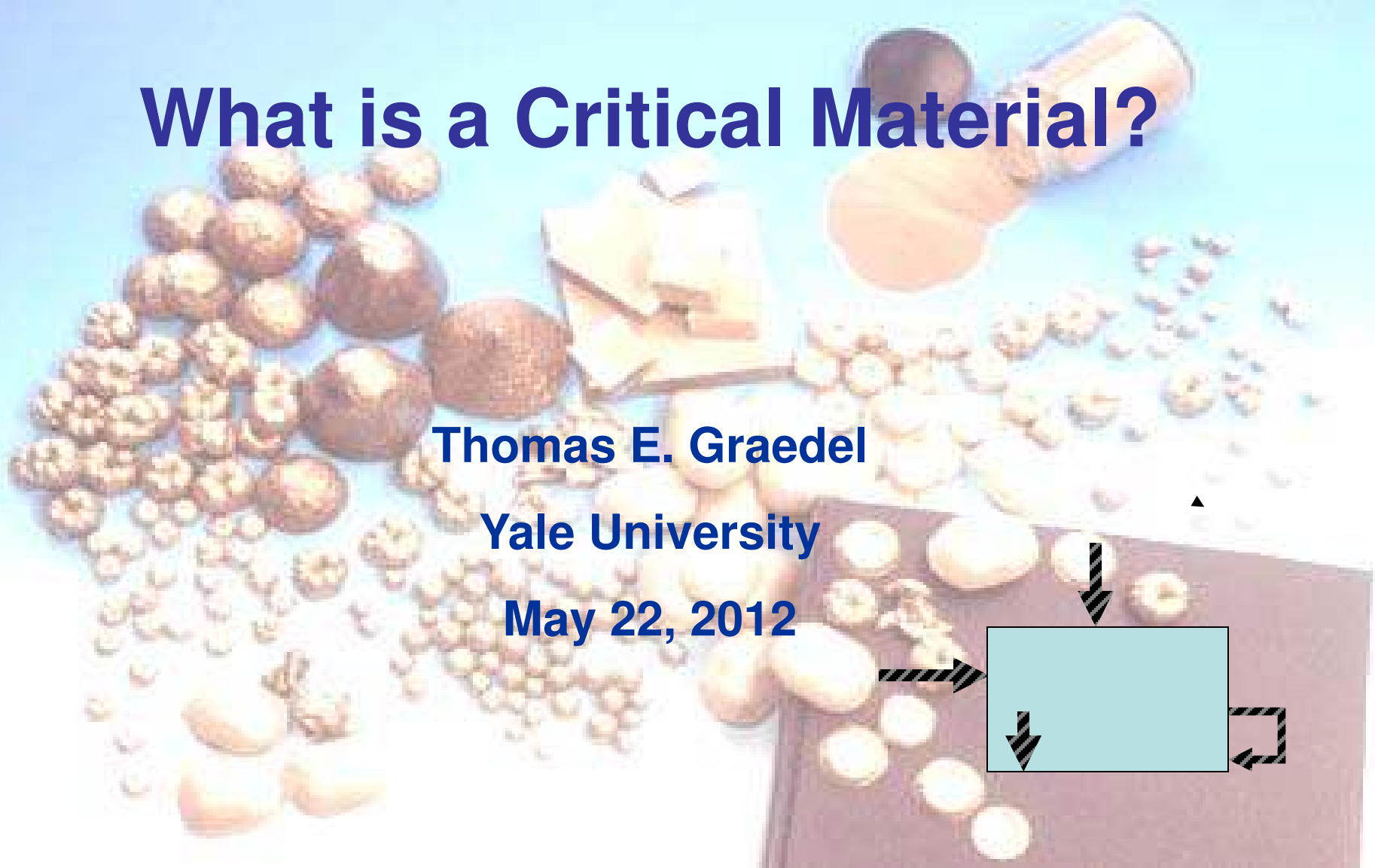


## What is a Critical Material?

Thomas E. Graedel

Yale University

May 22, 2012



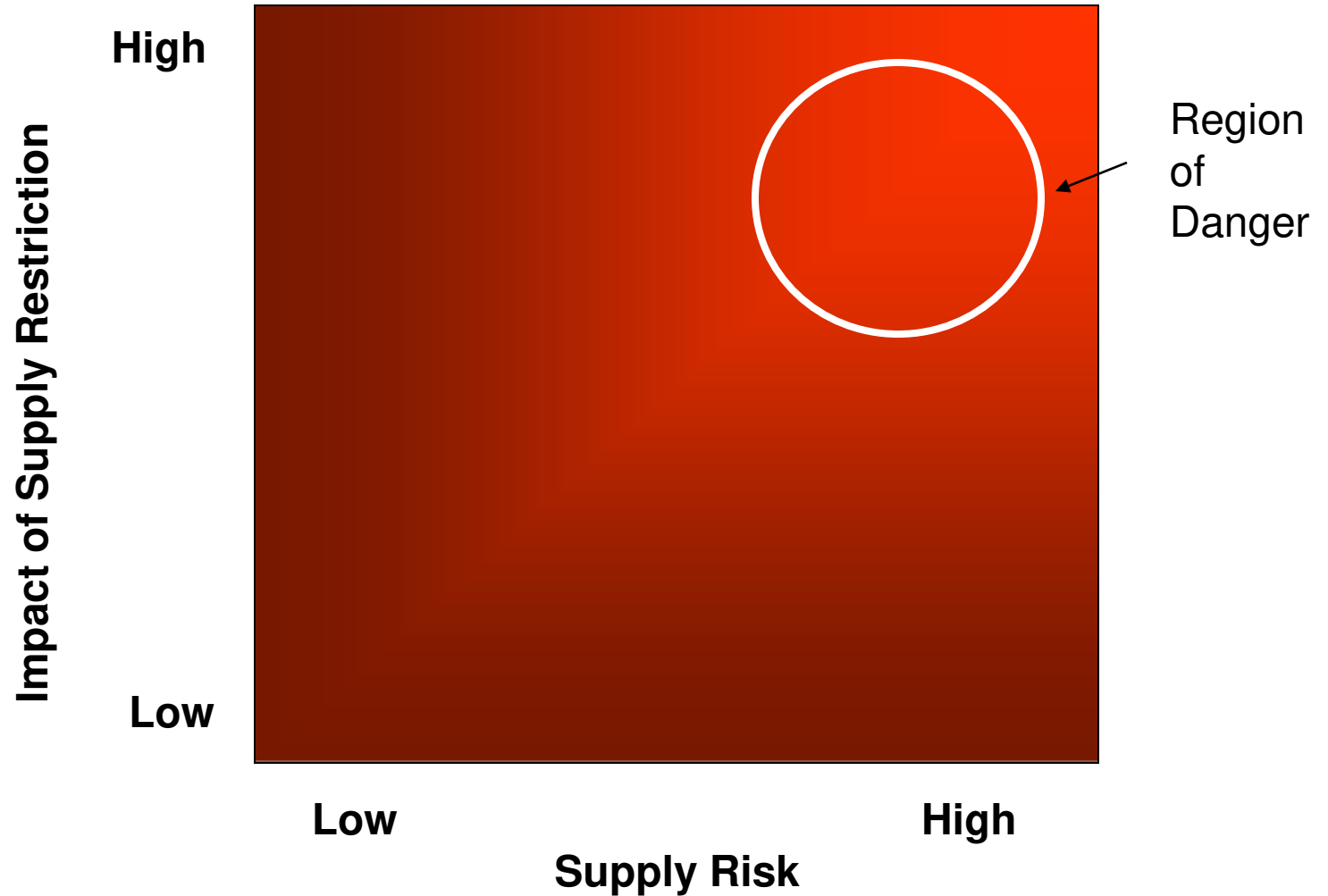


# Random Results in Criticality Assessment

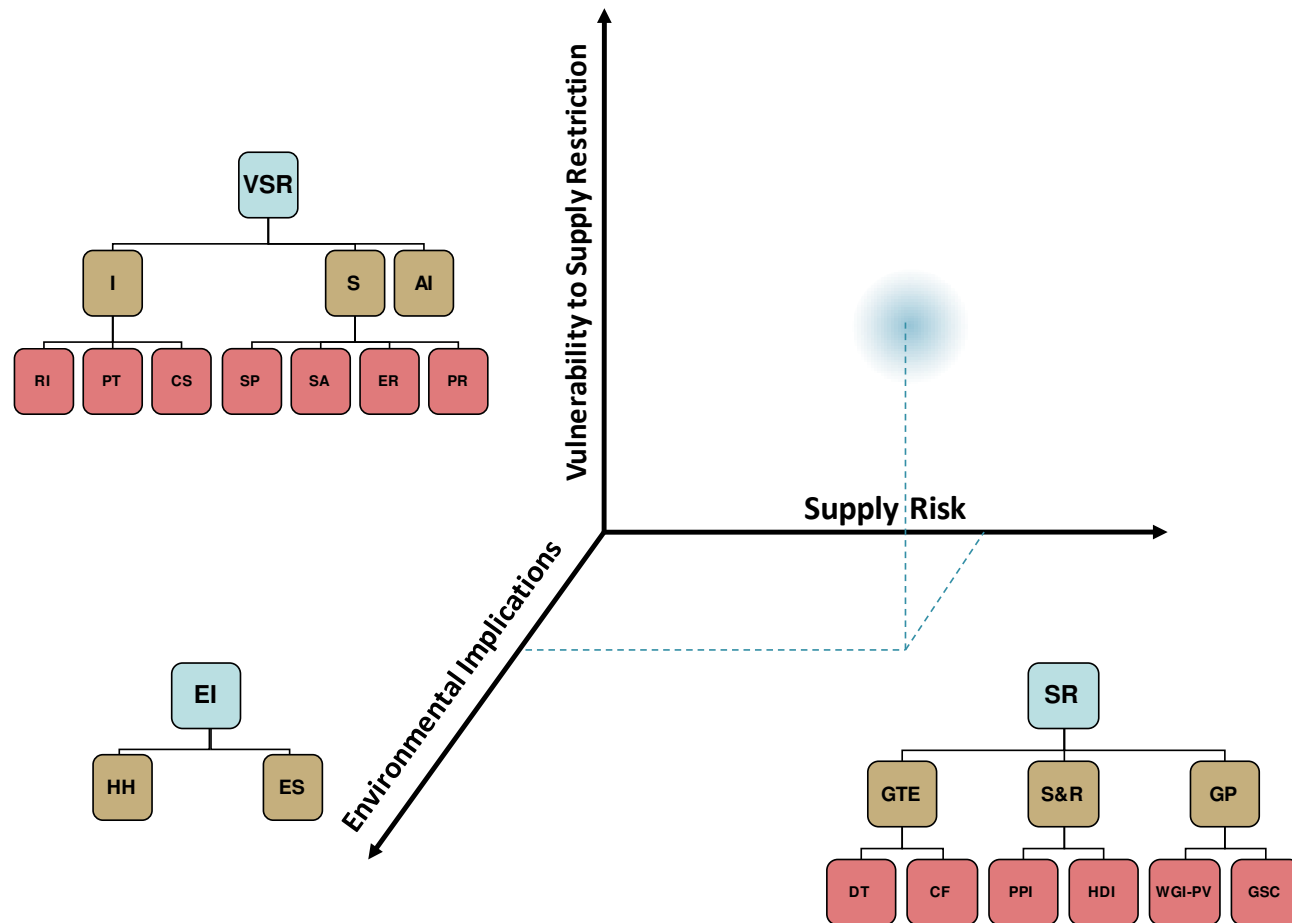
	EC	IDA	IW	NEDO	NRC	Oakd. Hollins	South Korea
Cu	No	No	Maybe	--	No	No	--
As	--	--	--	--	--	No	--
Se	--	--	Yes	No	--		No
Ag	No	No	Maybe	--	--	No	--
Te	No	No	--	No	--	Yes	No
Au	--	--	Maybe	--	--	No	--

