Center for Industrial Ecology
Yale School of Forestry & Environmental Studies

WORLD MATERIALS FORUM

Element Cycles and Criticality : A Focus on Minor Metals

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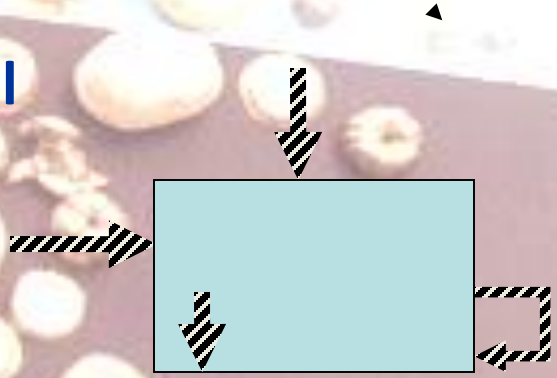
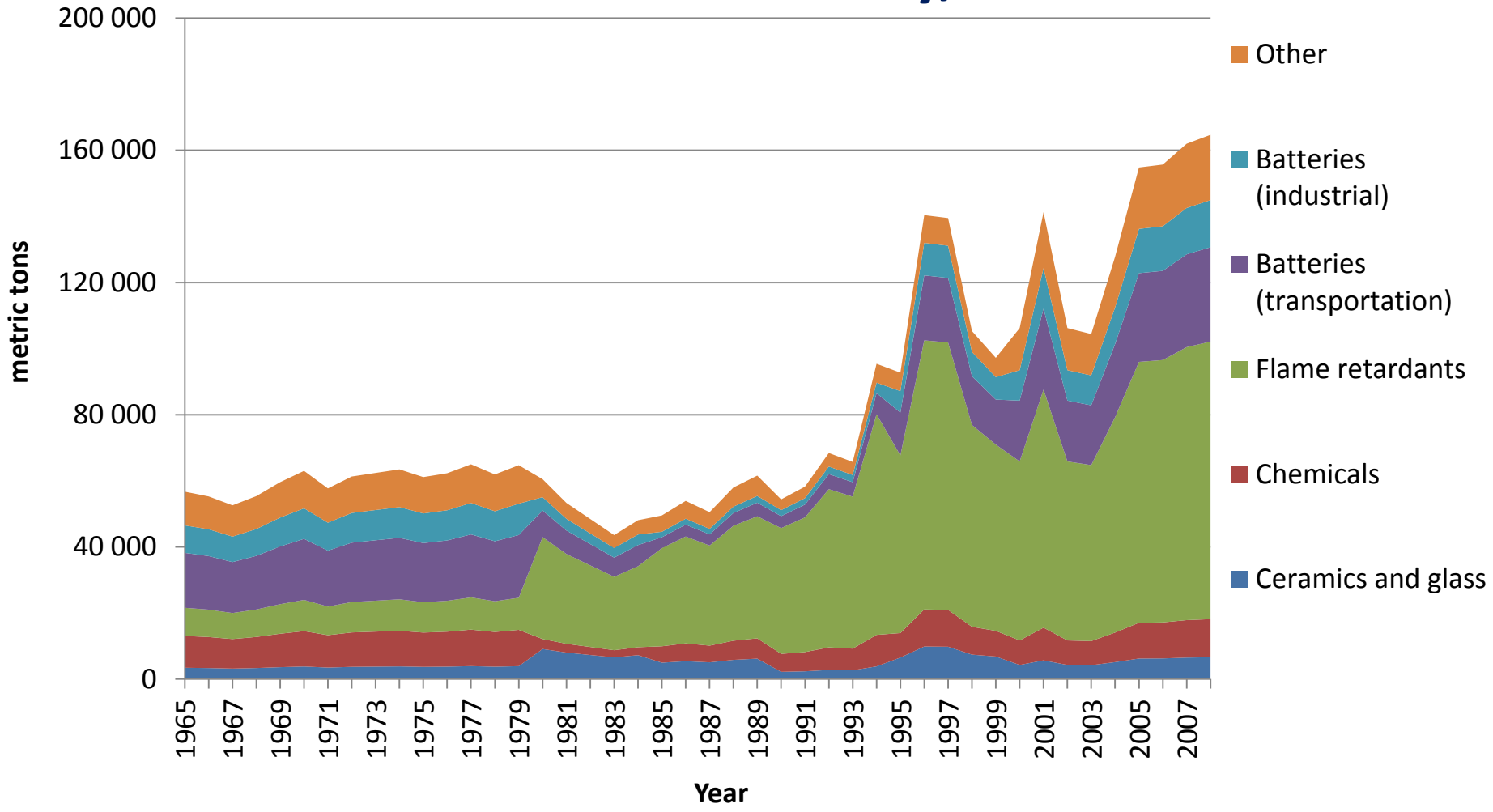


