud" in criticality space. This process is described in detail in the Supporting Information.

The criticality analysis at the corporate level is specific to an individual firm, its product line, its corporate strategy, its financial details, and its ability to innovate. Rather than apply the methodology to an existing firm, a process that would inevitably involve the use of proprietary data, we have chosen to "invent" an exemplar firm to illustrate the application of our methodology as follows.

Solar Future, Inc. This moderate-sized firm's principal business is the manufacture and installation of CIGS (copper indium gallium selenide) and CdTe (cadmium telluride) thin-film solar cells and is located in a developed country. Competitors have established technologies for alternative solar cell composition (amorphous and single-crystal silicon), so the business rests upon developing and deploying CIGS and CdTe technology. The values we designate for the VSR indicators of Solar Future, Inc. (other than those for substitution, which are not firm-dependent) are presented in the results with more details provided in the Supporting Information.

Actual firms may use the results from this artificial case study as a demonstration of the value of the methodology to their own particular circumstances.

For criticality at the national level, we demonstrate the utility of our approach by evaluating the United States. The United States has good copper family resources, a strong manufacturing heritage, and a relatively affluent population accustomed to technology's benefits.

The global level is addressed using the information and approaches described in ref 8.

The three components are themselves aggregates of several metrics each, as described in detail in ref 8 and its Supporting Information. As pointed out in that discussion, metrics of several different types are thereby aggregated, a process that involves a certain degree of arbitrariness. Different users may make different choices in carrying out the evaluation; nonetheless, by openly providing comprehensive information regarding our methodology, we enable users to apply the methodology precisely as they find it suitable to their own unique needs.

Because of the many individual indicators that must be evaluated as part of the methodology, and the difficulty in specifying the values for many of them with precision, we explicitly estimate for each indicator a quantitative uncertainty. We include these uncertainty values in presenting the results. In particular, our final criticality evaluations carry with them an uncertainty in each of the three criticality dimensions that is calculated as detailed in ref 8 and illustrated in the resulting diagrams.

Supply Risk for the Geological Copper Family Elements. SR consists of three components, geological, technological, and economic (GTE), social and regulatory (S&R), and geopolitical (GP). Each component, in turn, is comprised of indicators: depletion time (DT) and companion metal fraction (CF) for GTE, policy potential index (PPI) and human development index (HDI) for S&R, and worldwide governance indicators—political stability and absence of violence/terrorism (WGI-PV) and global supply concentration (GSC) for GP. The evaluation approach for each indicator is unique, but the result for each is transformed to a 0−100 (low to high SR) common scale. The ratings for the components and for the overall SR are generated by equally weighting the indicators, but unequal weighting is an option for the individual analyst (as discussed in more detail in the Supporting Information in ref 8).

The details of this analysis for the copper family elements are largely described in the Supporting Information, but a few explanatory comments are appropriate here. The first relates to DT. Whereas some analysts have previously used only the geological stocks for this calculation (e.g., Morley and Eatherley[6]), we assess also the in-use (above-ground) stocks, their in-use lifetimes, and their typical recycling rates. (This approach is expected to be particularly important for elements such as lead with short in-use lifetimes and high recycling rates.) A second remark is that we regard corporations and countries as more concerned with shorter term time horizons and global analysts with longer ones, so we utilize reserves for the geological stocks for the first case and reserve base for the second (in both cases with in-use recycling flows).

It is also important to note that the PPI, HDI, and WGI-PV scores are weighted by production. As described in ref 8, the production values used in weighting each country's contribution to the overall indicator score can relate to the metal's mining, smelting, or refining production for each of these indicators except PPI (because PPI is based explicitly on an evaluation of a jurisdiction's mining operation and potential).