# The Yale Approach to Criticality

# The Criticality Matrix and the “Region of Danger”



# The Three-Axis Criticality Evaluation Concept



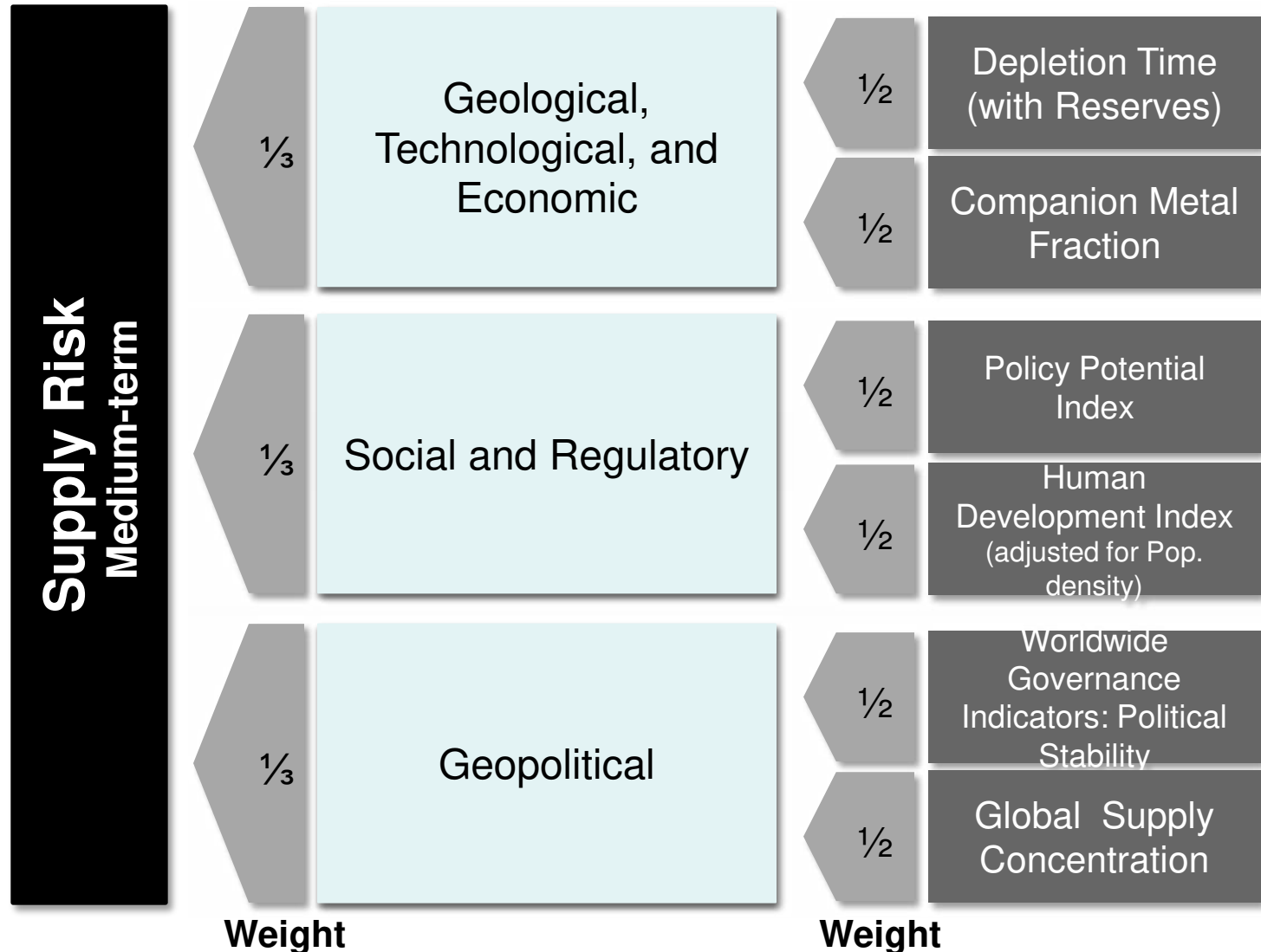
T. Graedel et al., *Env. Sci. Technol.*, 46, 1063-1070, 2012.

# Elements to be Analyzed in the Criticality Project

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	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
5	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
6	55 Cs	56 Ba	57-71	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
7	87 Fr	88 Ra	89-103	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
	Lanthanide Series			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
	Actinide Series			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

# Supply Risk Axis – Corporate and National

## Components



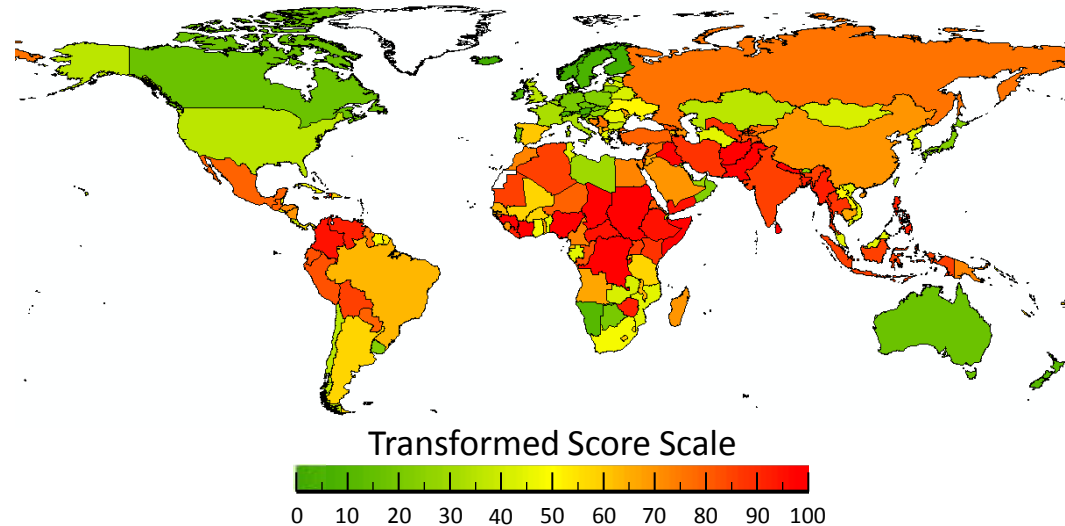


# Politically unstable nations pose a higher risk of supply restriction

## World Bank – WGI

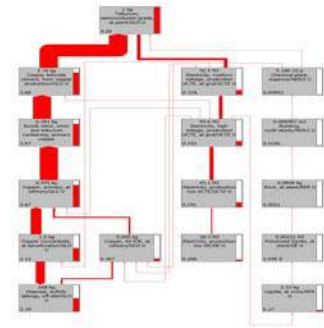
- Measures perceptions of the likelihood that a government will be destabilized or overthrown by unconstitutional or violent means
- Encompasses social, economic, and political factors associated with underlying vulnerability and economic distress

