Material Resources:

Is Their Availability Critical?

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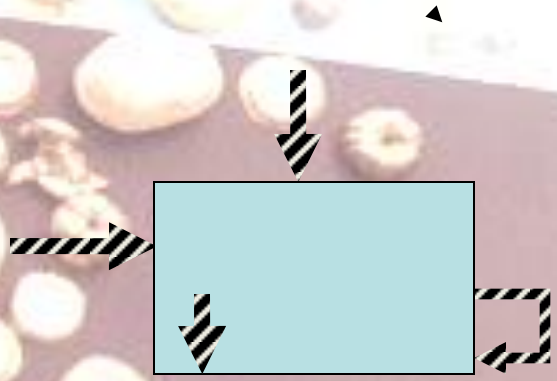
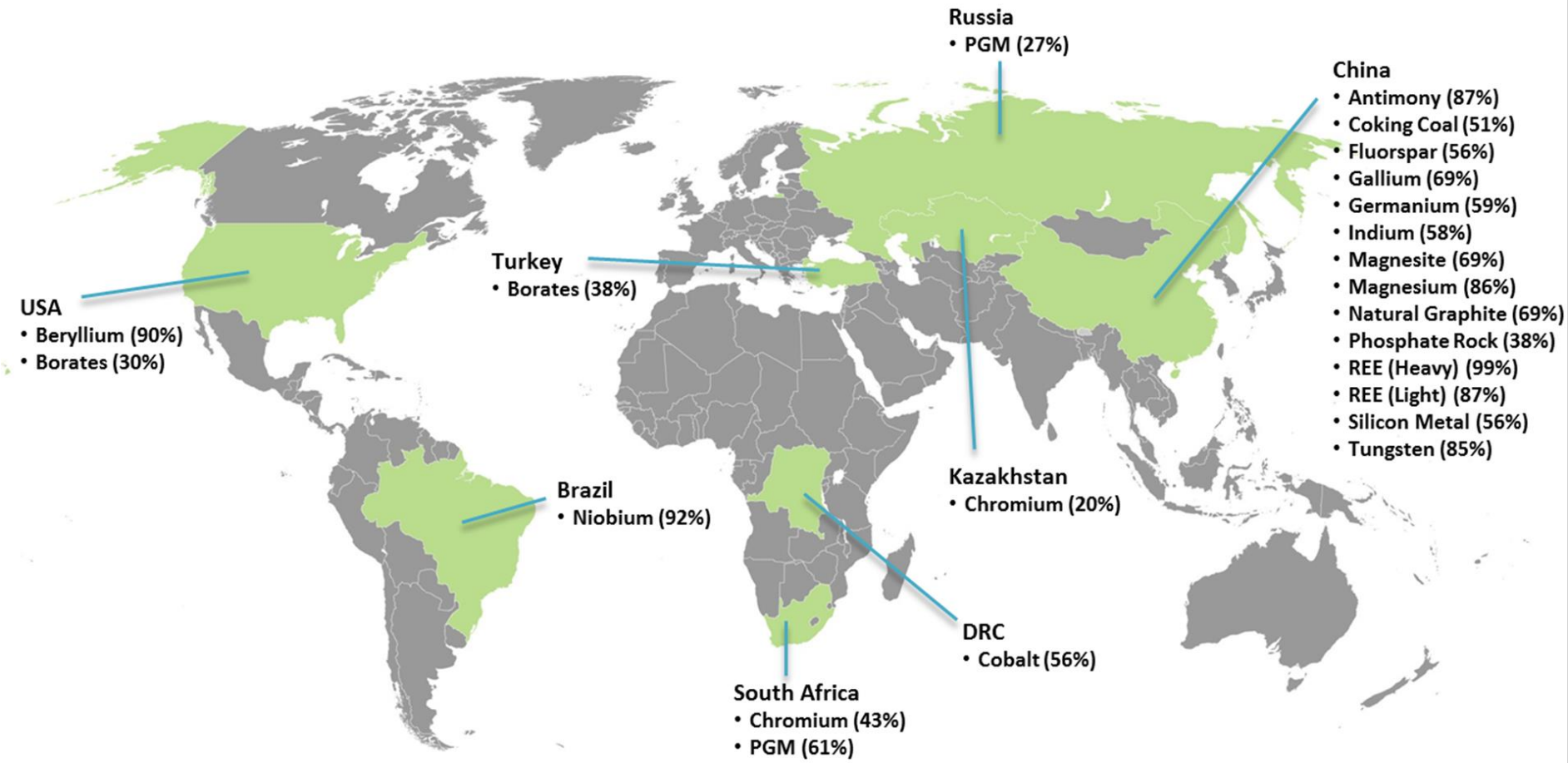
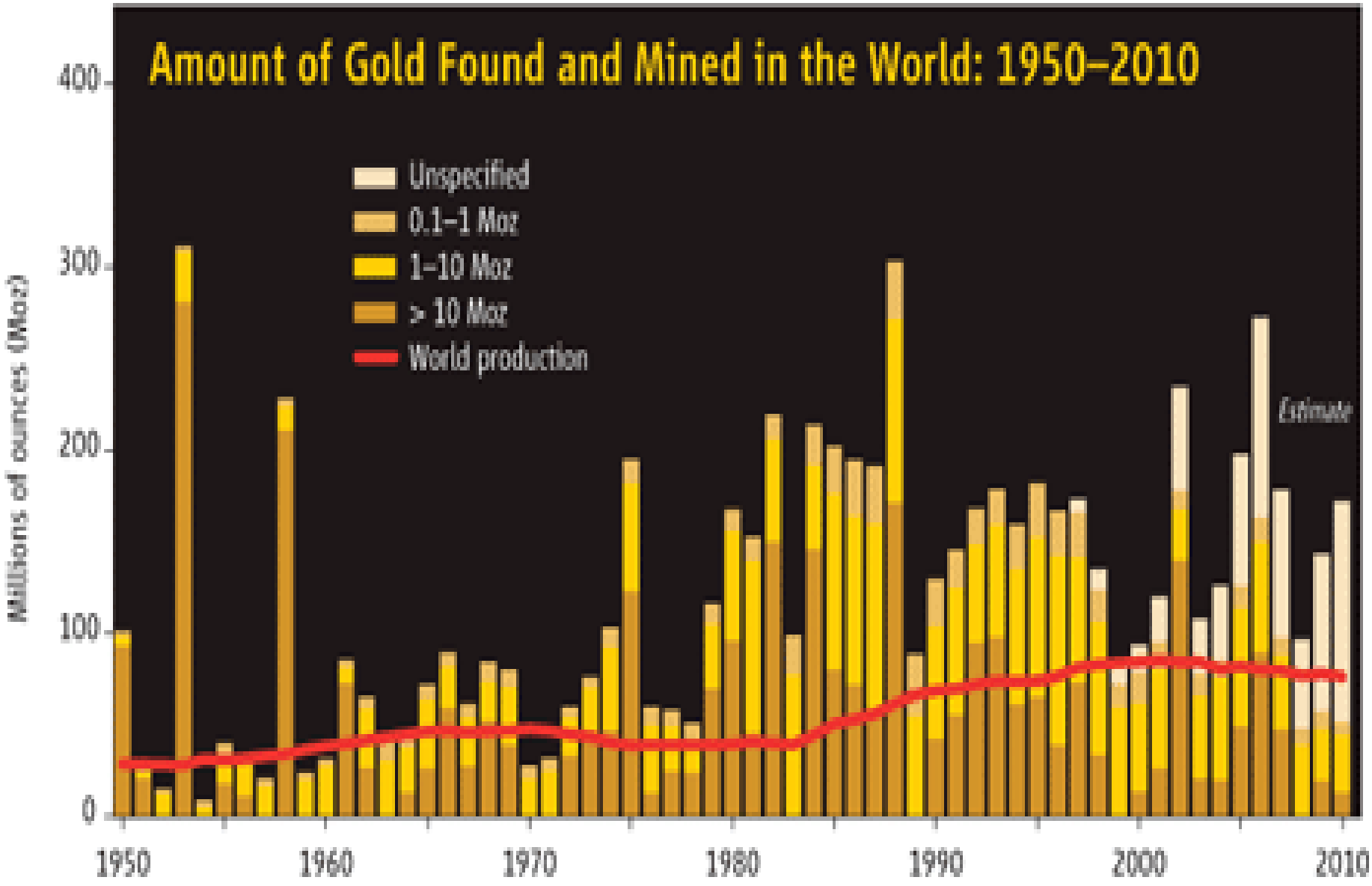