Score Scale

A

Element	Geological, Technological, and Economic								Social and Regulatory						Geopolitical						Supply Risk					
	DT_M		CF		DT_L		GTE		PPI		HDI		S&R		WGI-PV		GSC		GP		SR_M		SR_M (alternative weighting)		SR_L	
	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U
Cu	66	56 / 66 / 73	10	8 / 10 / 13	0	0 / 0 / 11	38	33 / 38 / 42	40	37 / 40 / 43	75	73 / 76 / 80	58	56 / 58 / 61	51	48 / 52 / 56	67	66 / 67 / 68	59	57 / 59 / 61	52	50 / 52 / 54	45	42 / 45 / 48	5	4 / 5 / 10
As	93	90 / 93 / 95	92	76 / 89 / 99	87	81 / 87 / 91	93	84 / 91 / 96	40	37 / 40 / 43	67	62 / 67 / 74	54	51 / 54 / 57	65	59 / 65 / 71	78	76 / 78 / 80	72	68 / 71 / 75	73	69 / 72 / 74	83	77 / 81 / 85	90	81 / 88 / 93
Se	83	82 / 85 / 88	100	100 / 100 / 100	45	39 / 53 / 63	91	91 / 92 / 94	40	37 / 40 / 43	86	78 / 83 / 88	63	59 / 62 / 65	30	25 / 31 / 38	72	68 / 69 / 71	51	47 / 50 / 54	69	67 / 68 / 70	80	79 / 80 / 81	73	70 / 76 / 81
Ag	85	82 / 87 / 91	71	60 / 71 / 84	70	64 / 73 / 80	78	73 / 79 / 86	48	44 / 48 / 53	75	70 / 74 / 78	61	59 / 61 / 64	60	55 / 59 / 62	59	59 / 59 / 60	60	57 / 59 / 61	66	64 / 66 / 69	72	69 / 73 / 77	70	65 / 72 / 79
Te	0	0 / 0 / 0	100	100 / 100 / 100	0	0 / 0 / 0	50	50 / 50 / 50	40	37 / 40 / 43	81	74 / 80 / 86	60	57 / 60 / 63	51	43 / 49 / 56	74	74 / 74 / 75	63	59 / 62 / 65	58	56 / 57 / 59	54	53 / 54 / 54	50	50 / 50 / 50
Au	0	0 / 0 / 12	12	9 / 12 / 15	0	0 / 0 / 0	6	5 / 6 / 12	49	46 / 49 / 53	69	66 / 69 / 72	59	57 / 59 / 61	59	55 / 58 / 62	52	52 / 52 / 53	56	54 / 55 / 57	40	39 / 40 / 42	23	22 / 23 / 27	6	5 / 6 / 8

B

Element	Human Health (supply source-weighted average points)	Ecosystems (supply source-weighted average points)	EI D	EI U
Cu	6.33	0.02	17	12 / 17 / 23
As	235.48	0.83	48	41 / 47 / 53
Se	0.22	0.01	2	1 / 2 / 3
Ag	52.50	0.78	35	30 / 35 / 40
Te	3.85	0.04	14	10 / 14 / 18
Au	6,497.57	71.07	76	68 / 75 / 84

C

Element	Importance								Substitutability												Ability to Innovate		Vulnerability to Supply Restriction			
	RI		PT		CS		I		SP		SA		SA (Alternative weighting)		ER		PR		S		CI		VSR_C		VSR_C (Alternative weighting)	
	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U
Cu	88	75 / 86 / 97	38	25 / 35 / 50	38	25 / 35 / 50	54	46 / 53 / 60	88	75 / 86 / 97	42	41 / 42 / 44	21	19 / 21 / 22	7	5 / 8 / 11	19	17 / 19 / 21	39	36 / 39 / 42	88	77 / 86 / 96	60	55 / 59 / 63	29	23 / 29 / 36
Se	63	50 / 61 / 75	38	25 / 35 / 50	63	50 / 61 / 75	54	46 / 53 / 61	38	25 / 35 / 50	45	43 / 45 / 48	23	21 / 23 / 24	100	100 / 100 / 100	3	2 / 3 / 3	46	43 / 45 / 49	88	75 / 86 / 97	62	57 / 62 / 66	43	36 / 42 / 49
Te	38	25 / 35 / 50	38	25 / 35 / 50	88	75 / 86 / 97	54	46 / 53 / 60	38	25 / 35 / 50	100	100 / 100 / 100	80	78 / 79 / 81	7	4 / 7 / 11	17	15 / 17 / 19	40	37 / 40 / 44	88	75 / 86 / 97	61	55 / 60 / 64	84	77 / 83 / 89