## 2008 Worldwide Governance Indicators – Political Stability & Absence of Violence/Terrorism



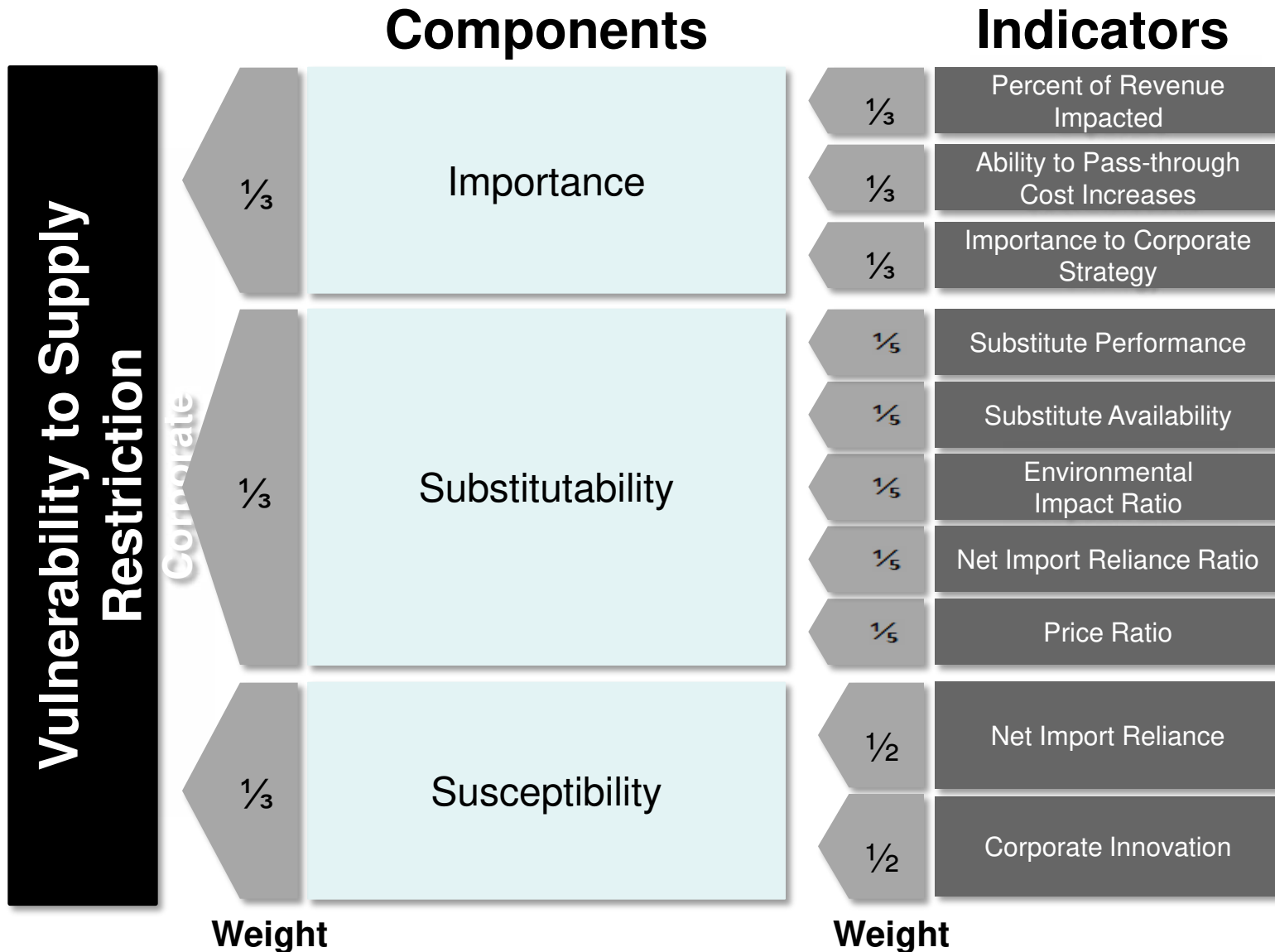
$$WGI\_PV_j^{Trans.} = 100 - WGI\_PV_j$$
$$WGI\_PV_i = \sum w_{i,j} \times WGI\_PV_j^{Trans.}$$

# Environmental Impact



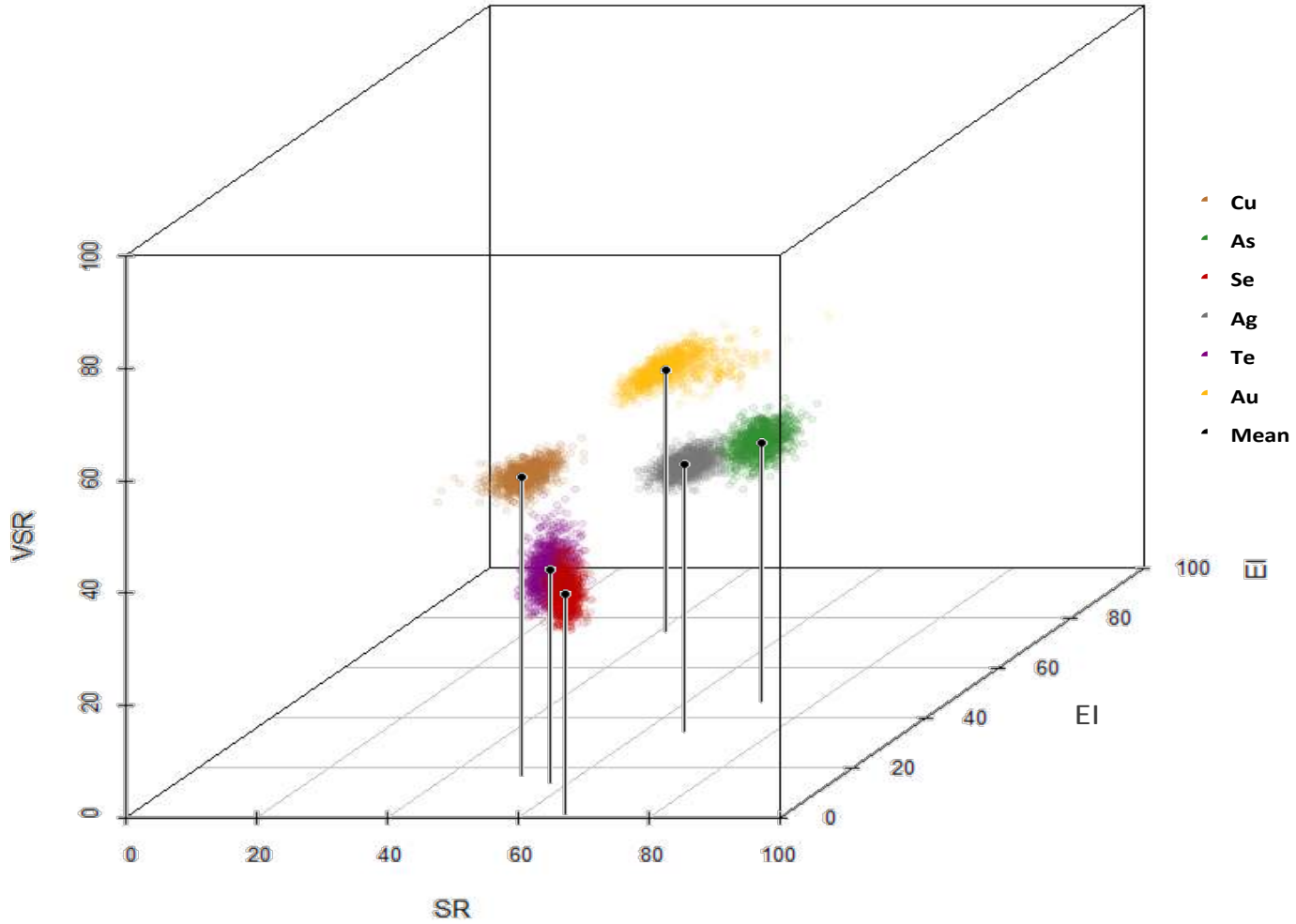
- Evaluates the potential environmental impact of using a metal in modern society
- Based on Ecoinvent database, ReCiPe (H) Endpoint impact methodology (world average normalization)
- Using the following impact category only:
  - Ecosystems
- Result is a single score for a cradle-to-gate environmental impact assessment

