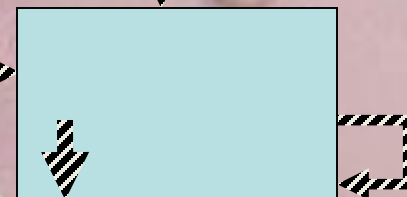




## Element Cycles and Criticality : A Focus on Minor Metals

Thomas E. Graedel

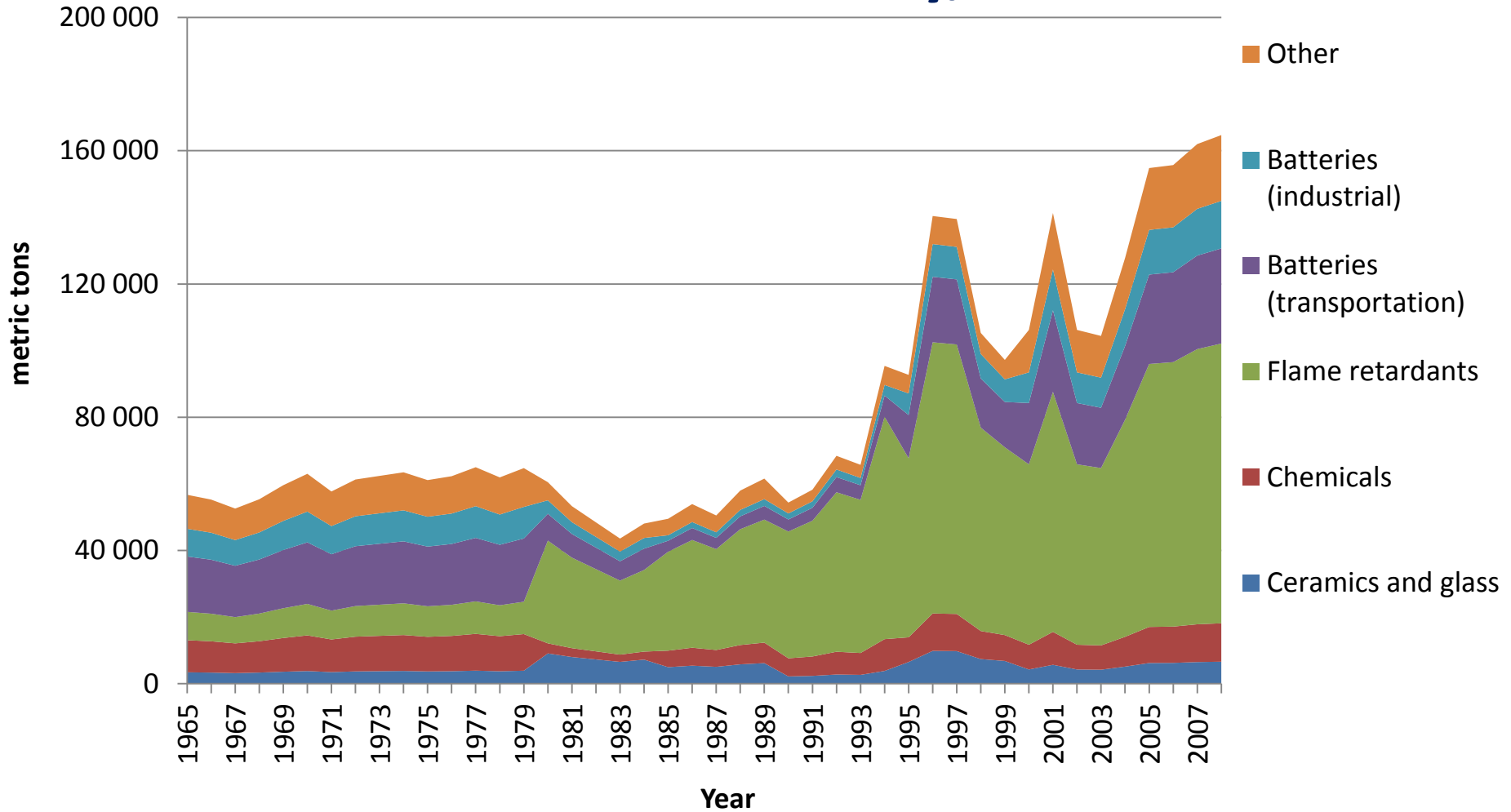
Yale University



# Important Points About Minor Metals

- Minor (or “specialty”) metals are vital to many modern technologies, as shown by their fast-changing uses
- Minor metals are mostly available only as by-products
- Minor metals have few good substitutes
- Minor metals have very low end-of-life recycling rates
- Minor metals have high levels of criticality compared with most more common metals