Figure 1. continued

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D

Element	Importance						Substitutability										Susceptibility						Vulnerability to Supply Restriction	
	NE		PPU_N		I		SP		SA		ER		IRR		S		IR		GII		SU		VSR_N	
	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U
Cu	97	83	100	91	99	89	70	63	47	46	7	5	14	12	35	33	32	27	29	24	30	27	54	51
		97		97		96		68		47		8		14		34		32		29		30		54
		100		100		100		74		49		11		17		36		37		34		34		55
As	0	0	89	70	44	35	38	26	74	69	18	13	18	17	37	34	100	74	29	24	64	51	49	43
		0		86		43		36		74		18		20		37		90		29		59		46
		0		98		49		49		82		24		25		41		99		34		65		49
Se	0	0	45	36	23	18	47	40	76	74	93	80	100	100	79	71	0	0	29	24	14	12	39	35
		0		45		23		46		76		90		100		78		0		29		14		39
		0		57		29		52		78		99		100		86		0		34		17		43
Ag	21	18	89	73	55	47	47	39	44	43	56	50	10	9	40	37	70	59	29	24	49	43	48	46
		21		87		54		45		44		56		10		39		70		29		49		47
		24		98		60		53		46		60		13		41		83		34		57		49
Te	0	0	25	19	13	10	38	30	76	74	33	13	34	28	45	38	80	67	29	24	54	48	37	33
		0		25		13		36		76		33		34		45		80		29		54		38
		0		33		17		44		78		54		42		54		94		34		62		43
Au	43	37	89	73	66	57	44	37	74	72	23	19	100	100	60	58	0	0	29	24	14	12	47	45
		43		87		65		43		74		23		100		60		0		29		14		46
		49		98		71		51		77		28		100		62		0		34		17		48

E

Element	Importance		Substitutability								Vulnerability to Supply Restriction	
	PPU_G		SP		SA		ER		S		VSR_G	
	D	U	D	U	D	U	D	U	D	U	D	U
Cu	78	65	70	64	6	6	7	5	28	26	53	50
		78		69		6		7		27		53
		92		74		7		10		30		56
As	60	48	38	27	51	41	18	13	36	30	48	42
		60		36		52		18		35		48
		76		46		66		24		41		56
Se	12	9	47	40	52	48	81	68	60	53	36	32
		12		46		52		80		59		36
		15		53		55		86		66		40
Ag	60	50	44	36	16	14	52	46	37	34	49	46
		60		41		16		52		36		49
		72		48		19		56		39		52
Te	8	7	35	29	58	57	29	8	44	35	26	22
		8		36		63		31		44		26
		10		44		69		55		52		30
Au	60	50	40	31	77	73	23	19	47	43	54	50
		60		39		78		23		47		54
		72		48		84		28		51		58

Figure 1. Resulting criticality assessment values for indicators, components, and axes of the geological copper family of elements. The abbreviations are as follows: DT_M = depletion time, medium-term perspective; CF = companion metal fraction; PPI = policy potential index; HDI = human development index; WGI-PV = worldwide governance indicators—political stability and absence of violence/terrorism; GSC = global supply concentration, SR_M = supply risk, medium-term perspective; DT_L = depletion time, long-term perspective; SR_L = supply risk, long-term perspective; EI = environmental implications; RI = percentage of revenue impacted; PT = ability to pass through cost increases; CS = importance to corporate strategy; SP = substitute performance; SA = substitute availability; ER = environmental impact ratio; PR = price ratio; AI = ability to innovate; VSR_C = vulnerability to supply restriction, corporate; NE = national economic importance; PPU_N = percentage of population utilizing, national; IRR = net import reliance ratio; IR = net import reliance; GII = global innovation index; VSR_N = vulnerability to supply restriction, national; PPU_G = percentage of population utilizing, global; VSR_G = vulnerability to supply restriction, global. For each indicator, component, and axis score, four values are provided per element. Under the column labeled "D", the default values are provided; these values are obtained when all of the stated assumptions are utilized. Under the column labeled "U", three values from the uncertainty analysis are provided per indicator for each element: the 5th percentile, the median, and the 95th percentile in that order from top to bottom. Note that values reported for all indicators are based on the appropriately weighted and scaled "transformed" scores (see ref 8 for details). More information regarding the assumptions and uncertainty analysis is provided in the Supporting Information. Note that DT_M (along with CF) was used to calculate GTE. Values are reported to the nearest whole number and colored according to the color ramp shown at the top of the figure.

The production process step that yields that highest risk score, indicating the part of the supply chain that is the riskiest, is utilized in the overall assessment. This comparison between the different production weightings is done independently for each factor. A metal can, for example, has the HDI indicator weighted by its smelting production values and its WGI-PV indicator weighted by its mining production values. For companion metals that have only refining (or smelting) production data, the PPI score of the host metal is used instead.