# Vulnerability – Corporate Level



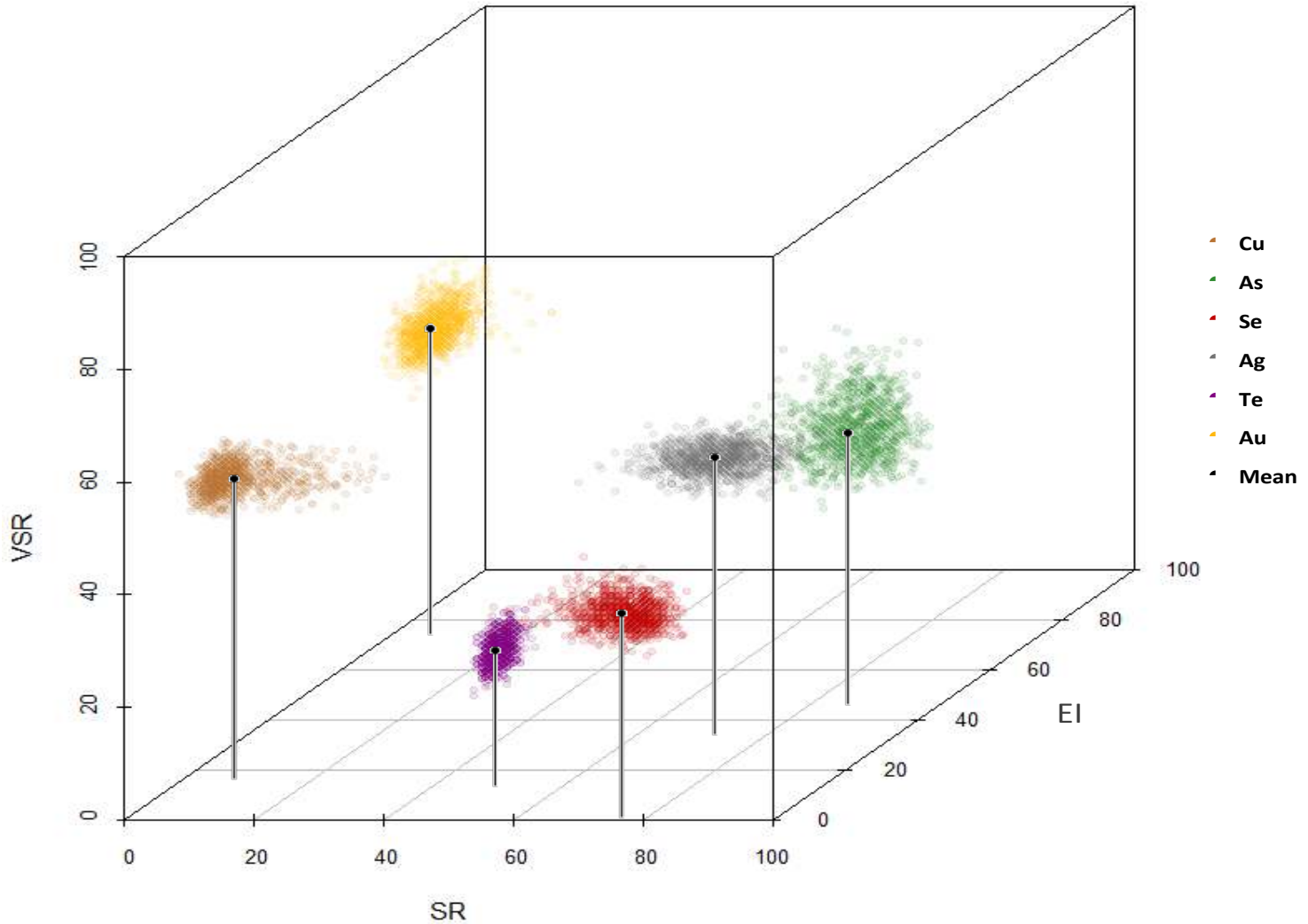
# A Sampling of Criticality Results

# Copper Family Criticality - US



# Copper Family Criticality - Global

N. Nassar et al., *Env. Sci. Technol.*, 46, 1071-1078, 2012



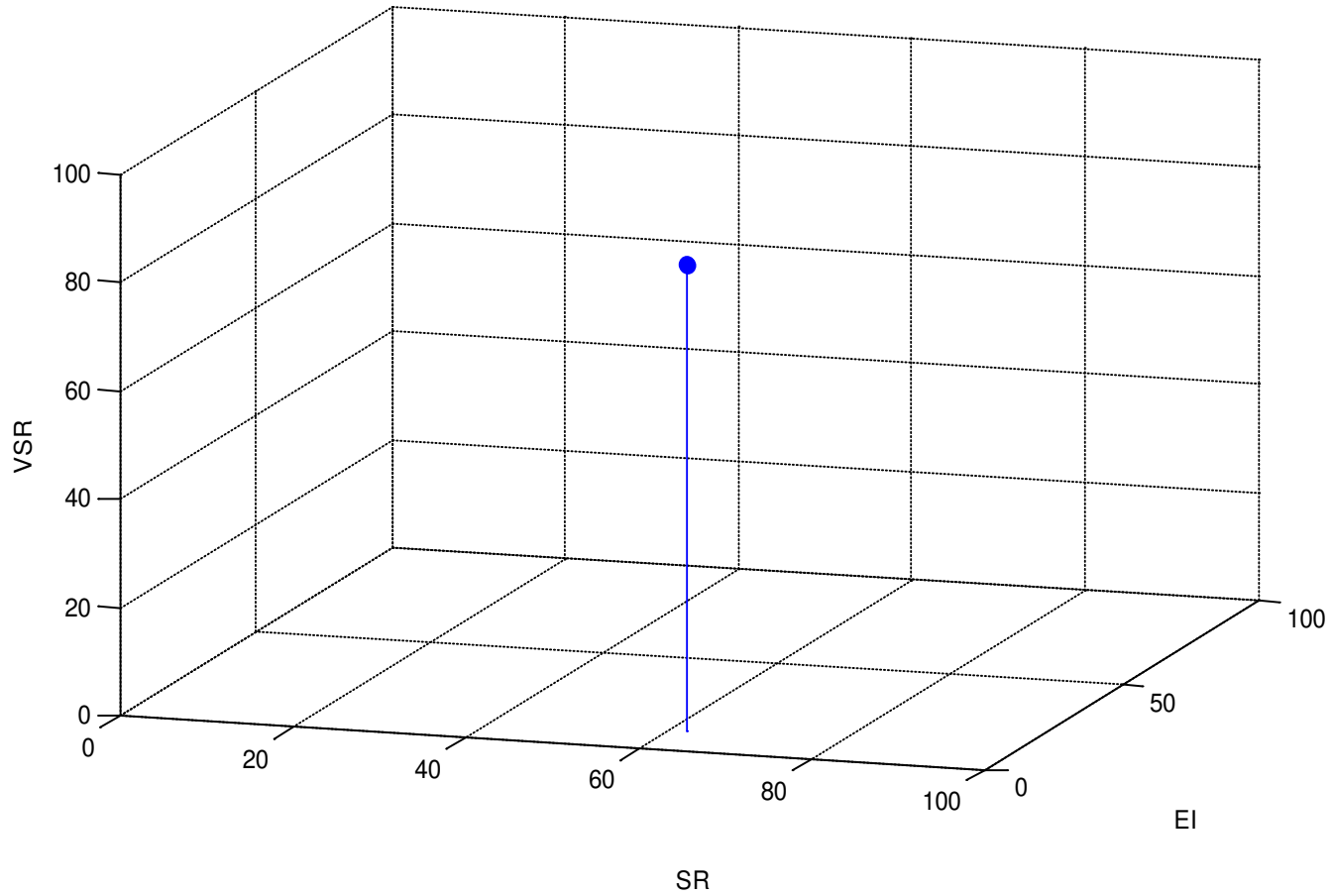
# A Criticality Analysis for Tin

# World Leading Countries in Tin Production

<b><i>Country</i></b>	<b><i>Mine production (tonnes)</i></b>	<b><i>% of global total</i></b>
China	115,000	44
Indonesia	60,000	23
Peru	38,000	15
Bolivia	16,000	6
Brazil	12,000	5
Total	261,000	100



# Tin Criticality : Generic Methodology



# Indicator Values

(utilizes generic substitutes for tin uses)

**Supply Risk**

Geological, Technological, and Economic			Social & Regulatory					Geopolitical				SR <sub>M</sub>	SR <sub>M</sub> alternative weighting*	
DT <sub>M</sub>	CF	GTE <sub>M</sub>	PPI		HDI	S&R	WGI		GSC		GP			
91	0	46	Tin mining	60	Tin smelting	65	63	Tin mining	76	Tin mining	76	76	62	87

**Vulnerability to Supply Restriction**

Importance				Substitutability						Susceptibility			VSR <sub>C</sub>
RI	PT	CS	I	SP	SA <sub>M</sub>	ER	IRR	PR	S	IR	CI	SU	
87.50	62.50	87.50	79.17	43.75	42.23	12.05	62.50	7.00	32.26	100.00	62.5	81.3	59.2

# Indicator Values

(assumes no suitable substitutes exist for tin uses)