# Global Uses of Antimony, 1965-2009



# Elements Addressed in the Yale Criticality Project

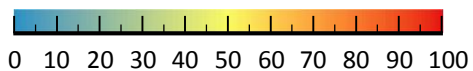
1 H																	2 He															
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne															
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar															
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr															
37 Rb	38 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	57-71 lanthanoids	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	89-103 actinoids	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	114 Fl		116 Lv																		
																		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
																		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

# The “companionality” of metals: the production of many metals is dependent on the production of carrier metals

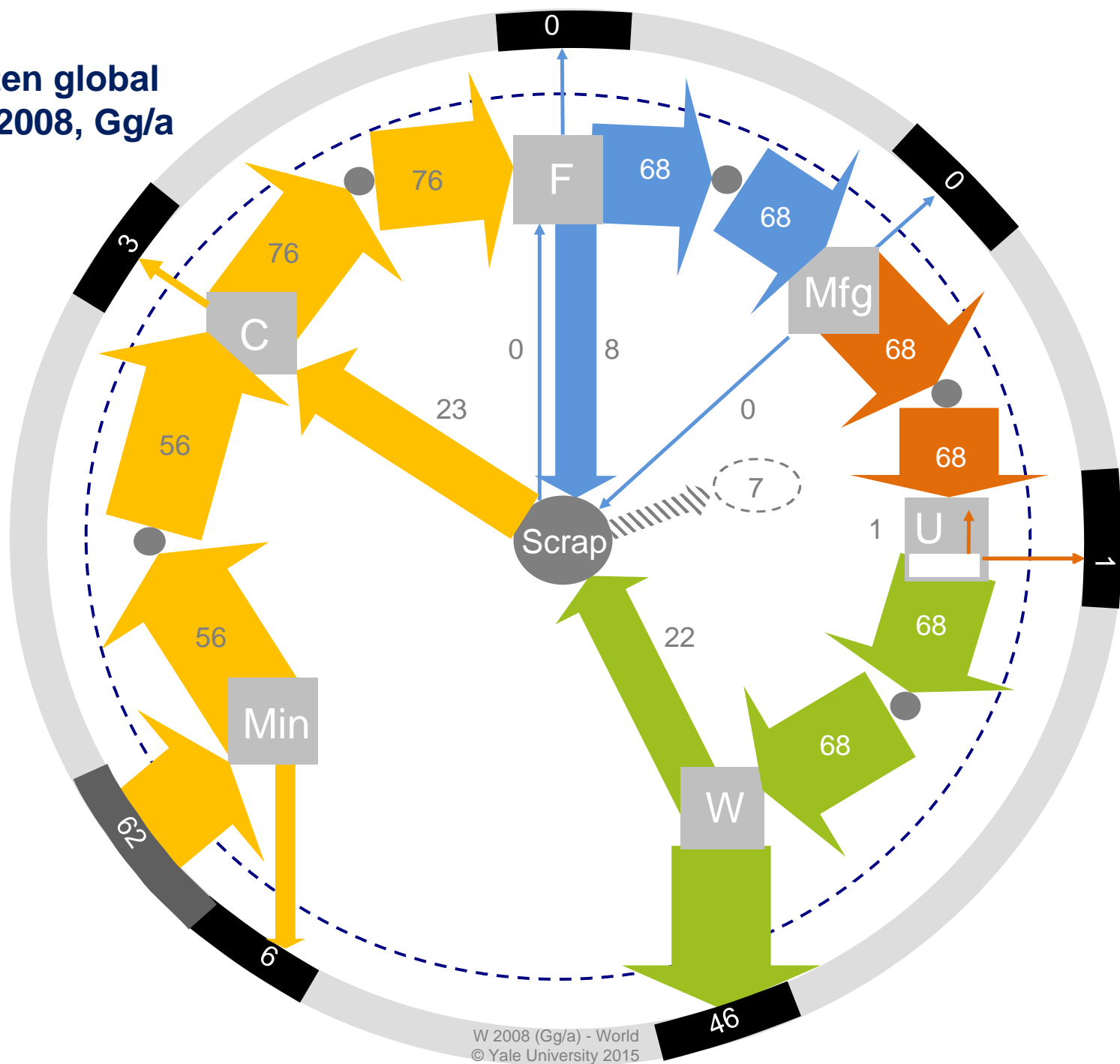
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	**	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Fl	Uup	Lv	Uus	Uuo

* Lanthanides	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
** Actinides	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