Environmental Implications for the Geological Copper Family Elements. Metals frequently carry 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 additional axis on the criticality diagram, EI, to depict the environmental effects of the various metals, thus moving the criticality evaluation from a matrix to a criticality space. EI is determined using inventory data from the ecoinvent life cycle inventory database, version 2.2,[9] and the ReCiPe end point impact method (with the "world" normalization and "hierarchist" perspective weighting), version 1.05,[10] using both primary and secondary resource flows and a functional unit of 1 kg. This provides a single score for a cradle-to-gate (from the unmined ore to the manufacturing front gate) environmental impact assessment on a per unit of mass (kilogram) basis, which is then transformed to a 0−100 (low to high EI) common scale. (A cradle-to-grave assessment might be preferable, but data to enable that analysis are not available, as discussed in the Supporting Information of ref 8.)

Vulnerability to Supply Restriction. As outlined below, VSR consists of a number of components that vary depending on the organizational level (i.e., corporate, national, and global) that is being evaluated.

- Global level: importance (I) and substitutability (S).
- National level: importance (I), substitutability (S), and susceptibility (SU).
- Corporate level: importance (I), substitutability (S), and ability to innovate (AI).

Each component, in turn, is comprised of indicators that are described in detail in ref 8. At the global level, I is comprised solely of the percentage of population utilizing (PPU) and S is comprised of the substitute performance (SP), substitute availability (SA), and environmental impact ratio (ER). At the national level, I is comprised of national economic importance (NE) and PPU, S is comprised of SP, SA, ER, and the net import reliance ratio (IRR), and SU is comprised of net import reliance (IR) and the global innovation index (GII). At the corporate level, I is comprised of the percentage of revenue impacted (RI), ability to pass through cost increases (PT), and importance to corporate strategy (CS), S is comprised of SP, SA, ER, and the price ratio (PR), and AI is comprised of corporate innovation (CI).

As with SR, the evaluation approach for each indicator is unique, but the result for each is transformed to a 0−100 (low to high VSR) common scale. The ratings for the components and for the overall VSR are generated by equally weighting each component and each indicator within a component, but unequal weighting is an option for the individual analyst.

The details of the VSR analysis for the copper family elements are largely described in the Supporting Information, but a few explanatory comments are appropriate here. To evaluate S, the VSR analysis requires that the principal end uses and the end-use breakdown as a function of the total use of the target metals be identified (see the Supporting Information). For each of these end uses the most suitable substitute material is determined and is termed the primary substitute. It is important to note that SA is determined by calculating SR for each of the primary substitutes, and these are again detailed in the Supporting Information.

■ RESULTS AND DISCUSSION

The results of our analysis for each of the individual metrics at the different organizational levels are shown in Figure 1. For each metric four values are provided. Under the column labeled "D" is the default value, which is the result obtained when all the assumptions outlined in the Supporting Information are adopted. Under the column labeled "U", three values from the uncertainty analysis are provided: the 5th percentile, the median, and the 95th percentile, respectively. The supply risk indicators and components comprise Figure 1A; recall that SR results are identical for corporate, national, and global assessments. Examine initially the row for copper, where a subscript "M" refers to the medium term and "L" refers to the long term for indicators for which a temporal distinction is necessary, all on a 0−100 scale. The HDI is the highest at 75, GSC is 67, and DT_M is 66; all others are moderate to low. Applying equal weighting produces an SR_M for copper of 52. The next column set provides the supply risk score when the GTE score is weighted as 2/3 of the overall score and the S&R and GP components are each given 1/6 weighting (see discussion below). Using this alternative weighting yields a medium supply risk score of 45 for copper. The final column set refers to the SR for the long-term perspective and incorporates only the DT_L and CF indicators, weighted equally. With very low values for both CF and DT_L, the resulting SR_L values for copper are also very low.

Arsenic presents a different picture. Almost all of its indicators are high to very high, giving arsenic very high SR. Selenium and silver are nearly as high. Gold is lowest. The long-term rankings show greater variability than the medium-term rankings—some quite high (arsenic, selenium, and silver), some quite low (gold and copper).

The environmental implications evaluations appear in Figure 1B; as with SR, they are independent of the organizational level. They range from very low (selenium) to very high (gold).