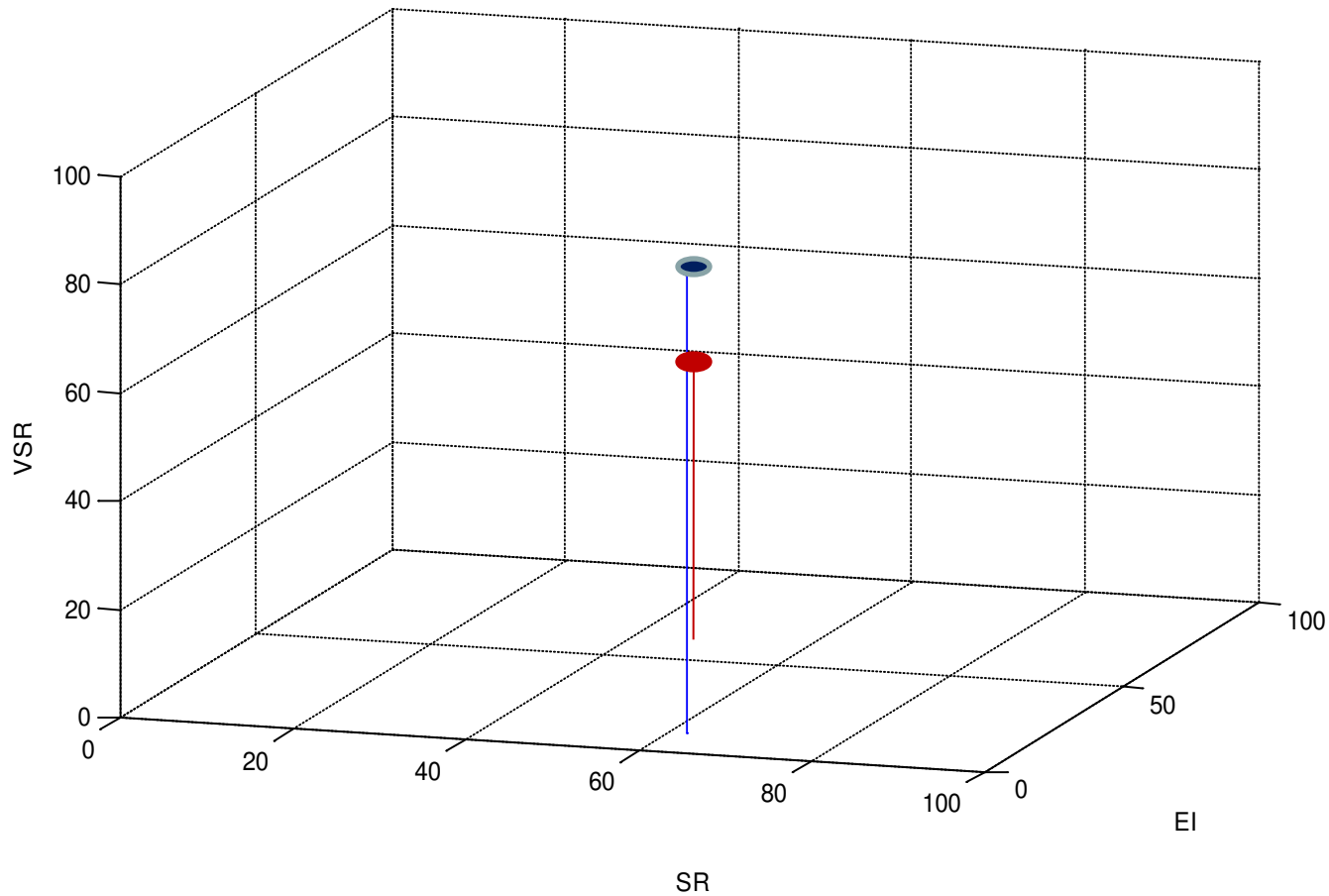
**Supply Risk**

Geological, Technological, and Economic			Social & Regulatory					Geopolitical					SR <sub>M</sub>	SR <sub>M</sub> alternative weighting*
DT <sub>M</sub>	CF	GTE <sub>M</sub>	PPI		HDI		S&R	WGI		GSC		GP	SR <sub>M</sub>	SR <sub>M</sub> alternative weighting*
91	0	46	Tin mining	60	Tin smelting	65	63	Tin mining	76	Tin mining	76	76	62	87

**Vulnerability to Supply Restriction**

Importance				Substitutability						Susceptibility			VSR <sub>C</sub>
RI	PT	CS	I	SP	SA <sub>M</sub>	ER	IRR	PR	S	IR	CI	SU	VSR <sub>C</sub>
87.50	62.50	87.50	79.17	100.00	100.00	100.00	100.00	100.00	100.00	100.0	62.5	81.3	85.8

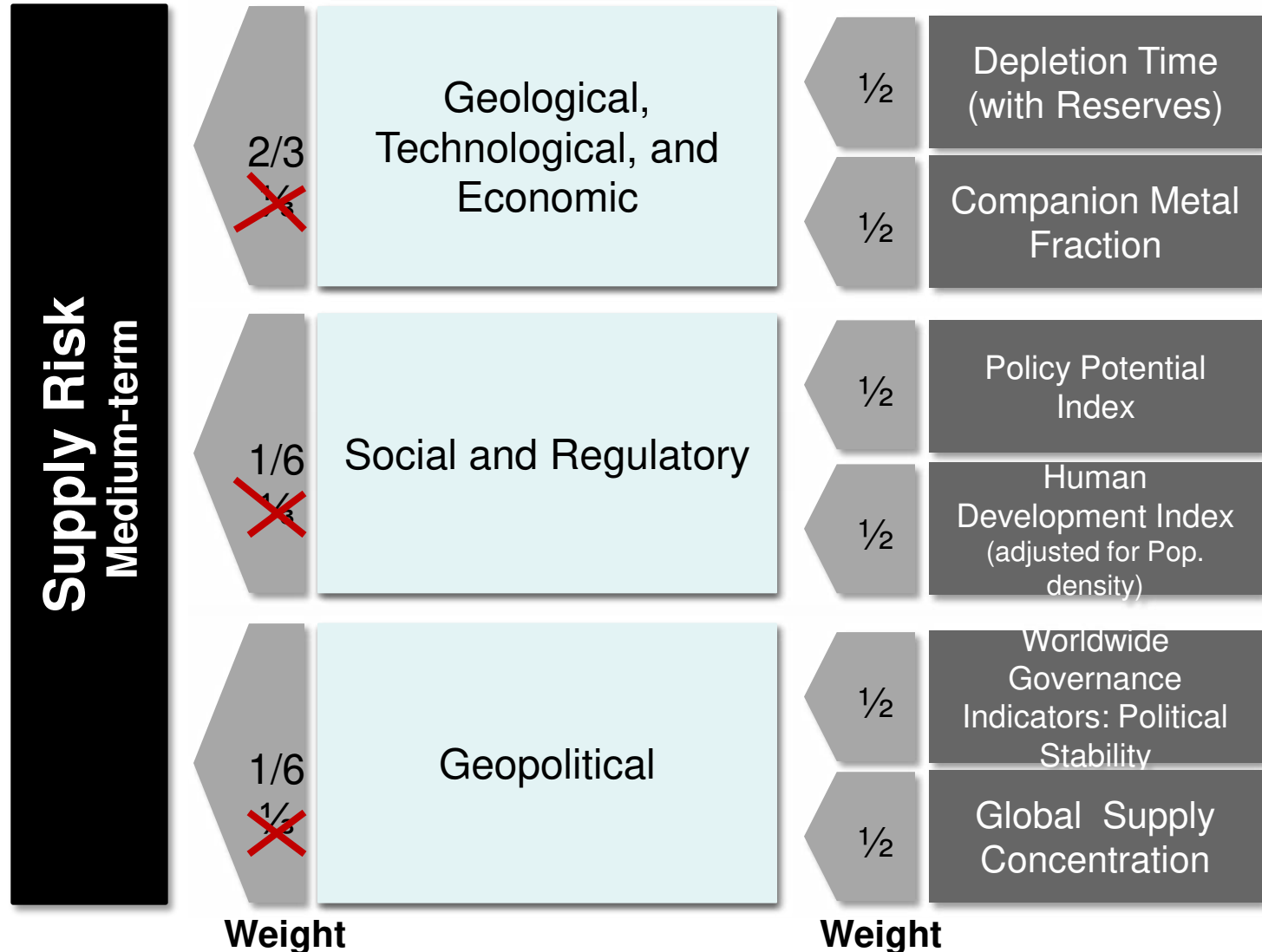
# Tin Criticality as a Function of Substitutability