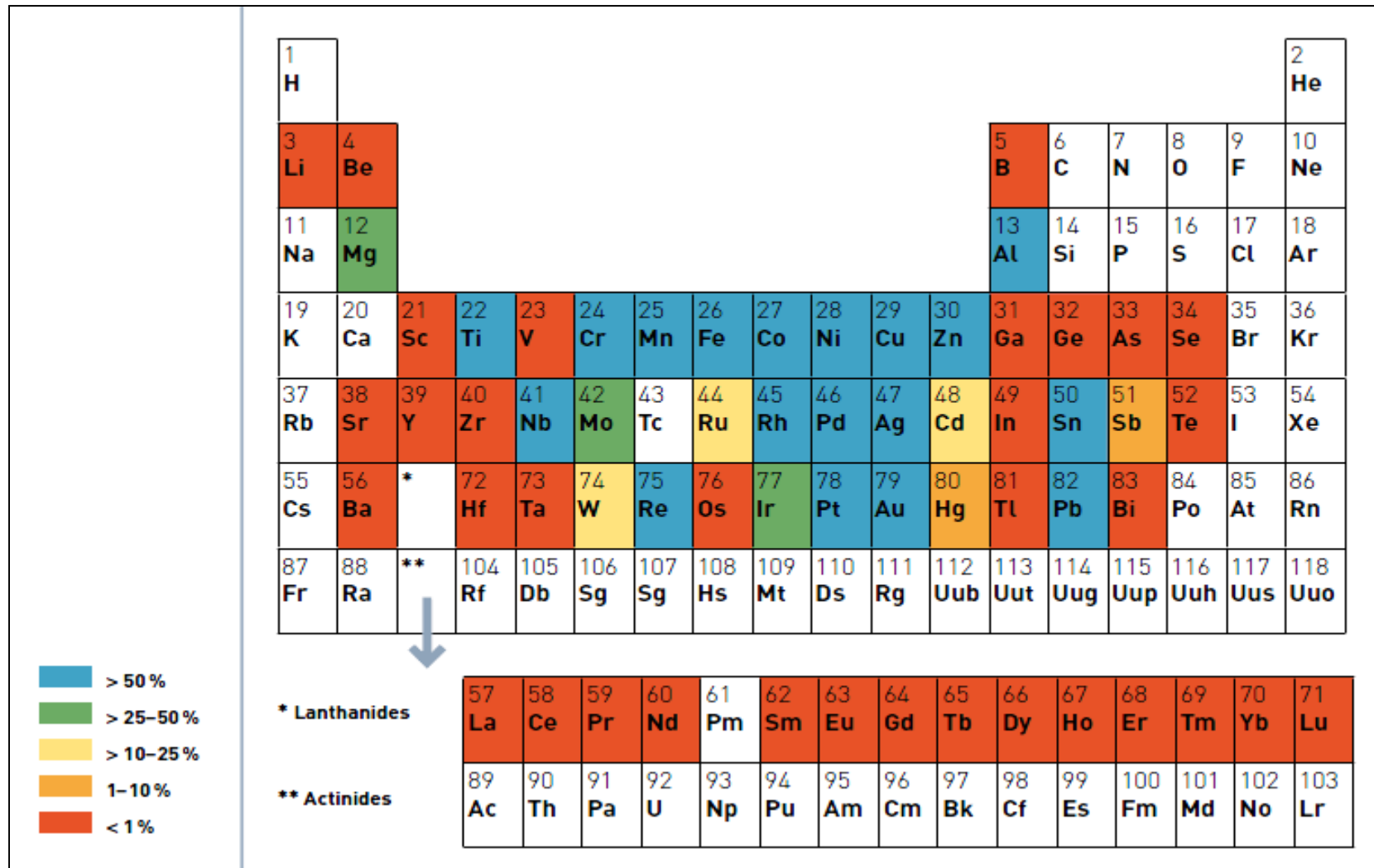
**% of primary production as companion**