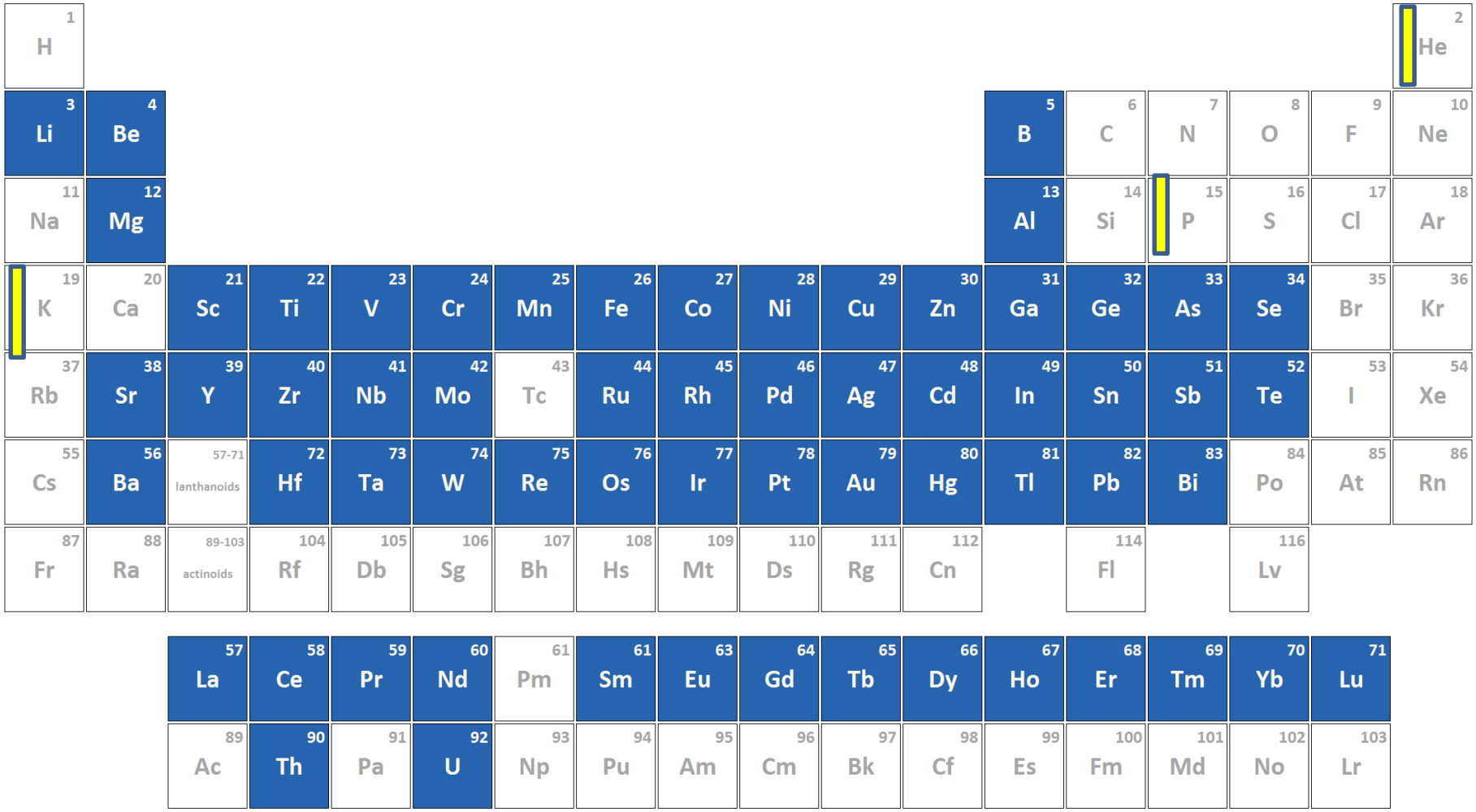
Important Points About Minor Metals

- 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

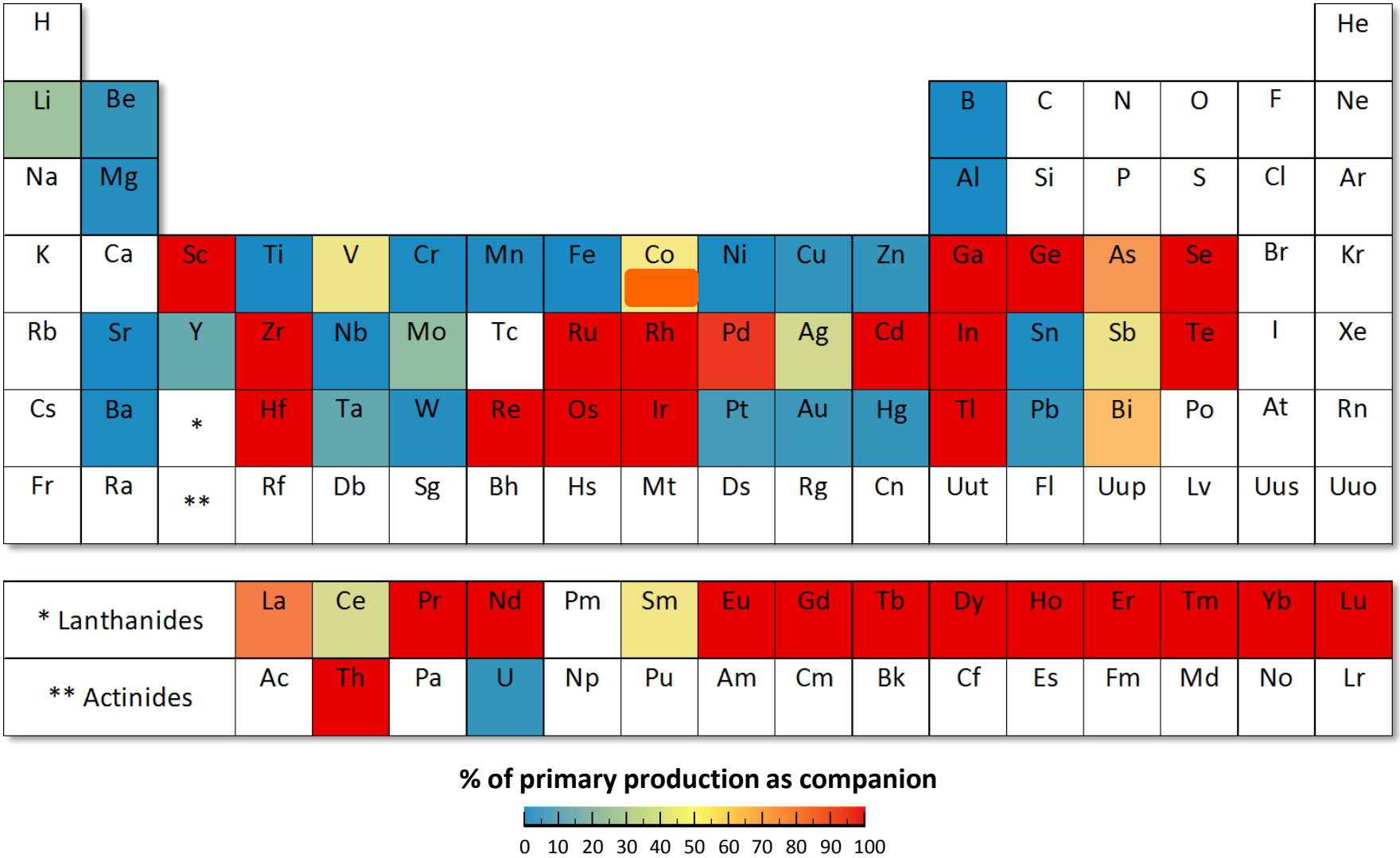
Global Uses of Antimony, 1965-2009