Criticality –
The quality, state, or degree of being of the highest importance

Critical minerals and their primary source countries (EU, 2014)

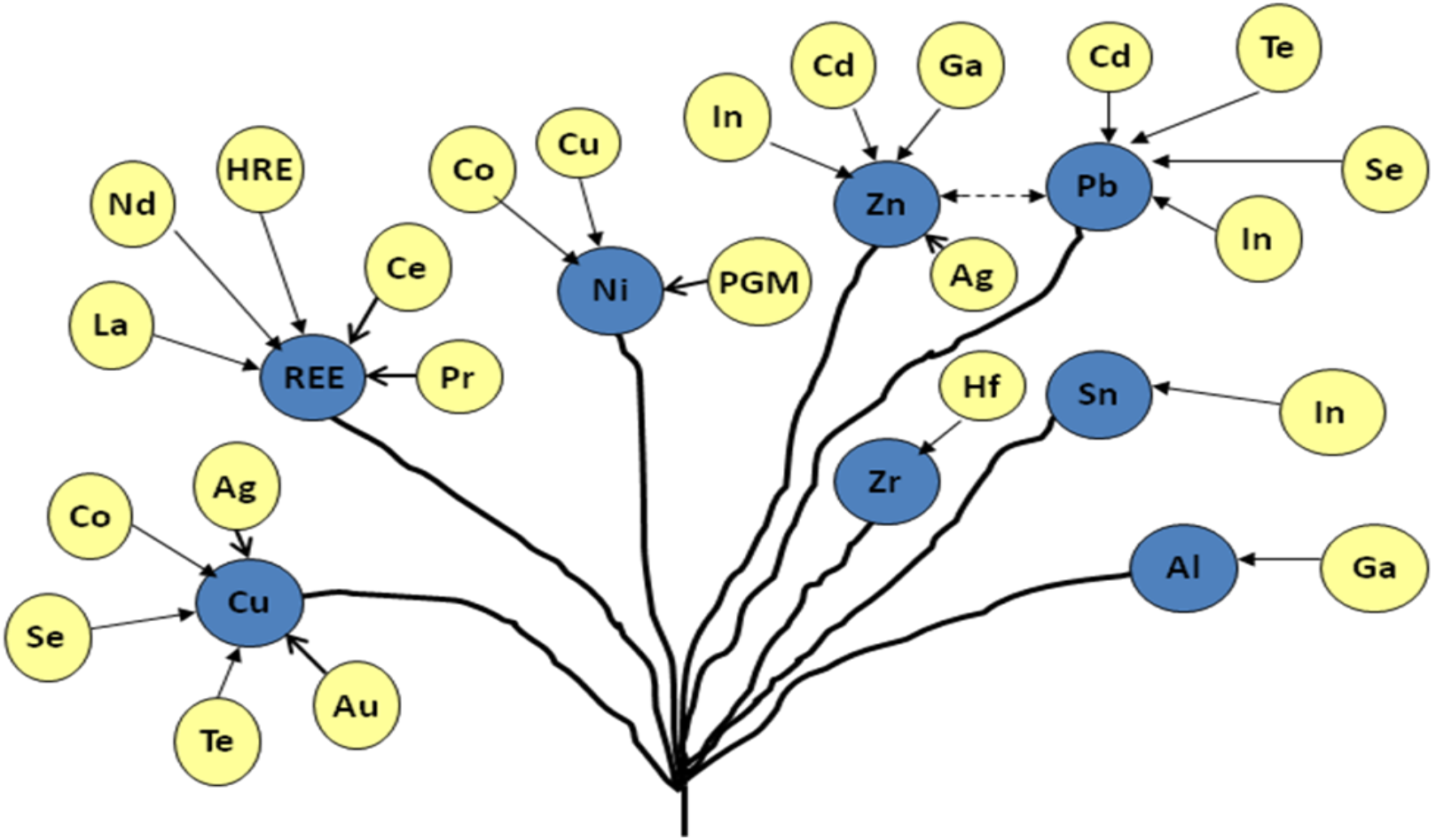


If we need more, why don't we mine more?