Vulnerability to supply restriction at the corporate level is shown in Figure 1C. Because Solar Future, Inc. does not employ silver, gold, or arsenic in its products, those elements do not appear. Under the current set of assumptions regarding Solar Future, Inc., copper, selenium, and tellurium have nearly identical VSR scores. The indicators contributing to these overall rankings are quite different, however. Copper is quite high for RI and SP but moderate to low for all other indicators, while tellurium is quite high for CS and SA and low for all other indicators. Solar Future, Inc.'s AI is assumed to be constant across the elements.

At the national (United States) level (Figure 1D), the VSR results range from 37 (tellurium) to 54 (copper). The indicators contributing to these overall rankings are also quite different. The value of NE for copper is quite high but low to very low for the other elements, for example, while IR is much higher for arsenic than for the others.

At the global level (Figure 1E), VSR values are moderately high for copper (53) and gold (54), lower for selenium (36), and lowest for tellurium (26). The results reflect wide variability in the evaluations for the four indictors that comprise the global VSR evaluation.

Figure 1 demonstrates an important aspect of criticality evaluation—that individual metrics can indicate a high level of criticality (as in the CF rating for Te) even as the overall component evaluation (as in the SR ratings for Te) is moderate. This circumstance emphasizes the importance of considering the full range of factors in assessing criticality rather than one or a small number of indicators.

The results of Figure 1 are plotted in criticality space in Figure 2. At the corporate level (Figure 2A), no significant separation occurs for the three elements. The Monte Carlo simulation-derived uncertainty cloud indicates a greater degree of uncertainty for VSR than for SR. Elemental distinctions are much greater at the national level (Figure 2B), with gold clearly in a different part of criticality space than arsenic or selenium. Here the arsenic uncertainty cloud is relatively symmetric, those for copper and gold showed greater uncertainty in EI, and tellurium and selenium continue their higher VSR uncertainty. On the global level (Figure 2C), distinctions are again clear, with selenium and tellurium positioned in close proximity due to similar scores for all three axes and gold and copper separated from the other elements due to their low supply risk. In most cases, the uncertainty clouds are larger than at corporate or national levels and show considerable diversity.

A measure of overall criticality, as described by Graedel et al.,[8] may be derived by calculating the "criticality vector magnitude" $||C||$ as follows:

$$\| C \| = \frac{\sqrt{SR^2 + EI^2 + VSR^2}}{\sqrt{3}} \quad (1)$$

Unequal weighting of the criticality vector magnitude components, rather than of some of their aggregated metrics, is an option for individual users, but we regard doing so as excessively arbitrary and do not advocate it.

The results are given in Table 1. By this measure, on a global basis, the criticality of arsenic is highest, followed by gold and silver. Nationally, gold and arsenic are the highest and tellurium is the lowest. At the corporate level, the criticality of the three elements is fairly even, with selenium somewhat higher than tellurium and copper.

To demonstrate the differences produced by alternative weighting, which users may choose to do, we have recalculated criticality for Solar Future, Inc. Because the metals on which Solar Future's products are based largely come from countries without significant political or social issues, the GTE component for SR was weighted at 2/3, and S&R and GP were weighted at 1/6 each. For VSR, Solar Future decided to include in its assessment only those metrics about which it was particularly concerned—the importance of specific metals to corporate strategy (CS) and the supply risk of possible substitutes (SA), so CS and SA were the only metrics considered and were weighted equally. No alternate weighting scheme was employed for EI. The result is that copper's SR decreases from 52 to 45 and its VSR decreases from 60 to 29. Selenium's SR increases from 69 to 80, but its VSR decreases from 62 to 43. Tellurium's SR remains about the same, decreasing slightly from 58 to 54, but its VSR increases from 61 to 84. These changes cause significant movement for these elements in criticality space, as shown in Figure 3. The uncertainty cloud differences are large and clearly visible. The effect of the alternative weighting on the criticality vector