Elements Addressed in the Yale Criticality Project

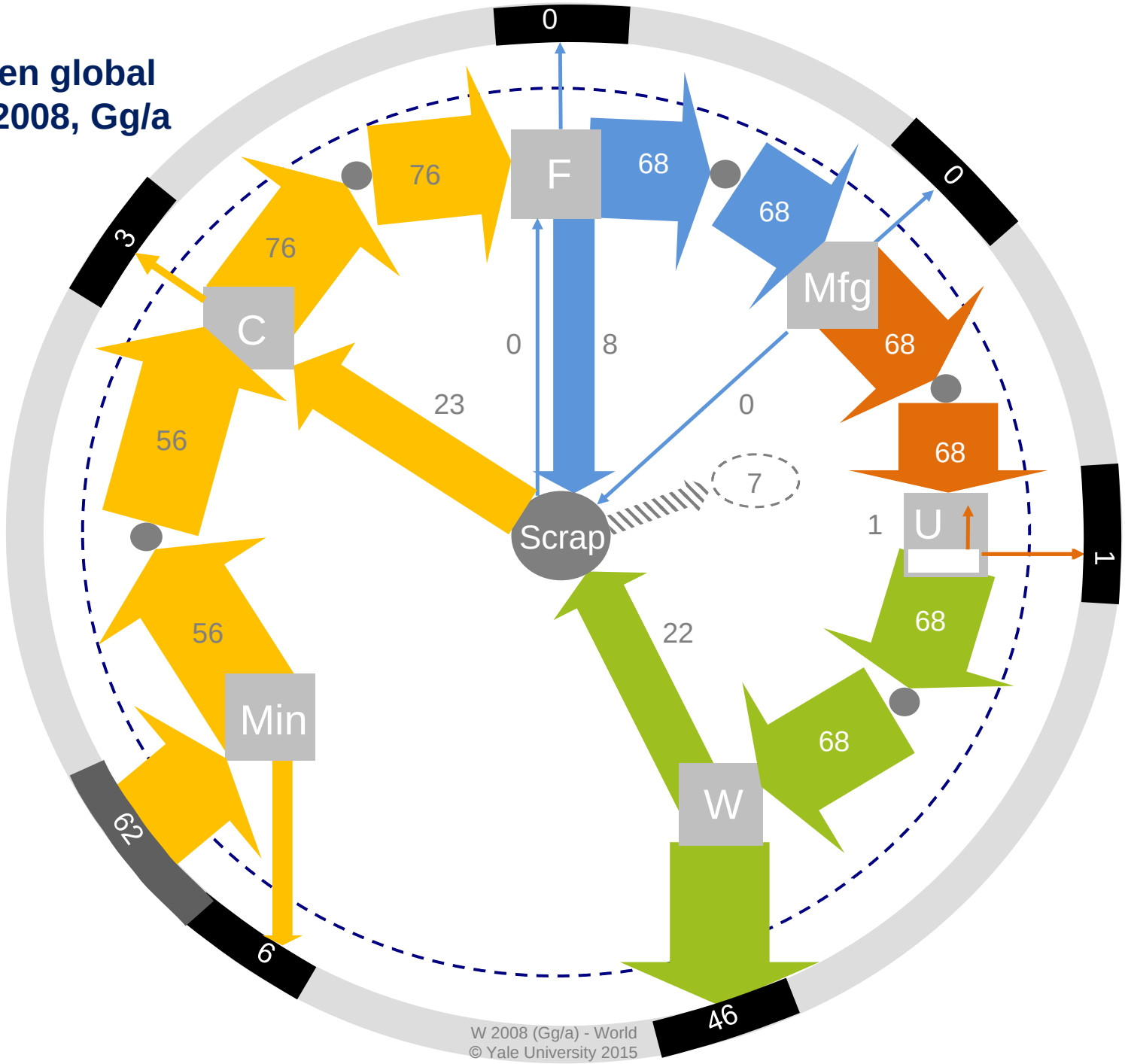


The “companionality” of metals: the production of many metals is dependent on the production of carrier metals