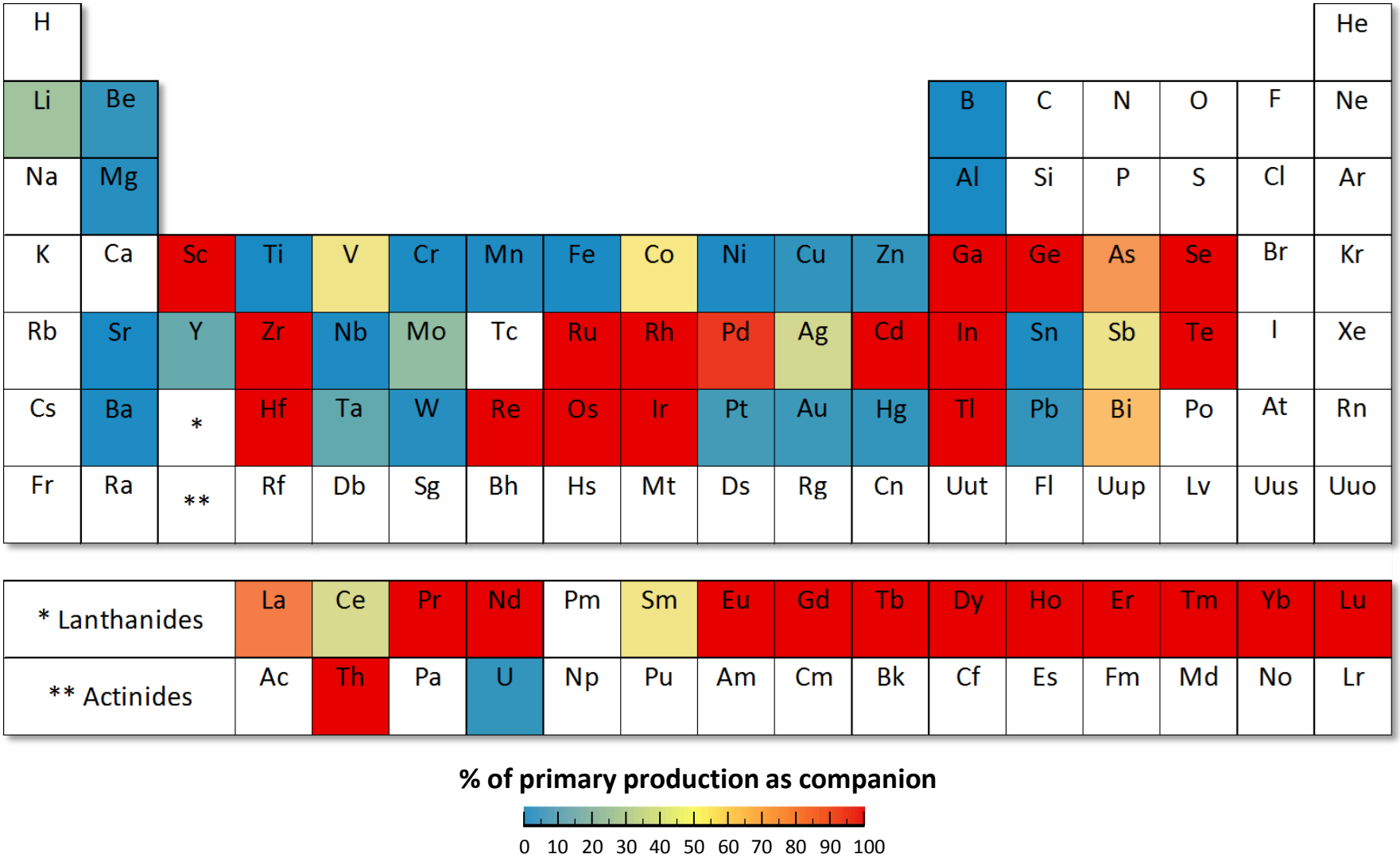


Source: Minex Consulting, 2011

The Host-Companion Flower Garden of Metals



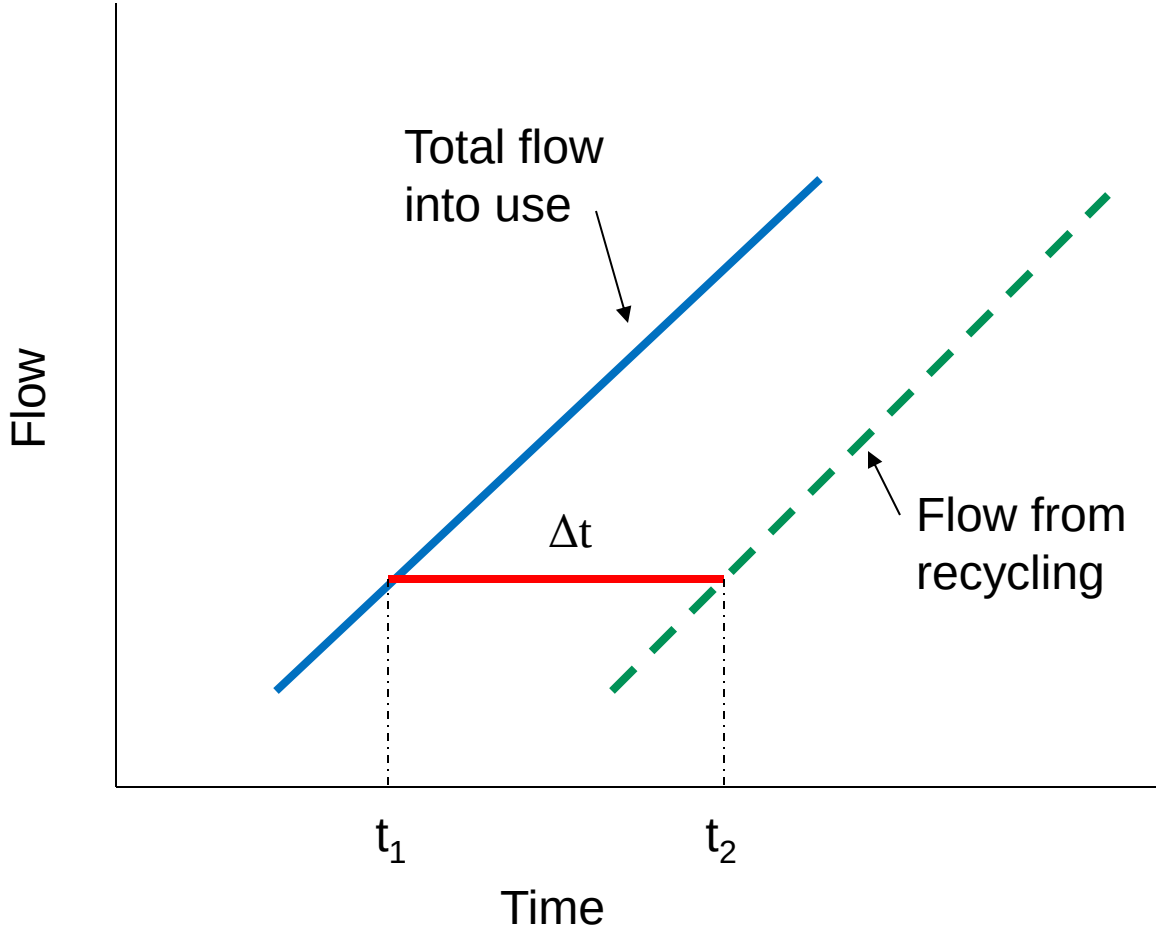
The “companionality” of metals



N. T. Nassar, et al., *Science Advances, 1*, e1400180 (2015)

If something is scarce,
why don’t we
recycle more?

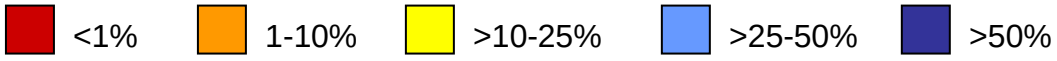
Contributions of Recycling in a Growing Economy



End-of-life recycling rates for sixty-two metals

1 H																2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	(117) (Uus)	118 Uuo

* **Lanthanides**	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
** **Actinides**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