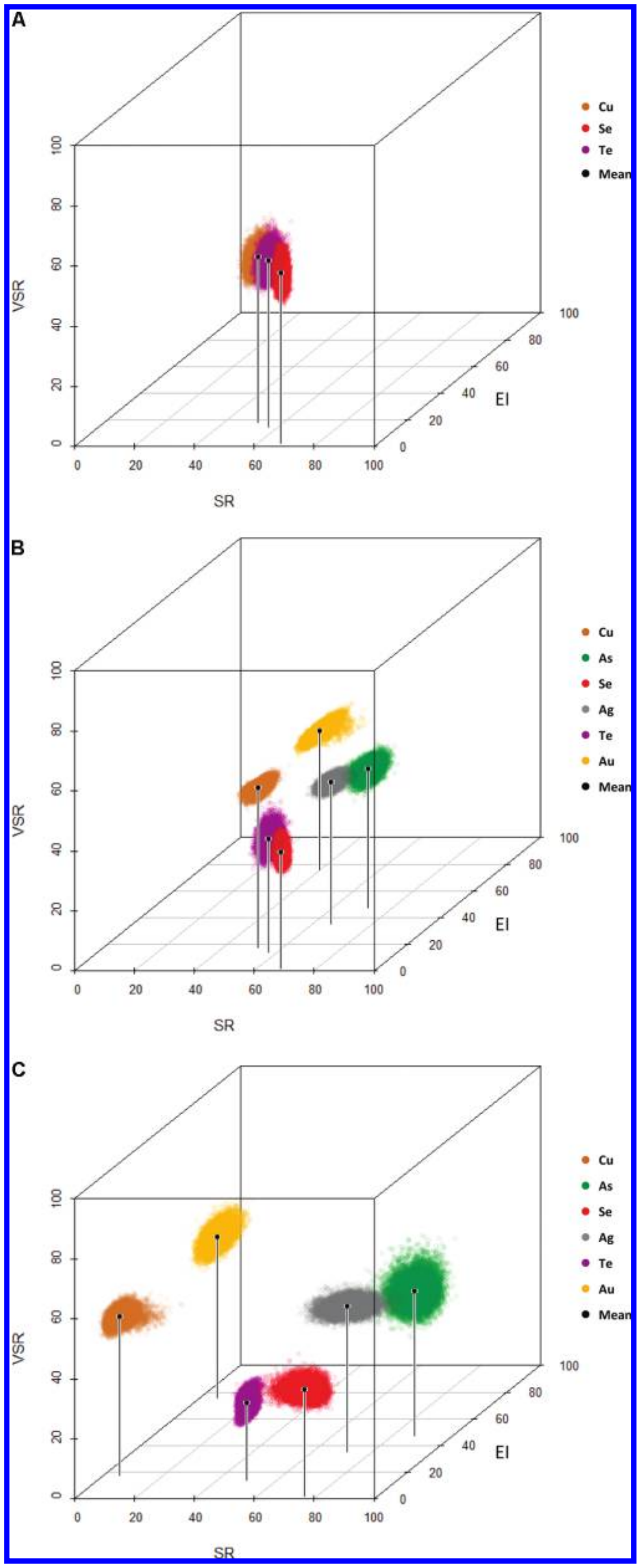

Figure 2. Locations of the geological copper family of elements in criticality space: (a) corporate level, for Solar Future, Inc., a putative corporation whose principal products are CIGS and CdTe solar cells (2008 epoch), (b) national level, for the United States (2008 epoch), and (c) global level (2008 epoch). The highest level of criticality is at 100, 100, 100 (back right top).

Table 1. Criticality Vector Magnitudes for the Geological Copper Family

Element	Global		National (United States)		Corporate (Solar Future, Inc.)		Corporate (Solar Future, Inc.) Alternative weighting	
	D	U	D	U	D	U	D	U
Cu	32	31	44	43	47	45	32	30
		32		44		47		32
		34		45		49		35
As	65	60	57	54				
		64		56				
		67		59				
Se	47	45	45	44	54	51	52	51
		49		45		53		52
		51		47		55		54
Ag	53	51	51	50				
		54		51				
		58		53				
Te	33	32	40	39	49	46	58	55
		33		40		48		58
		35		42		50		60
Au	54	50	57	53				
		54		56				
		58		60				