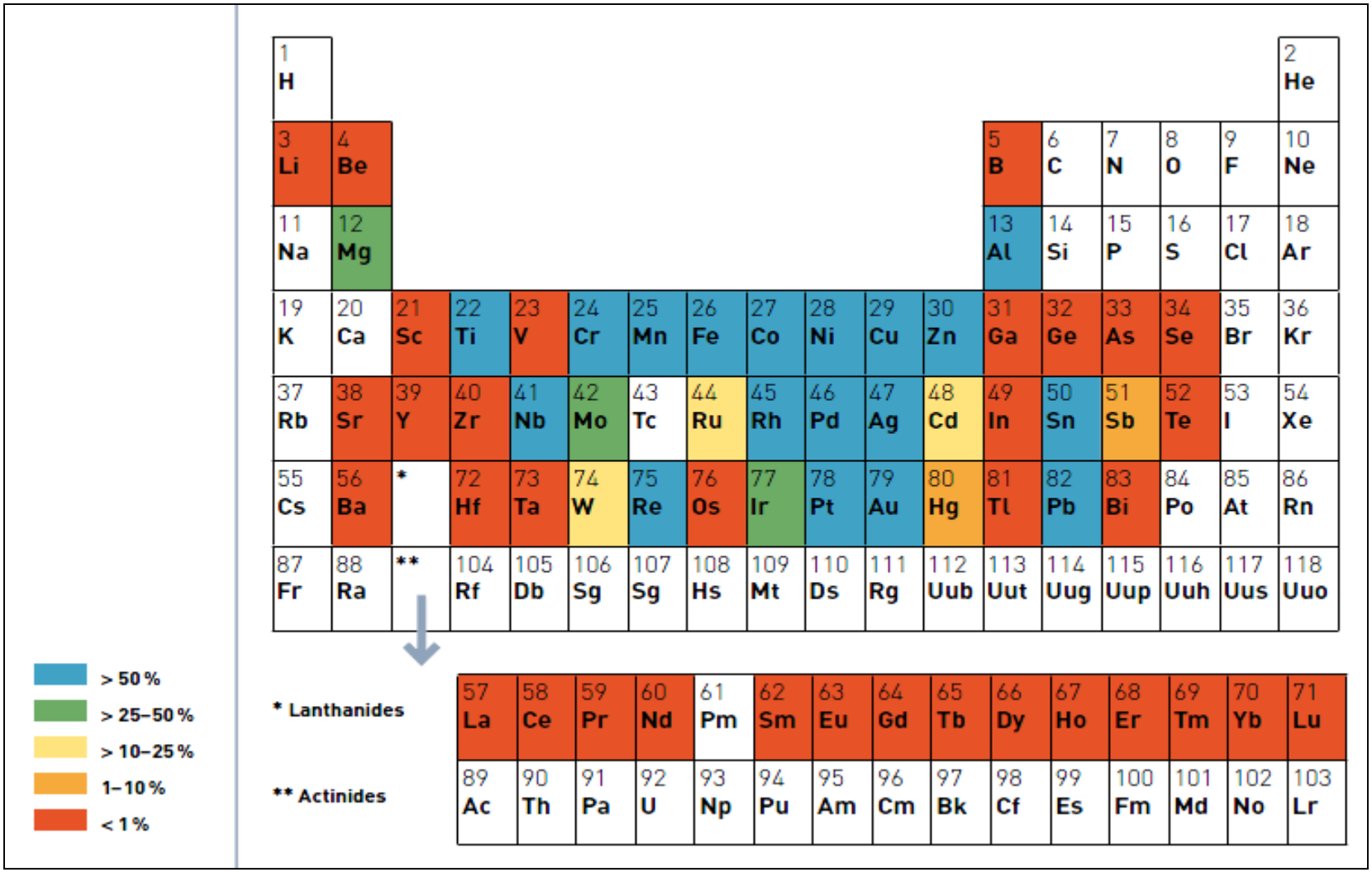
Source: N. T. Nassar, T. E. Graedel, E. M. Harper, Byproduct metals are technologically essential but have problematic supply. *Science Advances*, in press (2015).