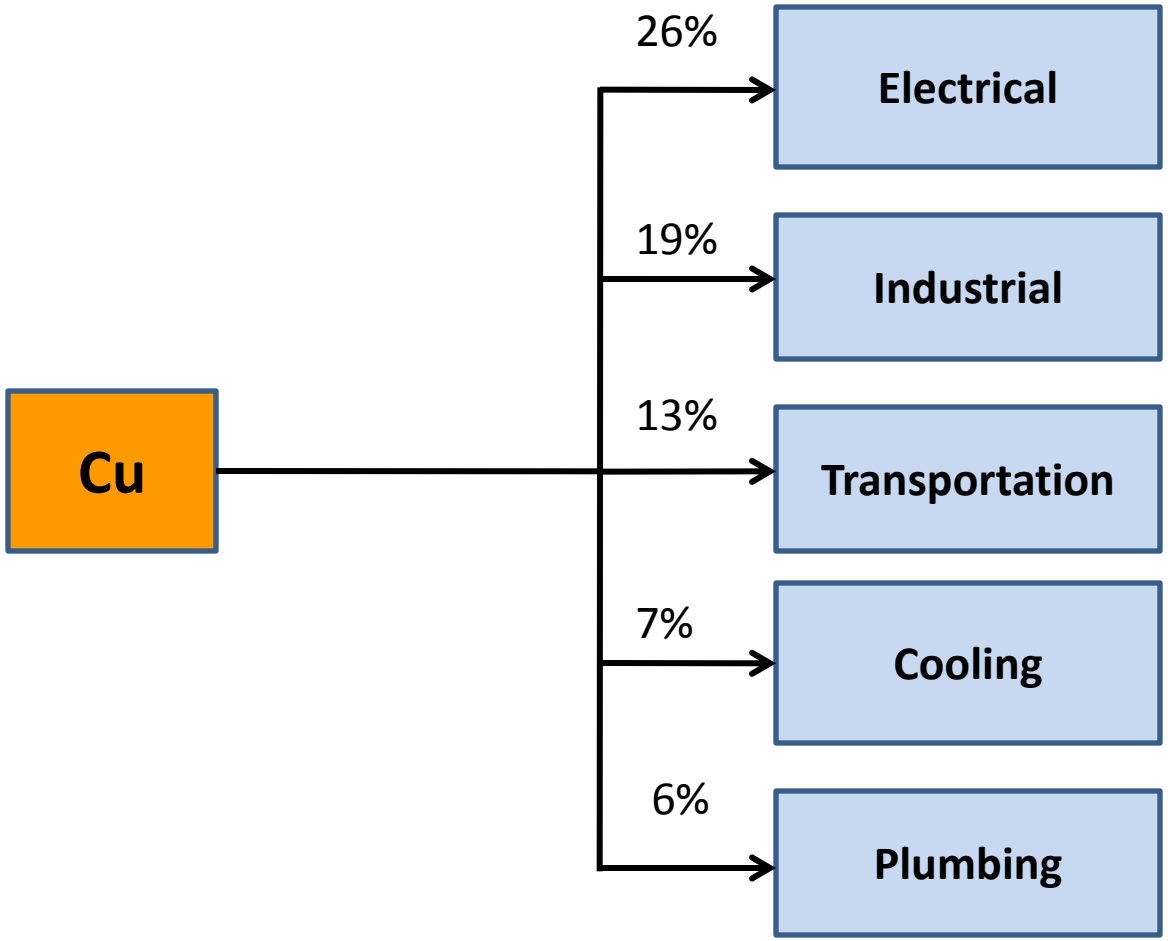


T. Graedel, et al., *Journal of Industrial Ecology, 15,* 355-366, 2011

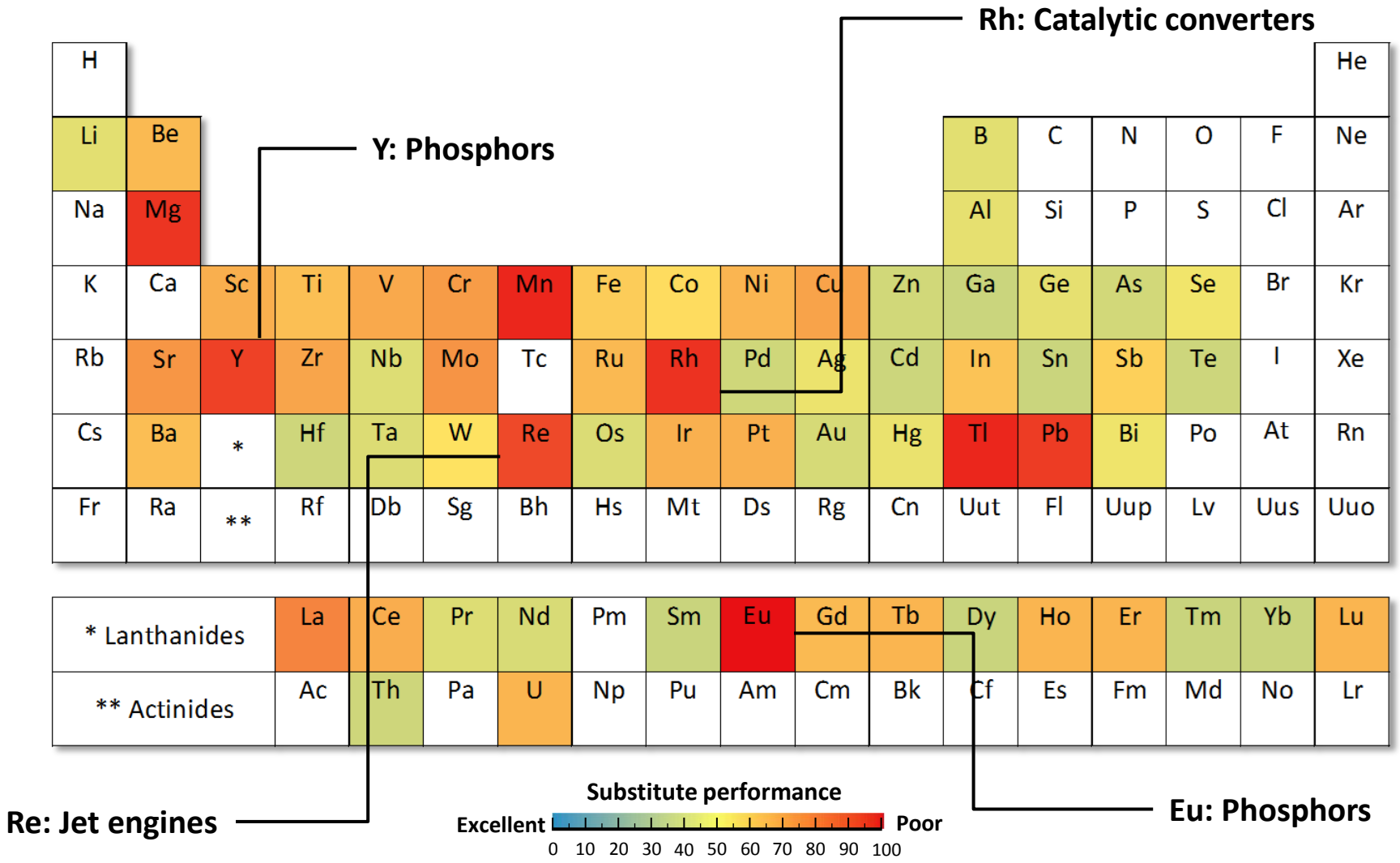
If something is scarce,
why don’t we
substitute something else?