# Tungsten global cycle, 2008, Gg/a

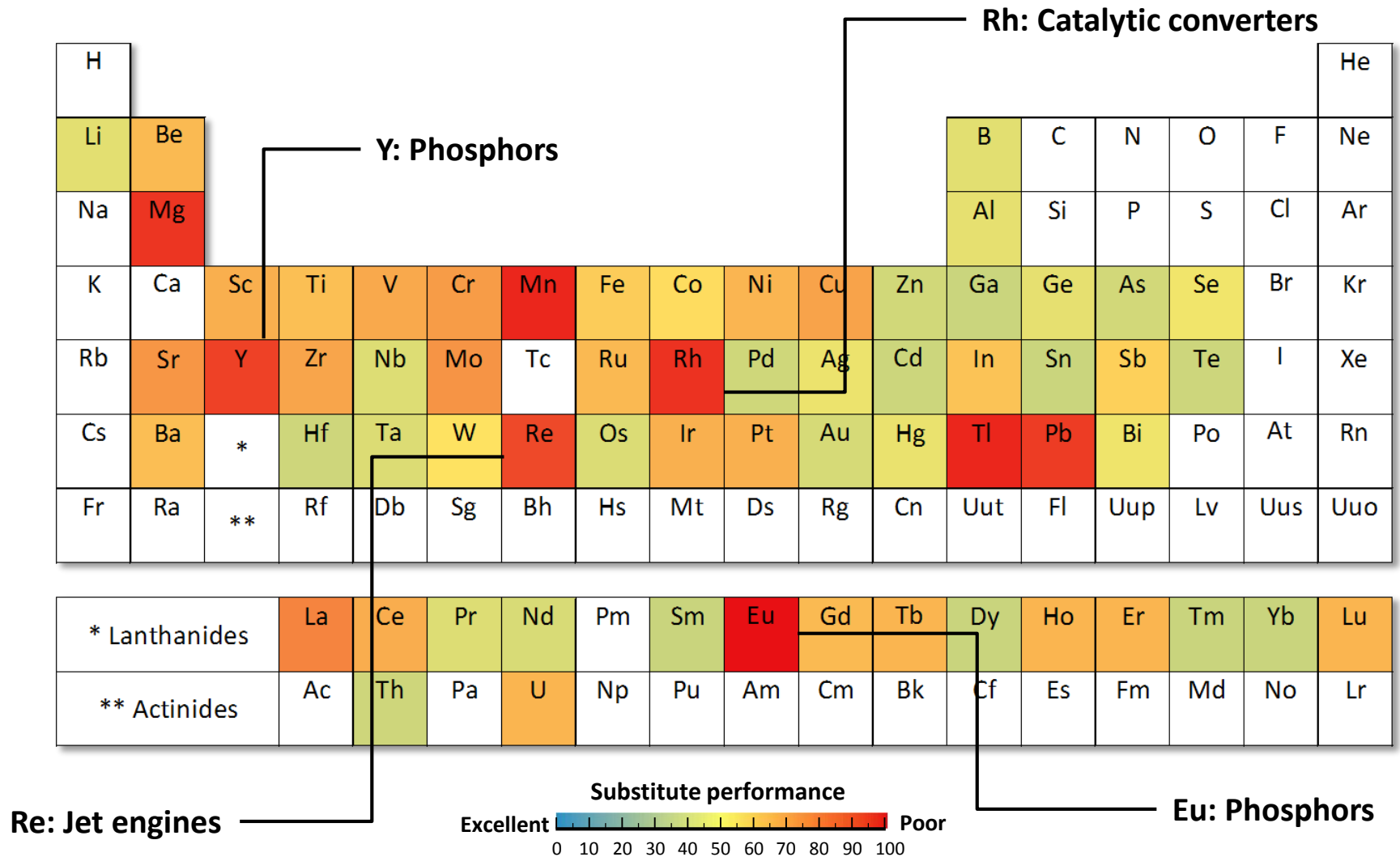


# End-of-life recycling rates of metals



(UNEP, *Recycling rates of metals*, 2011)