Tungsten global cycle, 2008, Gg/a



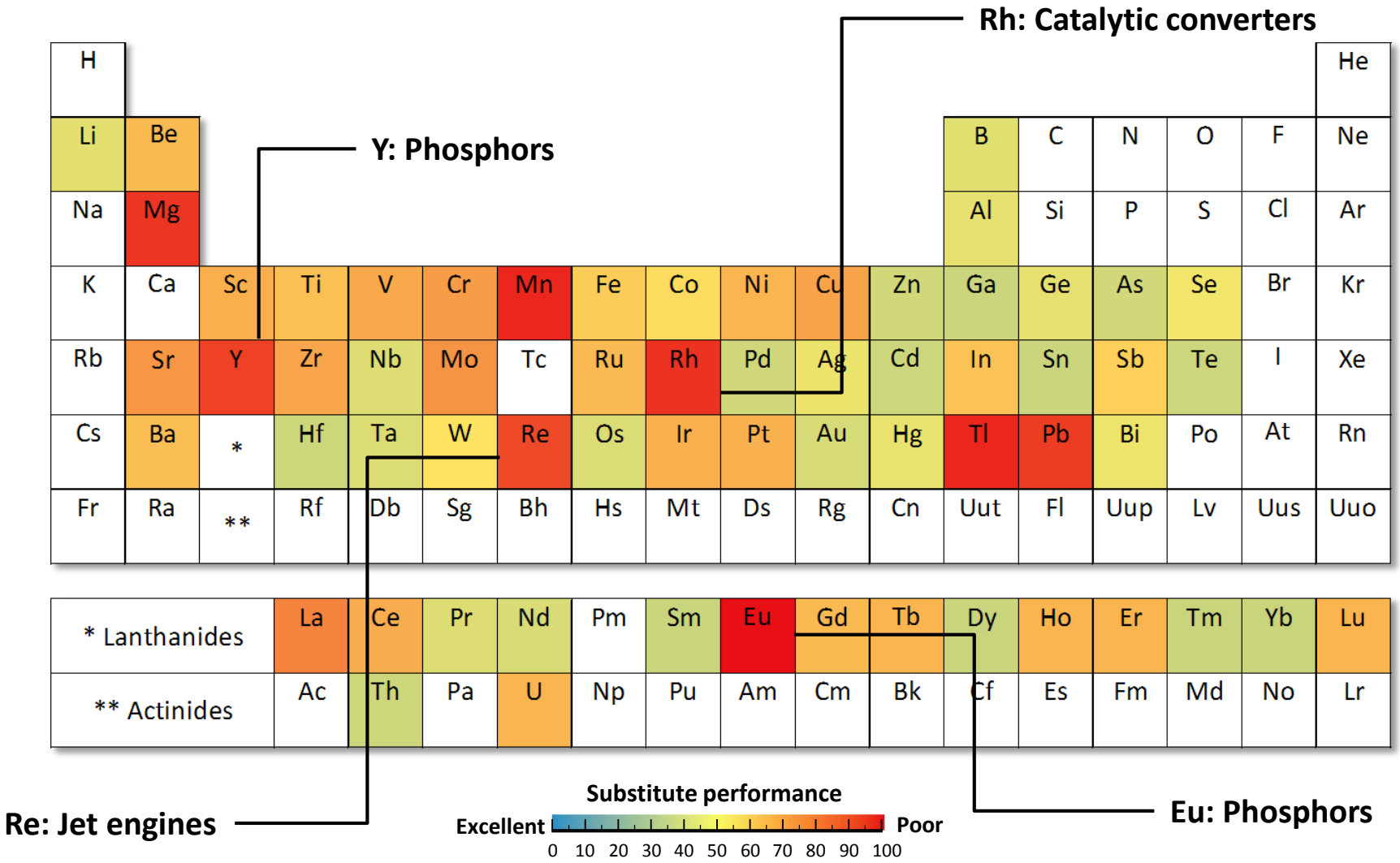
W 2008 (Gg/a) - World

End-of-life recycling rates of metals



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

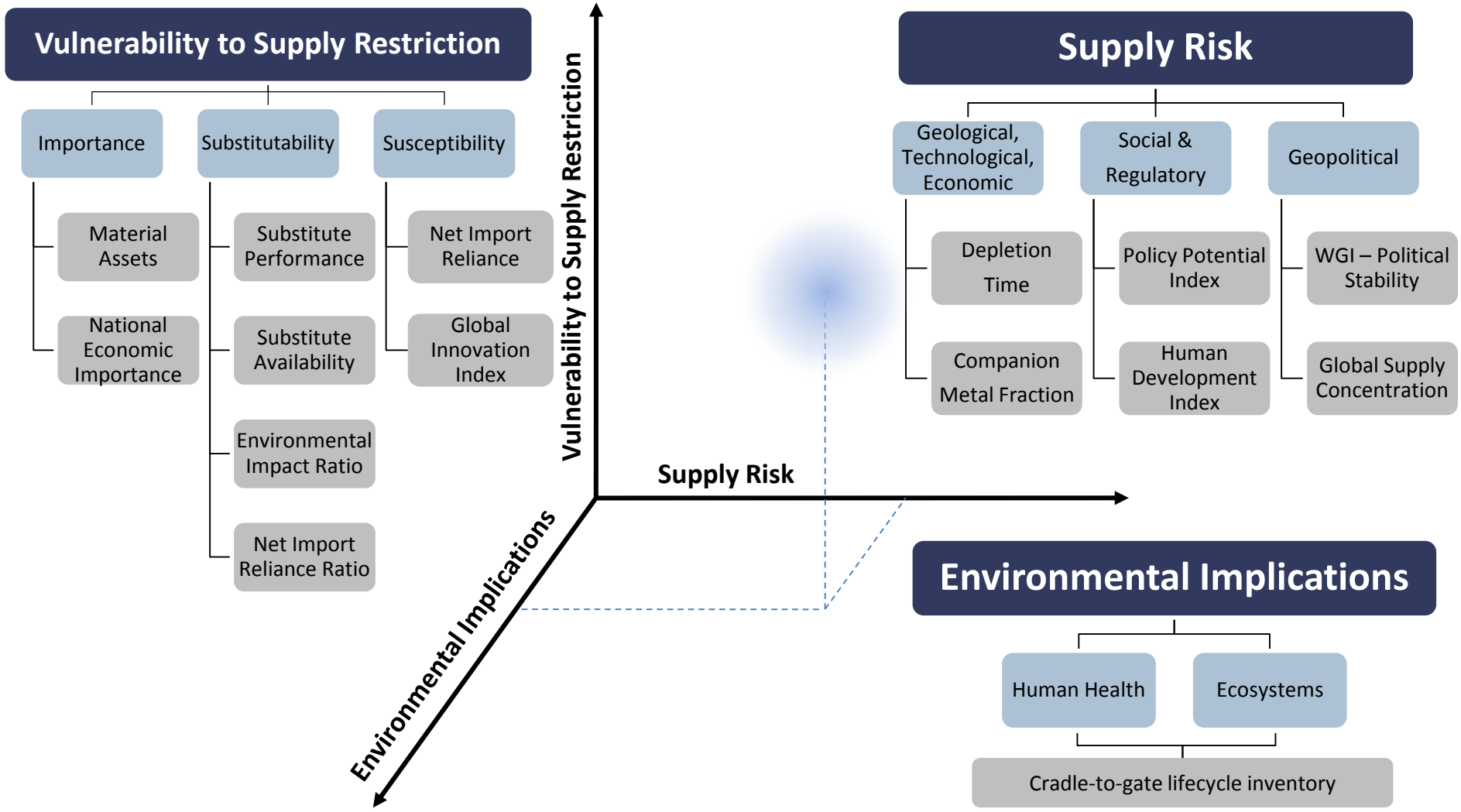
The substitutability of metals