Substitutability

Copper Example: Stage 1 – Identify Uses and Use Fractions

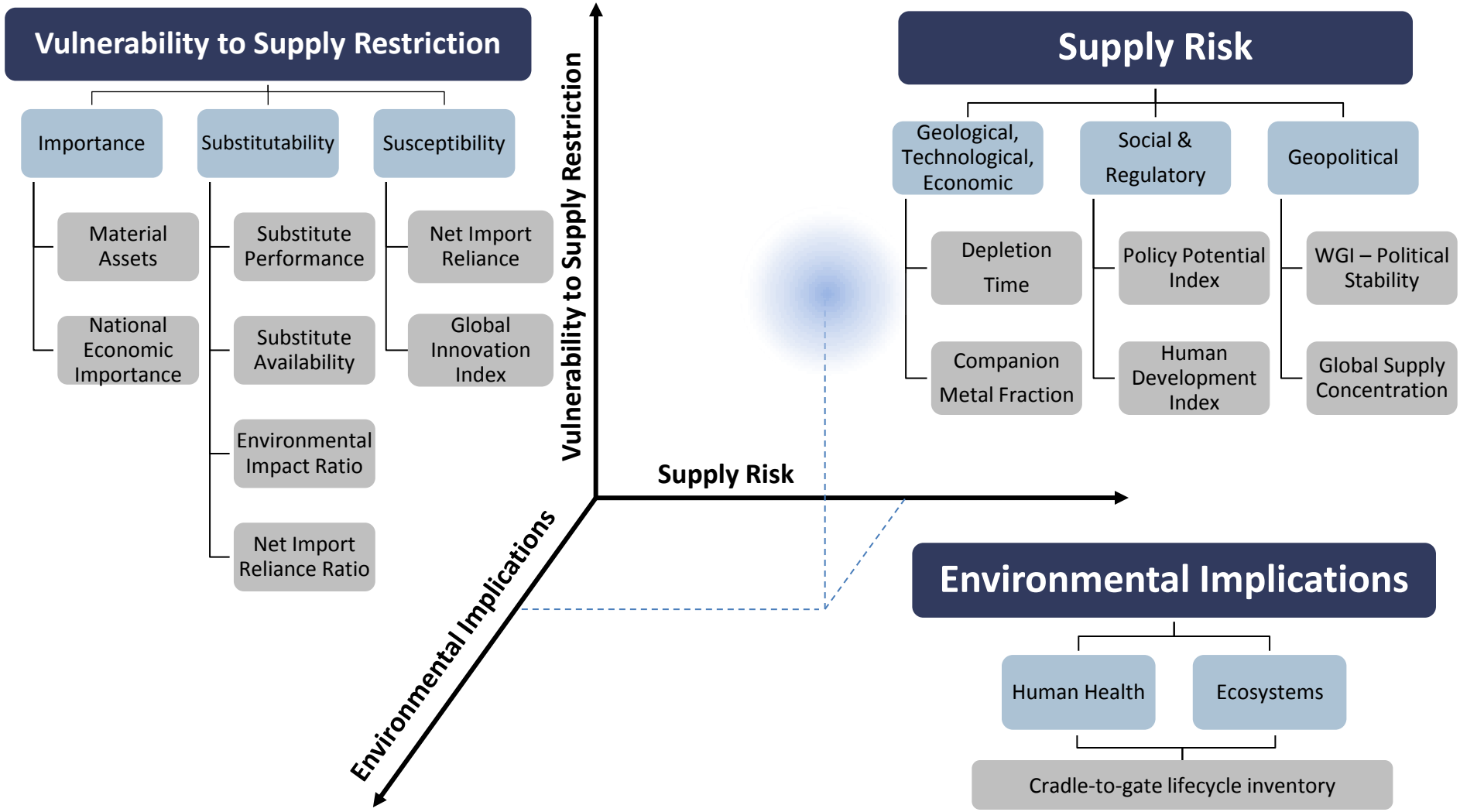


The degree of substitutability of metals in current applications



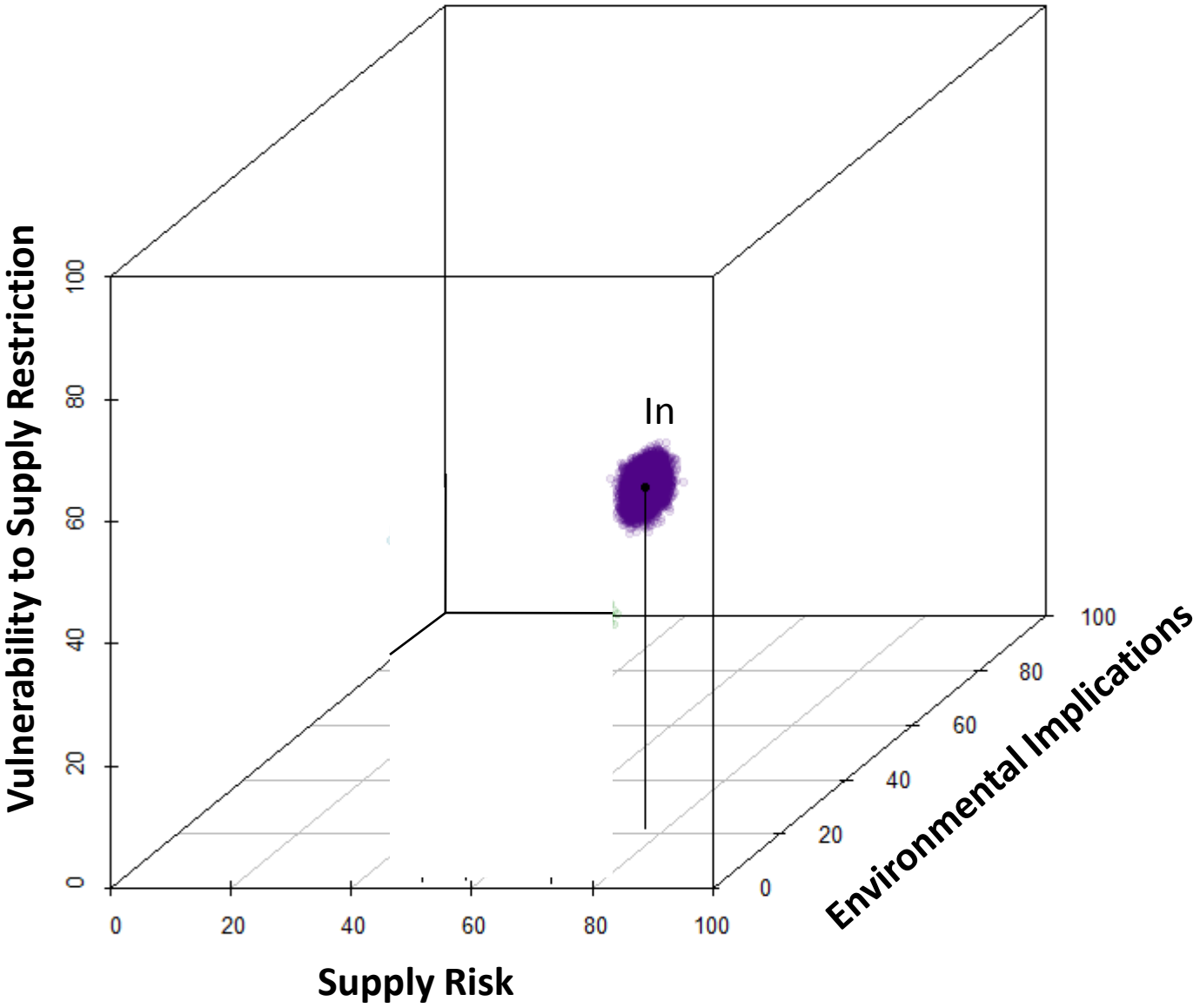
T.E. Graedel, et al., *Proceedings of the National Academy of Sciences of the U.S., 112*, 6295-6300, 2015