Score Scale

0 10 20 30 40 50 60 70 80 90 100

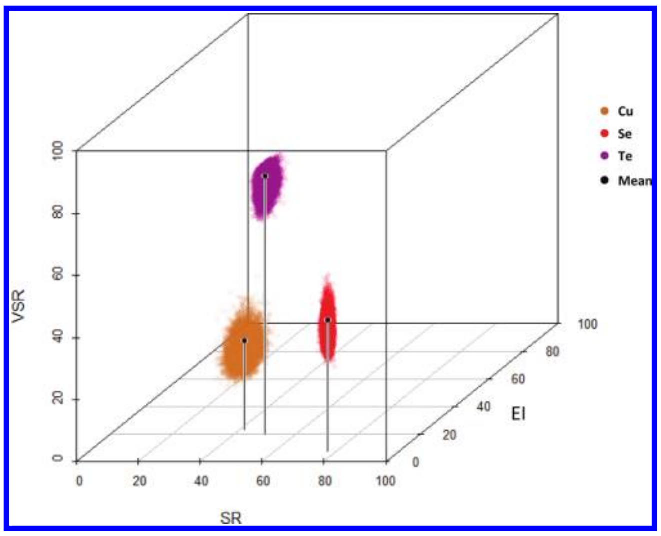

Figure 3. Locations of the relevant geological copper family elements in criticality space for Solar Future, Inc. if the GTE component is weighted at 2/3 of the overall supply risk score, with the remaining components weighted at 1/6 each. For vulnerability to supply restriction, CS and SA indicators are the only indicators considered and are weighted equally. The environmental implications axis scores are unchanged.

magnitudes (Table 1), is modest with copper decreasing from 47 to 32, selenium decreasing slightly from 54 to 52, and tellurium increasing from 49 to 58.

In very recent years, a number of organizations have made determinations of the "criticality" of some members of the geological copper family. We summarize the results in Table 2; they reflect the assessment diversity noted in a recent review.[7] The IW study[4] singles out selenium as "high risk" and copper, silver, and gold as "medium risk". The Oakdene Hollins study[6] identifies gold and silver as among the seven elements designated as "insecure". Our evaluation distinguishes criticality at different organizational levels. We regard tellurium as having among the lowest criticality at the global level, and for the specific corporation we have addressed with alternative weighting, tellurium is the highest of the three elements the corporation uses. At the global level, arsenic is surely of more concern than silver or gold, by our methodology, while copper and tellurium appear to be of less concern. Given the expected continued decline of arsenic use, however, we expect a similar decline in its criticality.

A particular feature of these results is the calculation and display of Monte Carlo simulation-derived uncertainty clouds for the three-dimensional aggregate evaluations. The relative magnitudes and shapes of the clouds add considerable

Table 2. Criticality Designations in Seven Selected Studies[a]

element	EC study[2]	IDA study[3]	IW study[4]	NEDO study[5]	NRC study[1]	Oakdene Hollins study[6]	South Korea approach[11]
Cu	not critical	no shortfalls	medium risk		not critical	not insecure	
As						not insecure	
Se			high risk	not critical		not insecure	not critical
Ag	not critical	no shortfalls	medium risk			insecure	
Te	not critical	no shortfalls		not critical			not critical
Au			medium risk			insecure	

[a]Adapted from ref 7. Copyright 2011 American Chemical Society.

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perspective to the results, providing an easy to comprehend picture of the degree of confidence that should be placed in the criticality results.

The parameters used in these criticality evaluations are, of course, not static. Because they will evolve over time, there is utility both for a static assessment, as done here for year 2008, and for a dynamic assessment that looks into the future. An extension of the present work, now in progress, will provide criticality estimates for several different development scenarios for the period 2010–2050.

Overall, we regard this work as justifying our methodology of criticality assessment. It incorporates essentially all factors thought to influence metal criticality, including geological, technological, social, regulatory, and geopolitical metrics. While complex, it is wholly transparent, and the indicators can be weighted as deemed appropriate by the users. It explicitly derives results at different organizational levels and calculates and displays the estimated uncertainty for each of the three aggregated axis values.

A final word is appropriate: there is no such thing as "critical" or "not critical", and we have avoided making such a distinction. There are, however, metals that are more critical than others under some conditions, for some users, and for some time scales. This immediately suggests that policy options should be explored when high-criticality situations are encountered. For example, a corporation could choose to invest directly in a mine rather than to purchase metal from the global market, or to develop product designs that avoid metals with high supply risk or high environmental implications. Countries could take steps to ensure raw material supplies for their important industry sectors, as is happening at present in countries around the world (generally without the detailed evaluation information of which this paper is an example). As always, knowledge is power, and the additional knowledge provided by criticality assessments is likely to enable better decisions to be made in the interest of corporations, countries, and the planet. This sort of thinking and action will be increasingly important as ever-increasing rates of material use force all of us to think more deeply about issues of resource sustainability.

ASSOCIATED CONTENT

Supporting Information

Detailed accounting of the data used in analyzing criticality, detailed results for each indicator and component, and detailed results for the uncertainty analysis. This material is available free of charge via the Internet at http://pubs.acs.org.

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