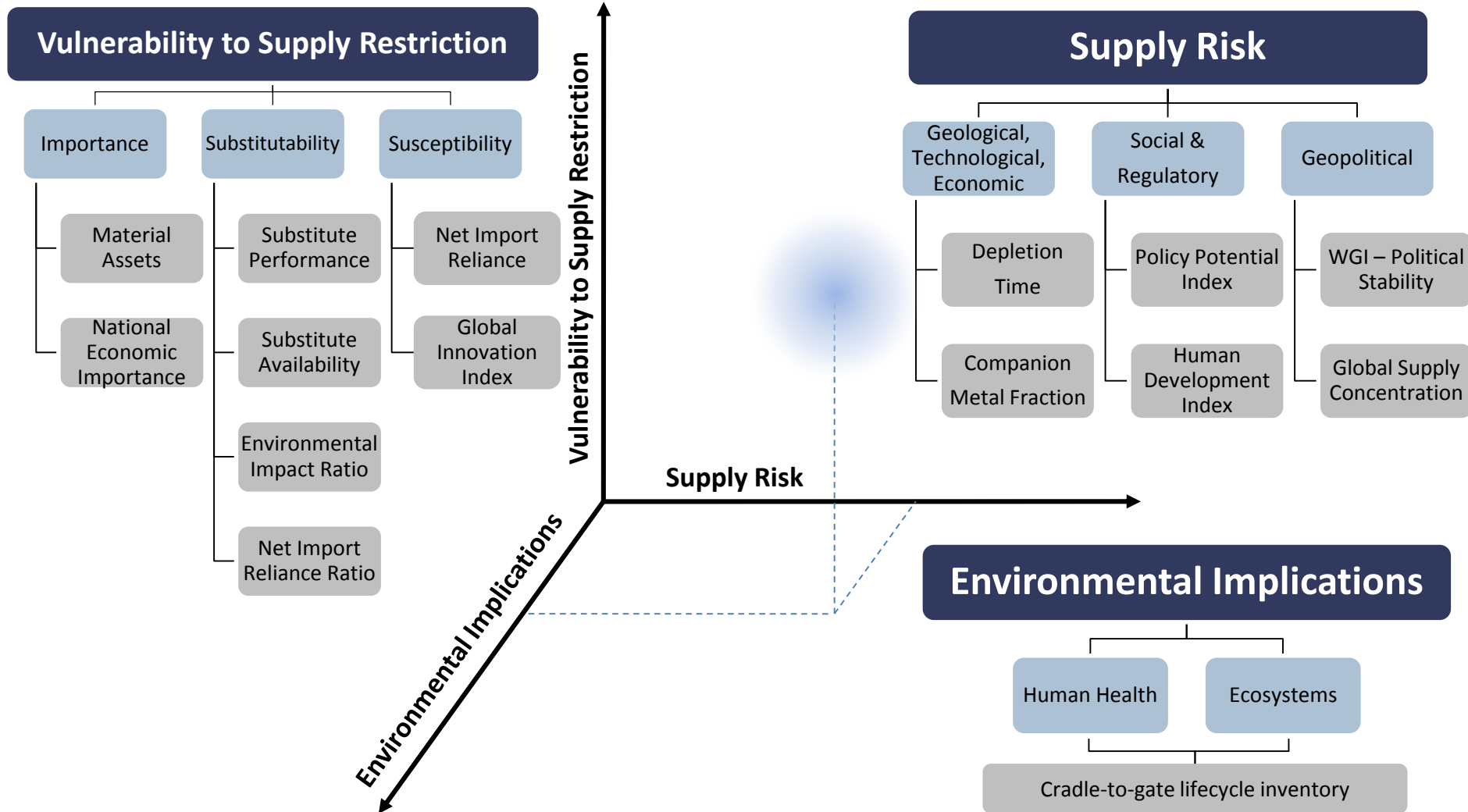
# The substitutability of metals



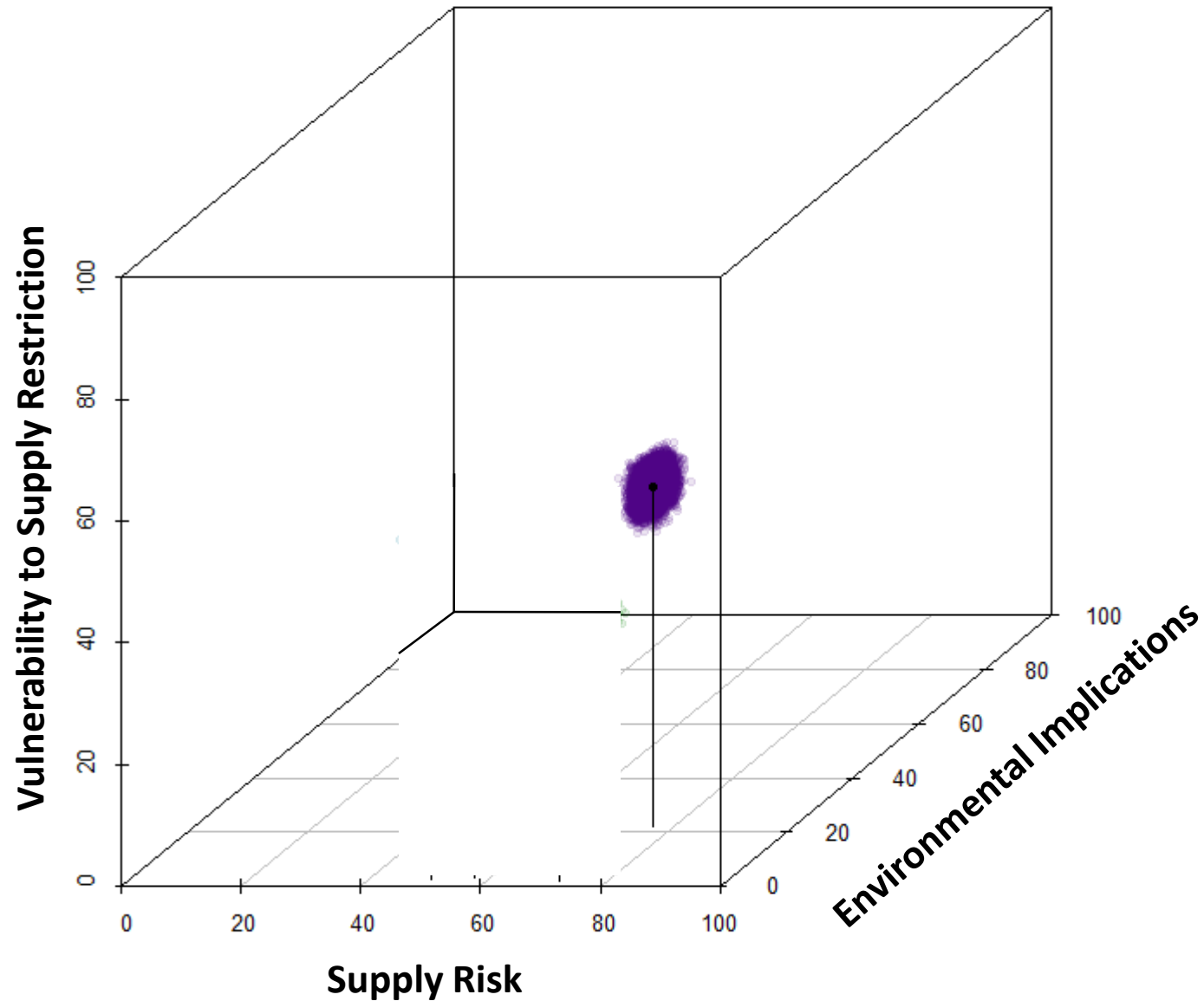


**Criticality –**  
**The quality, state, or degree**  
**of being of the highest**  
**importance**

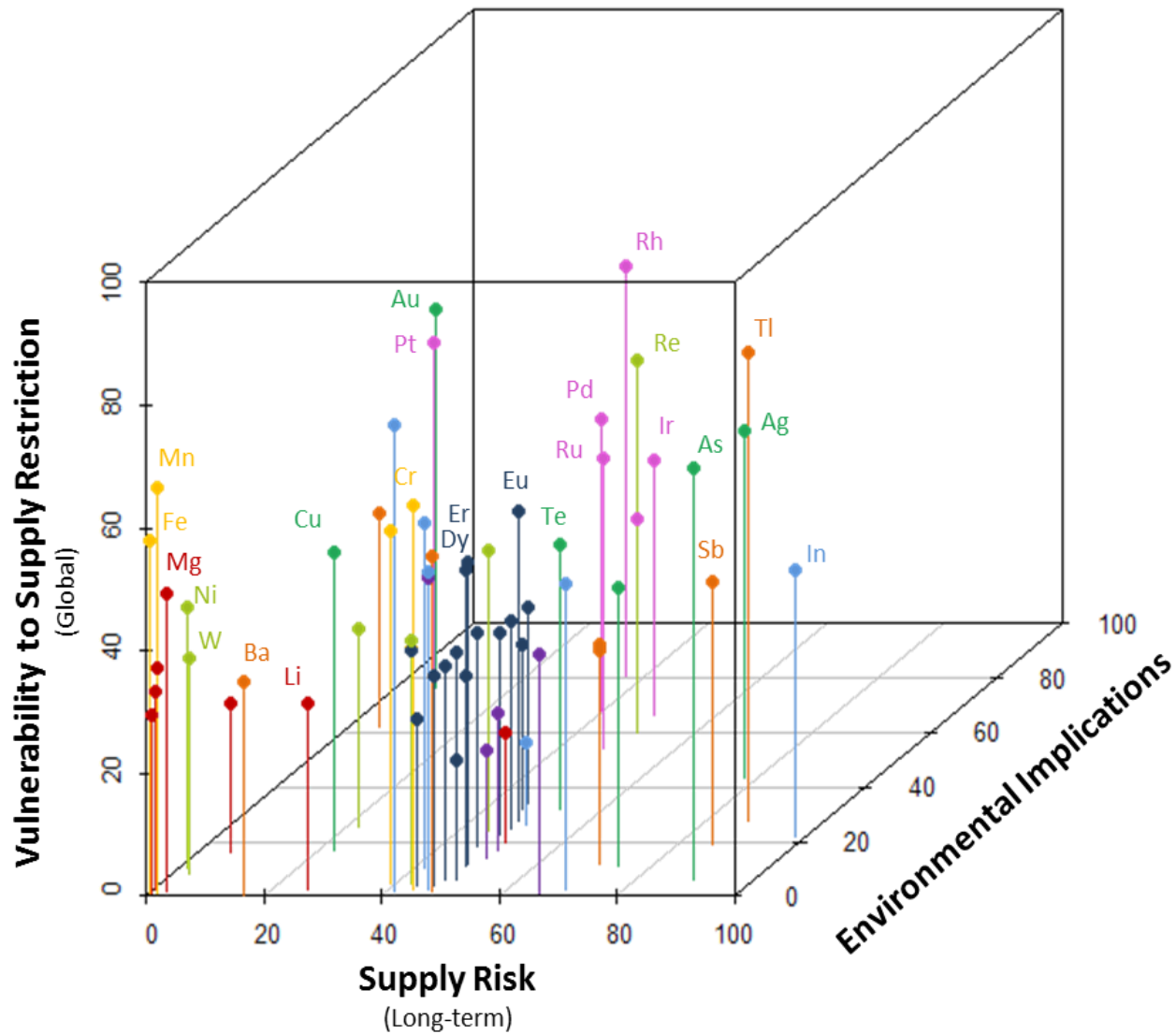
# The 3-Axis Approach to Criticality



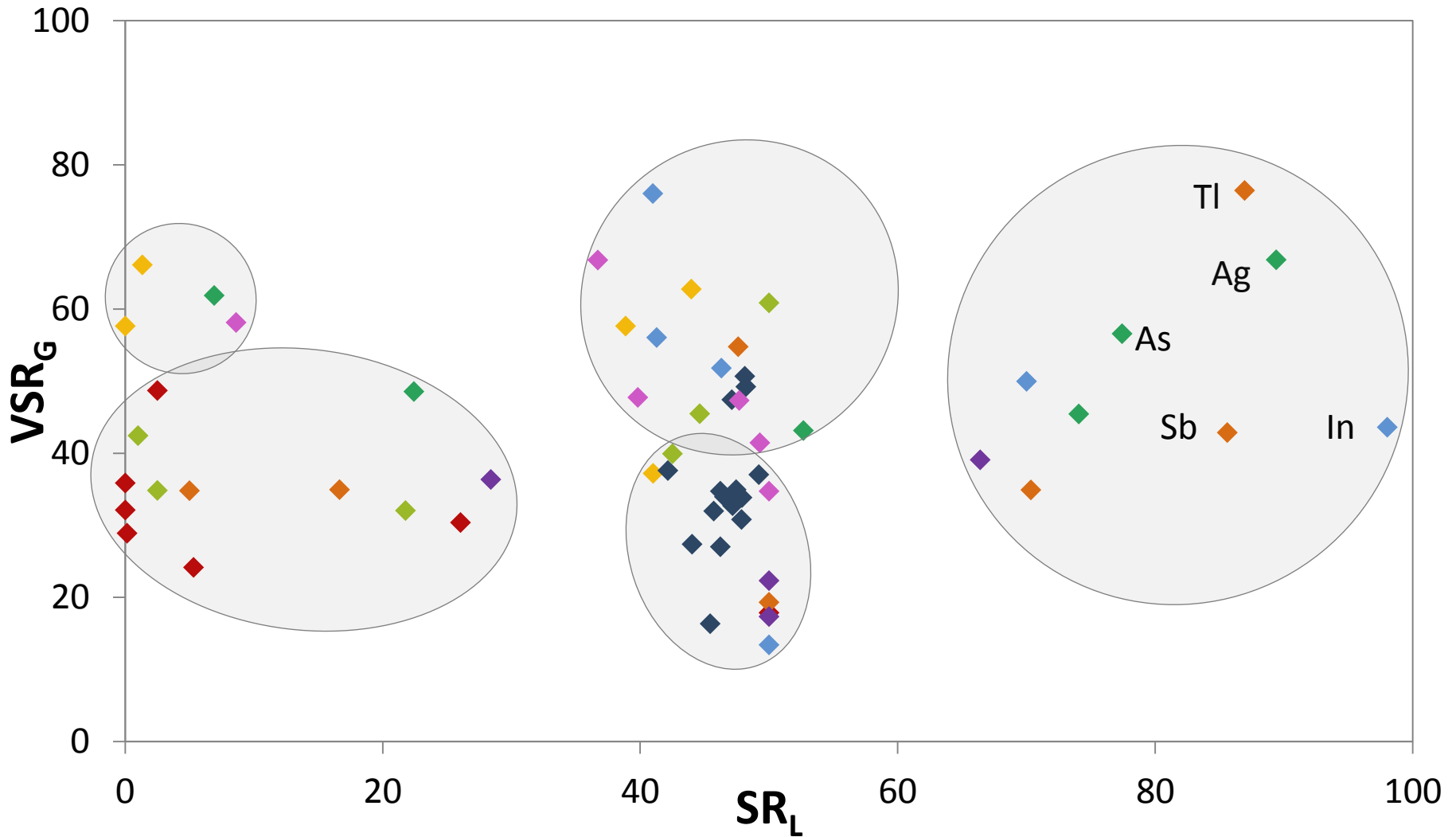