The Yale 3-Axis Approach to Criticality

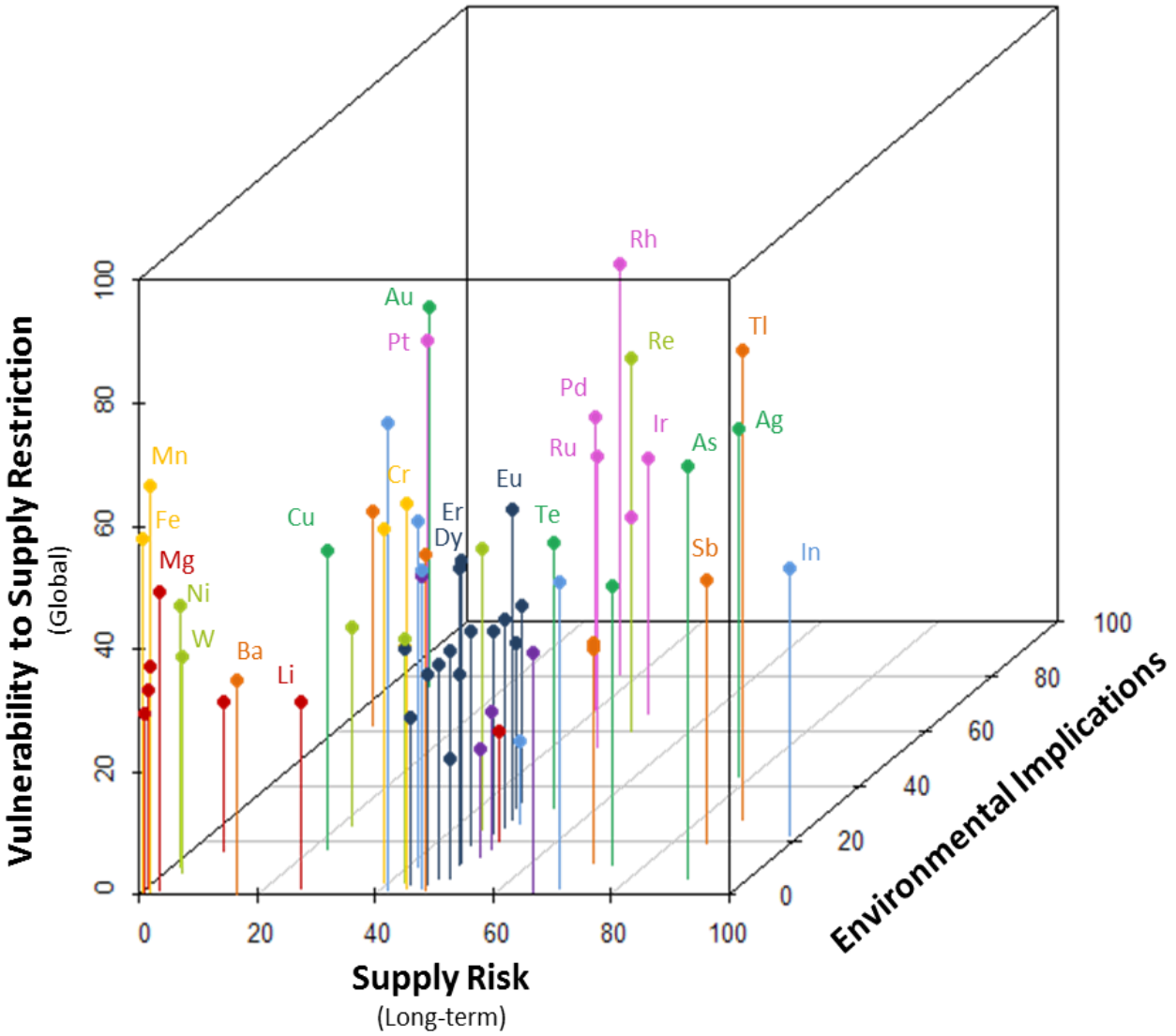


T.E. Graedel, et al., *Proceedings of the National Academy of Sciences of the U.S., 112*, 4257-4262, 2015