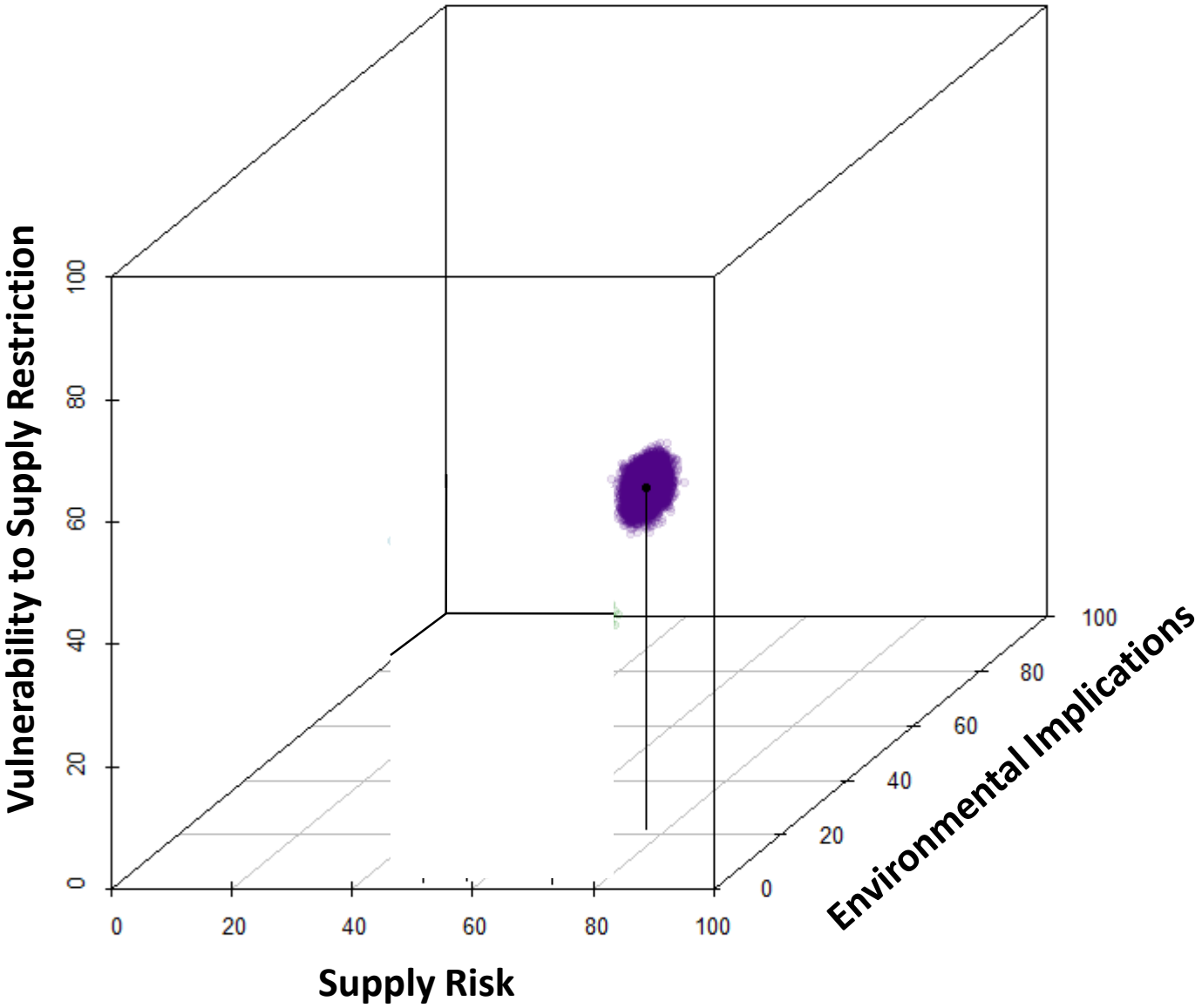
Source: Graedel, T. E.; Harper, E. M.; Nassar, N. T.; Reck, B. K., On the materials basis of modern society. *Proceedings of the National Academy of Sciences* **2013,** *doi: 10.1073/pnas.1312752110*.