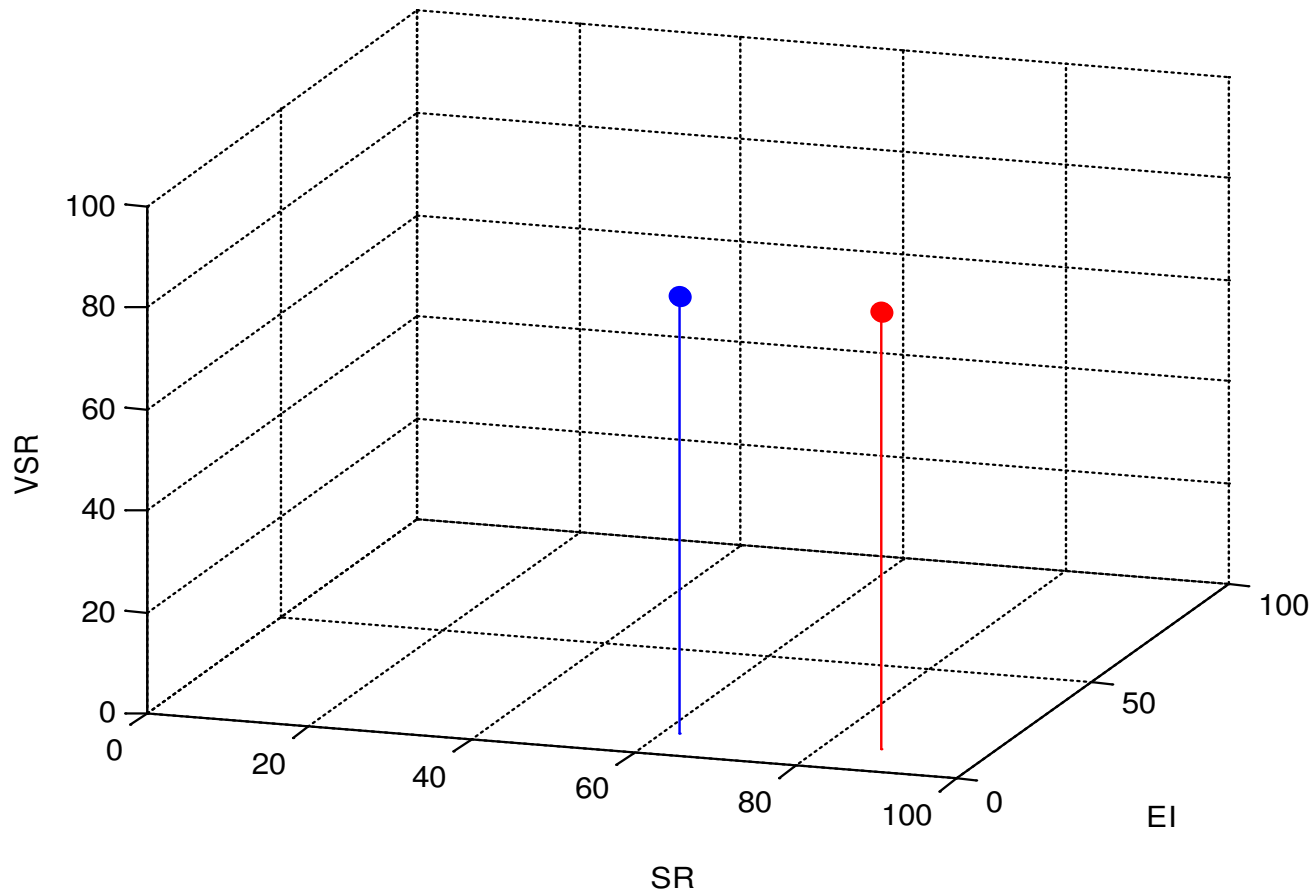
Red: generic substitutes; blue: no suitable substitutes

# Supply Risk Axis – Corporate and National

## Components








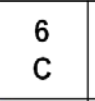
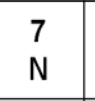
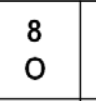
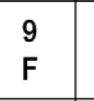
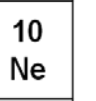



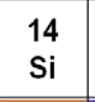
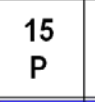
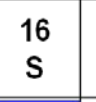
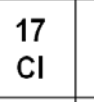
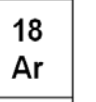
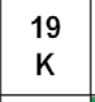
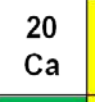
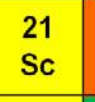
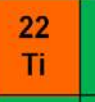
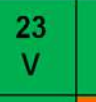
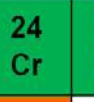


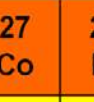
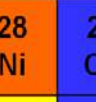
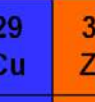
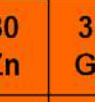
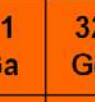
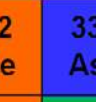
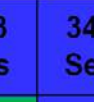

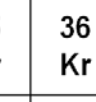



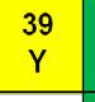

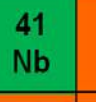








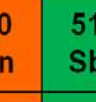
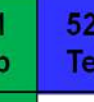
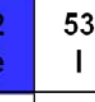
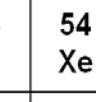
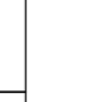
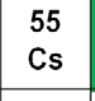

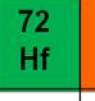










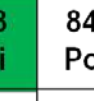
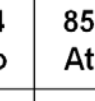
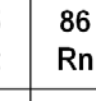

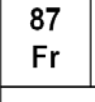
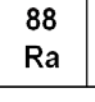
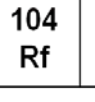
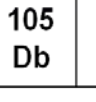
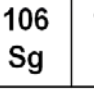
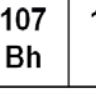
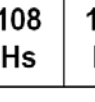
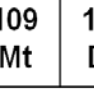
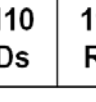
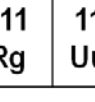
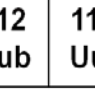
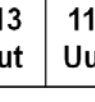
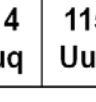
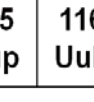
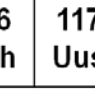
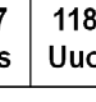
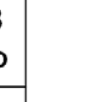
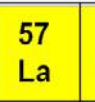














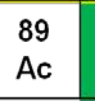
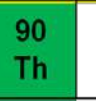
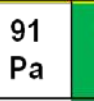

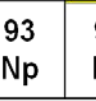
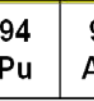
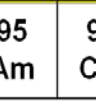
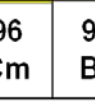
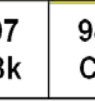
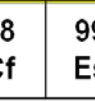

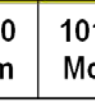
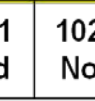
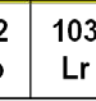



# Tin Criticality – Alternative Weighting of Supply Risk Components



Blue: no weighting; Red: weighting GP 2/3, GTE 1/6, SR 1/6

# Criticality Project Plan – May, 2012

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
1	1 H		 Published					 Completed											2 He
2	 3 Li	 4 Be		 In Progress				 Planned					 5 B	 6 C	 7 N	 8 O	 9 F	 10 Ne	
3	 11 Na	 12 Mg											 13 Al	 14 Si	 15 P	 16 S	 17 Cl	 18 Ar	
4	 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	
5	 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	
6	 55 Cs	 56 Ba	57-71	 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	
7	 87 Fr	 88 Ra	89-103	 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	
	Lanthanide Series			 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	
	Actinide Series			 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	

# Evaluating Criticality: A Summary

- What is critical to one organization may not be critical to another, and methodologies must take this into account
- Criticality is best regarded as an attribute of degree rather than as a state, and the important information is *why* a metal's criticality is what it is, not *whether* the metal is "critical" or not
- The Yale comprehensive critical metals assessment will be complete by the end of 2012