Indium criticality – global level

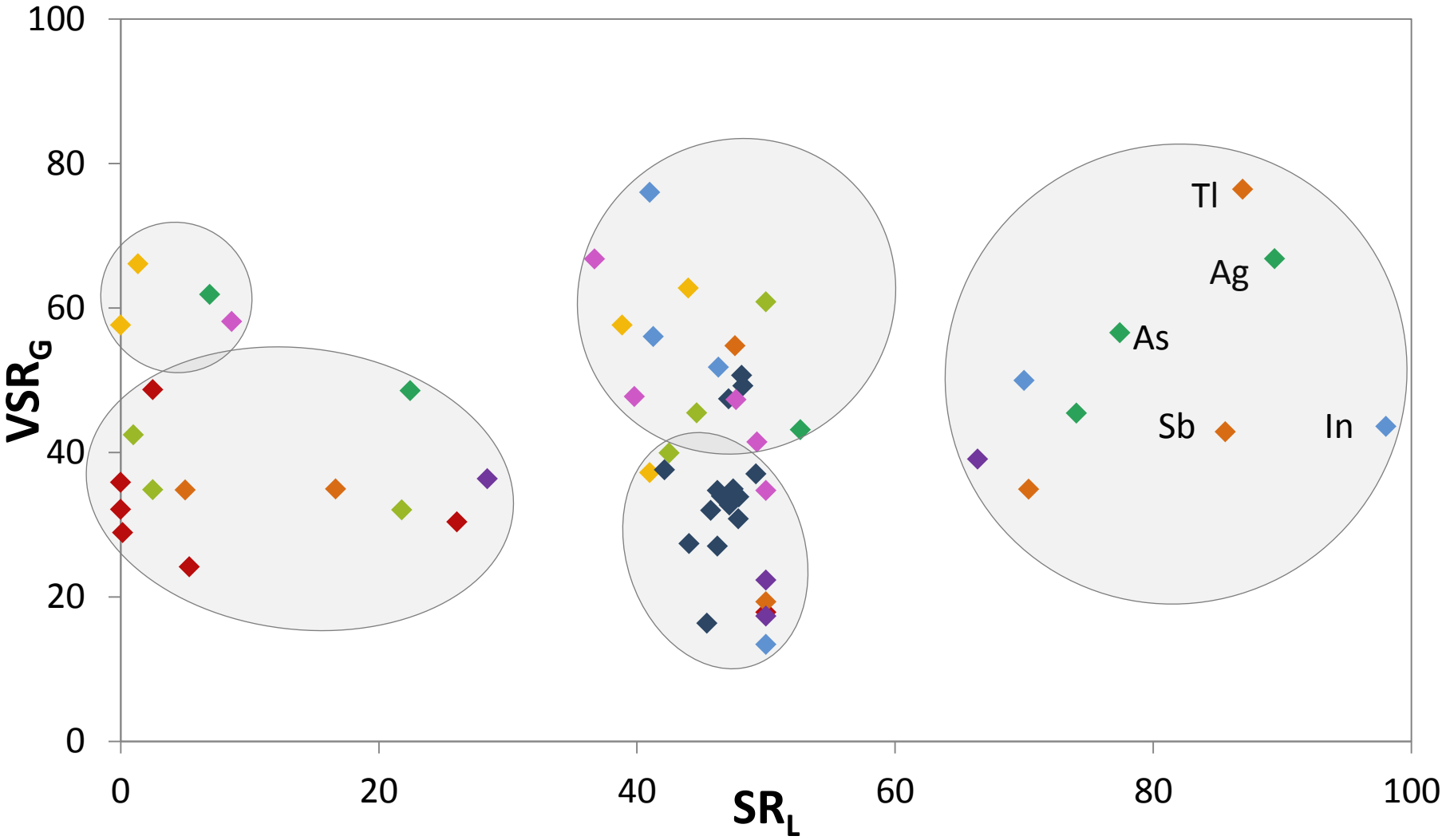


The three-dimensional criticality of the 62 metals of the periodic table

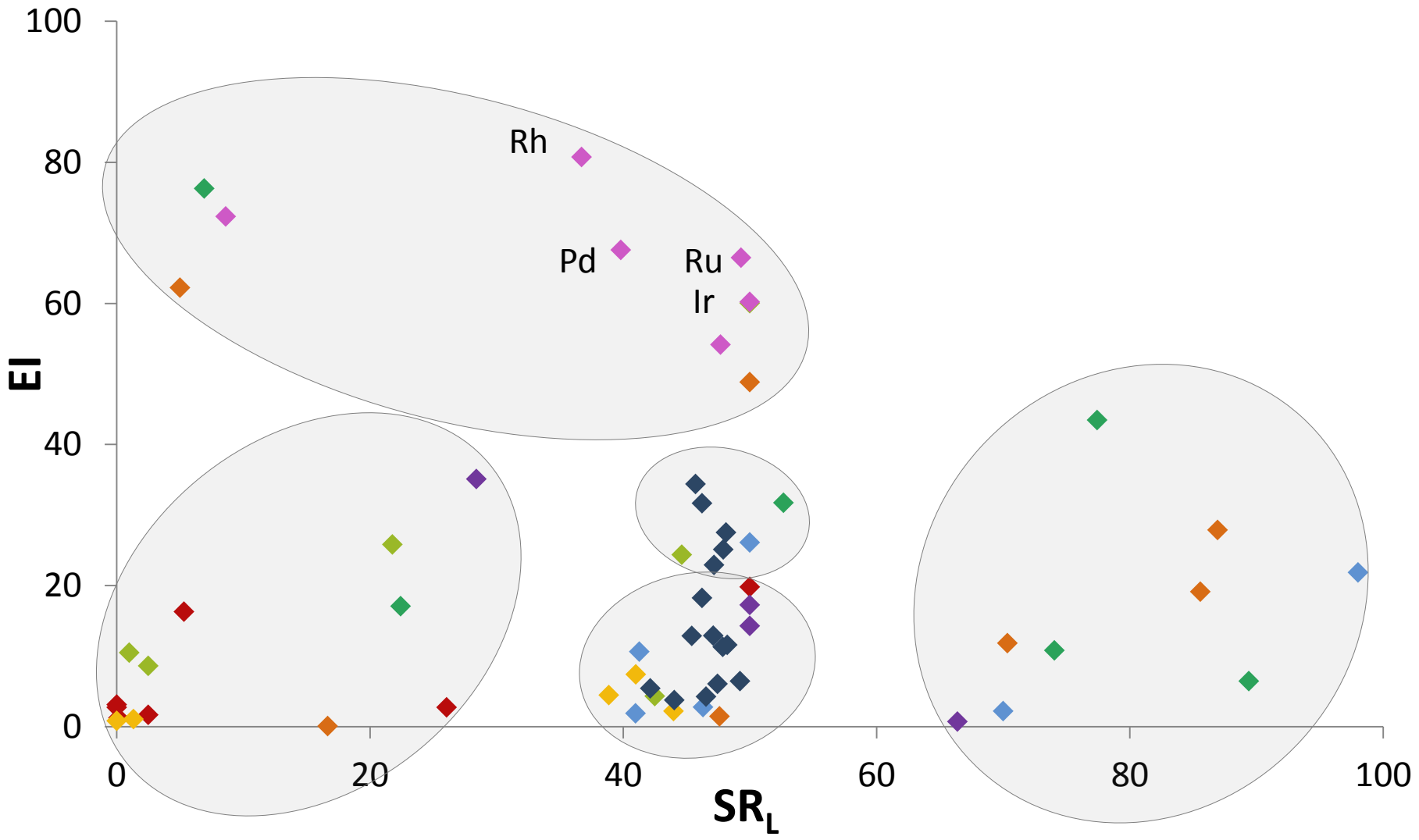


T.E. Graedel, et al., *Proceedings of the National Academy of Sciences of the U.S., 112*, 4257-4262, 2015

Global-Level Criticality Assessment: Supply Risk and Vulnerability Axes



Global-Level Criticality Assessment: Supply Risk and Environmental Axes



Characteristics of High Criticality

- Largely or entirely available only as a byproduct of more abundant metals
- Used in small quantities in specialized high-technology applications
- Has no suitable substitute or substitutes across its spectrum of uses

Summary

- In addressing the minerals availability issue, our Yale research group has completed evaluating the criticality of 62 metals at the global and US levels, including studies of substitutability, by-products, and recycling potential

- Aspects and users of criticality evaluations are too diverse for there to be a single list of “critical” or “not critical” materials

- Nonetheless, over the next 2-3 decades, the biggest challenges appear to be for the specialty “byproduct” metals, rather than for the major metals with which we are most familiar