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

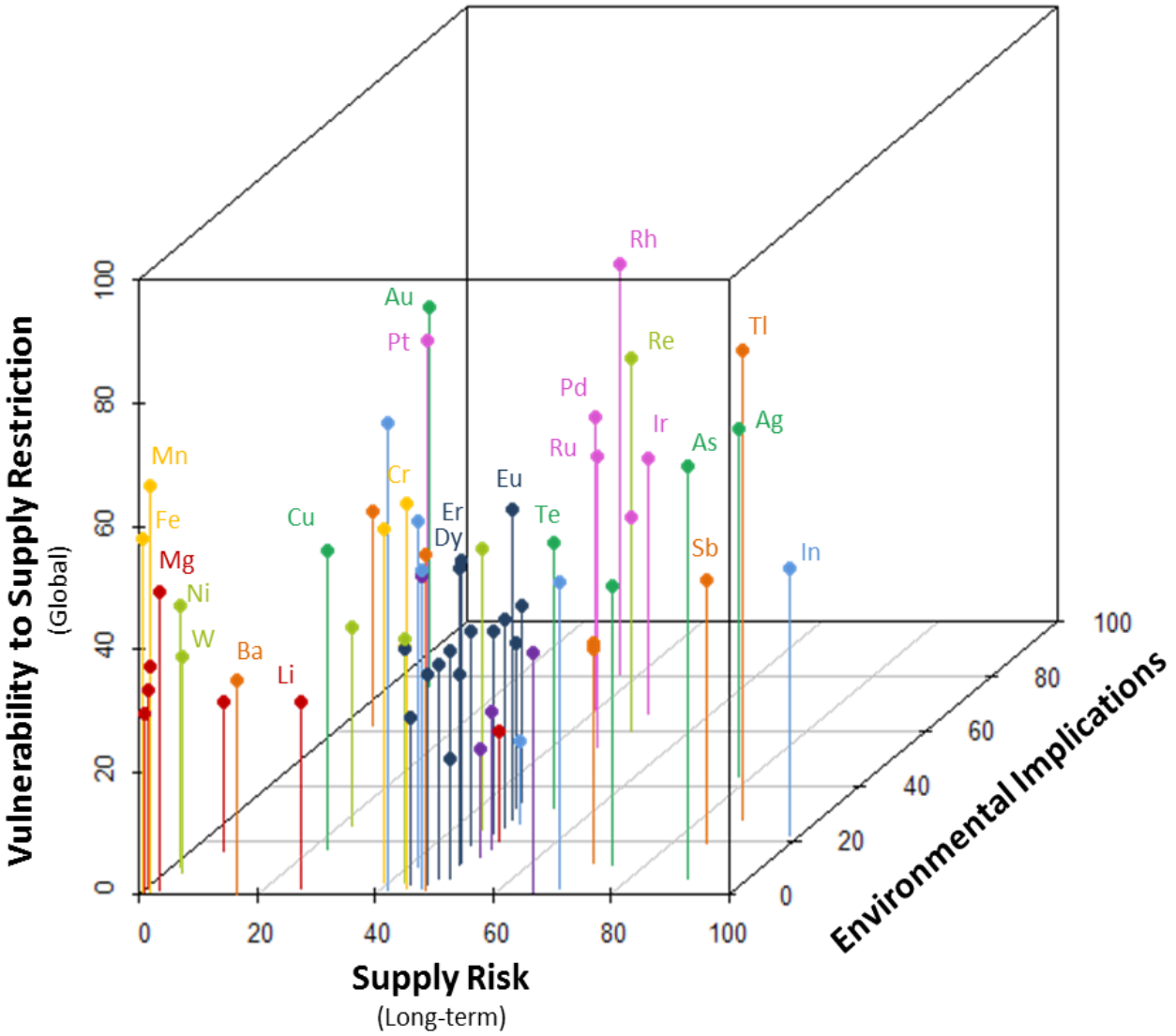
The 3-Axis Approach to Criticality



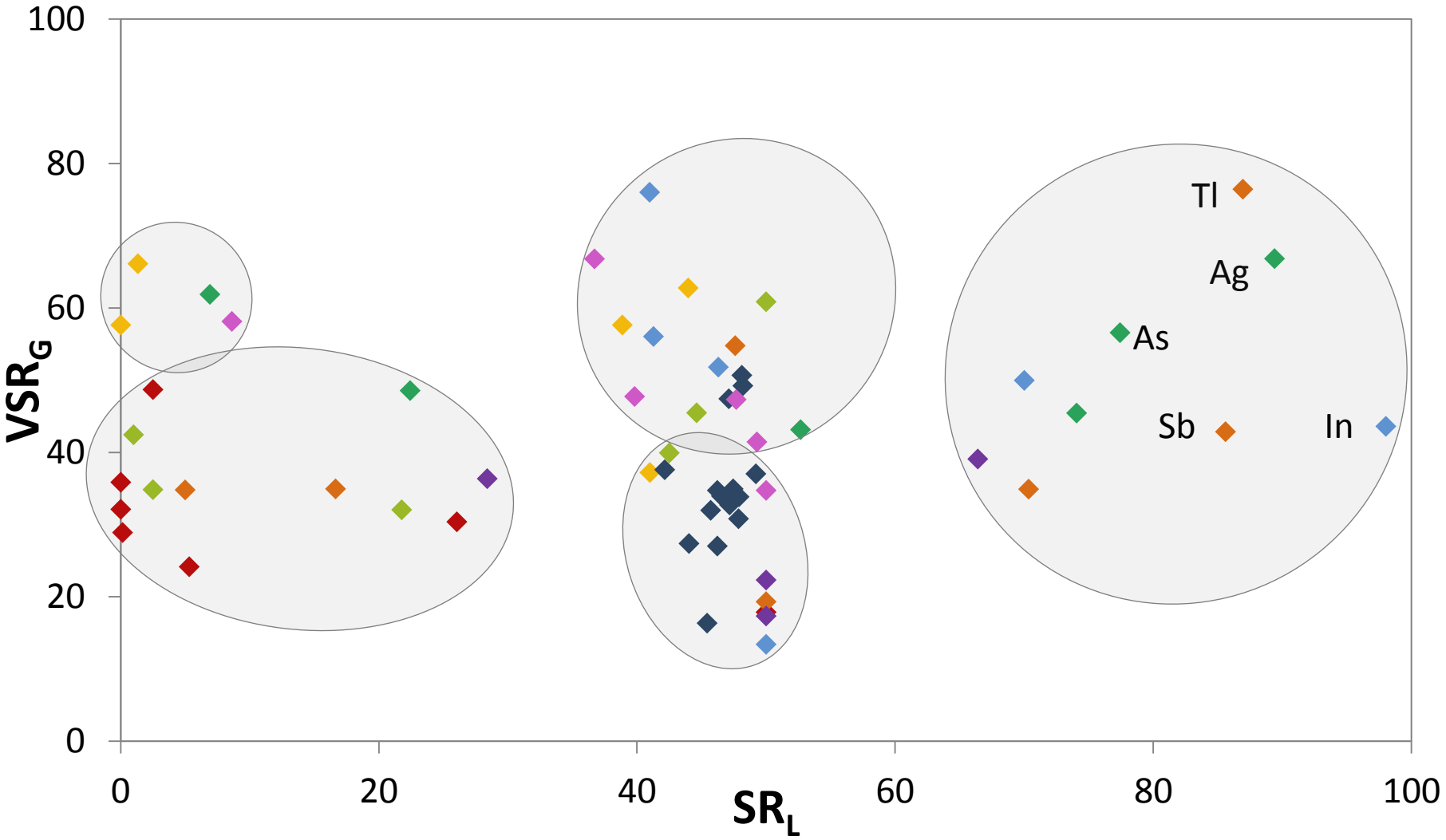
Silver criticality – global level



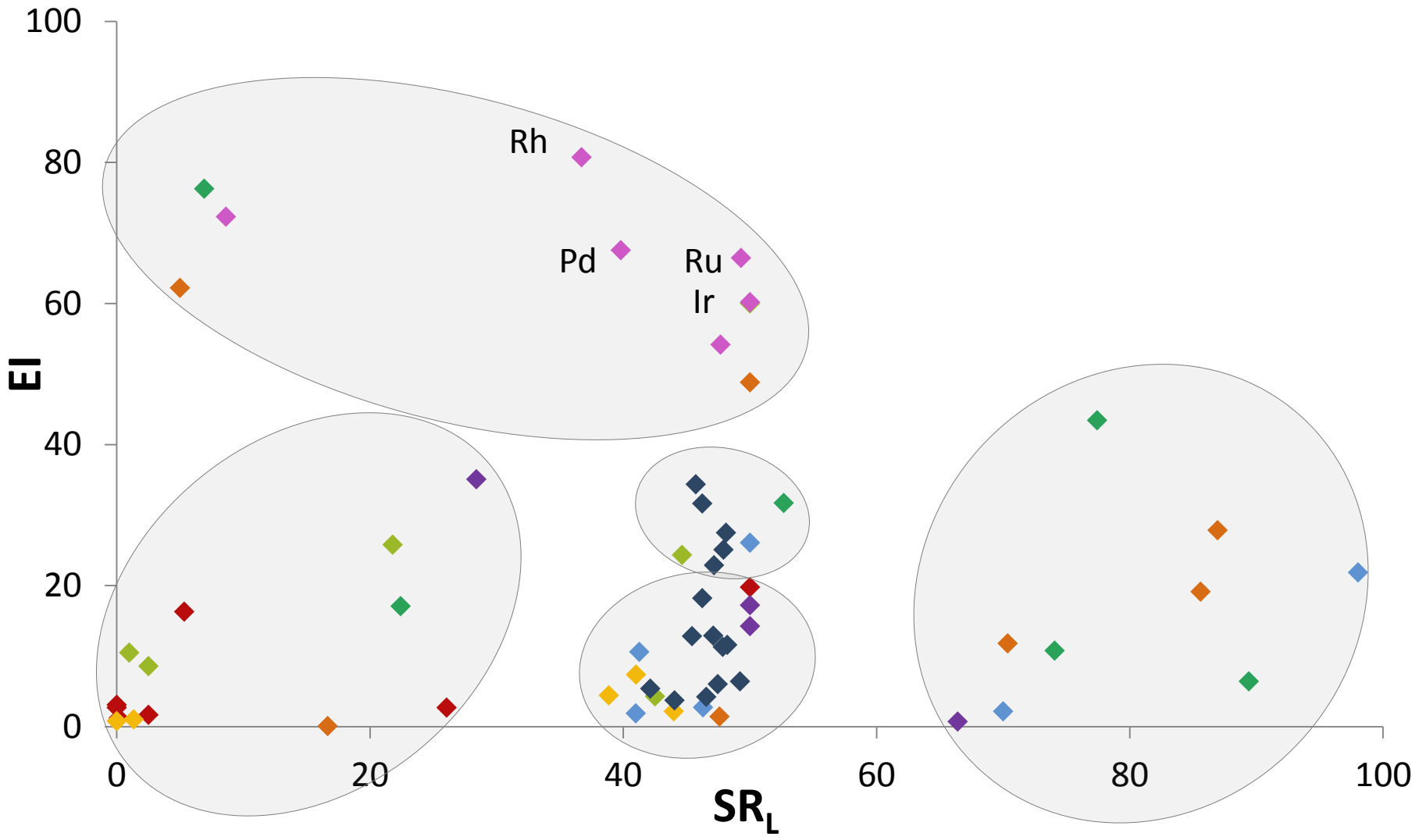
The three-dimensional criticality of the 62 metals of the periodic table



Global-Level Criticality Assessment: Supply Risk and Vulnerability Axes



Global-Level Criticality Assessment: Supply Risk and Environmental Axes



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