# Silver criticality – global level



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

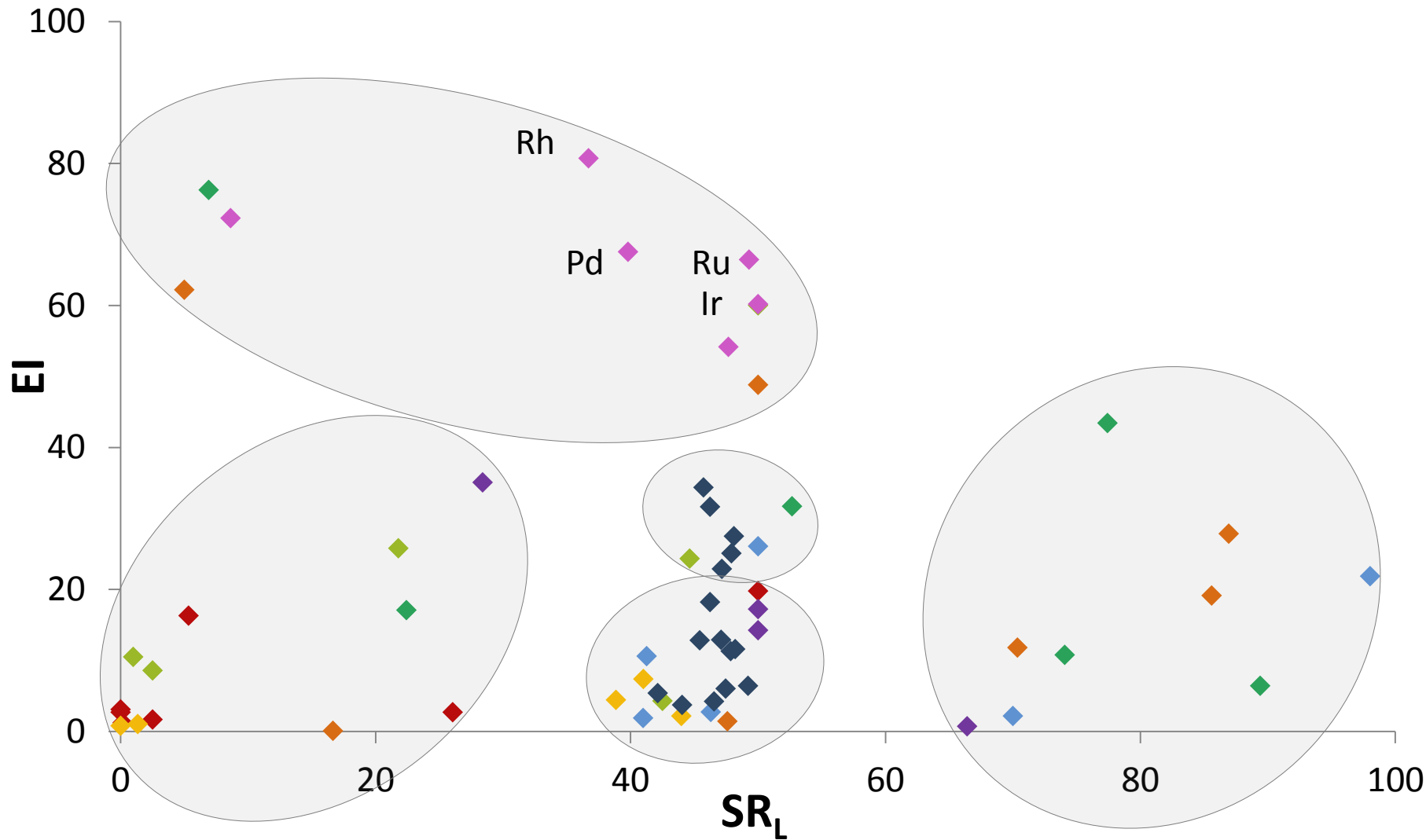


# Global-Level Criticality Assessment: Supply Risk and Vulnerability Axes



- Light metals
- Specialty metals
- Iron & its principal alloying elements
- Superalloy metals
- Copper group
- Zinc, tin, lead group
- Rare earth elements
- Nuclear energy metals
- Platinum-group metals

# Global-Level Criticality Assessment: Supply Risk and Environmental Axes



- Light metals
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# Characteristics of High Criticality

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

# A Thought to Take With You

By-product metals rank quite high in long-term criticality. Their recovery from ores (and long-term storage, if necessary) should be strongly encouraged lest modern technology become strongly constrained