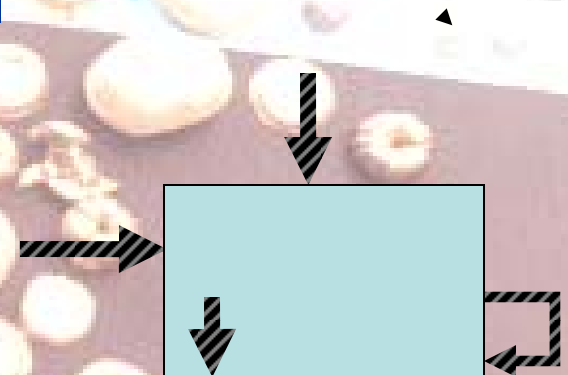




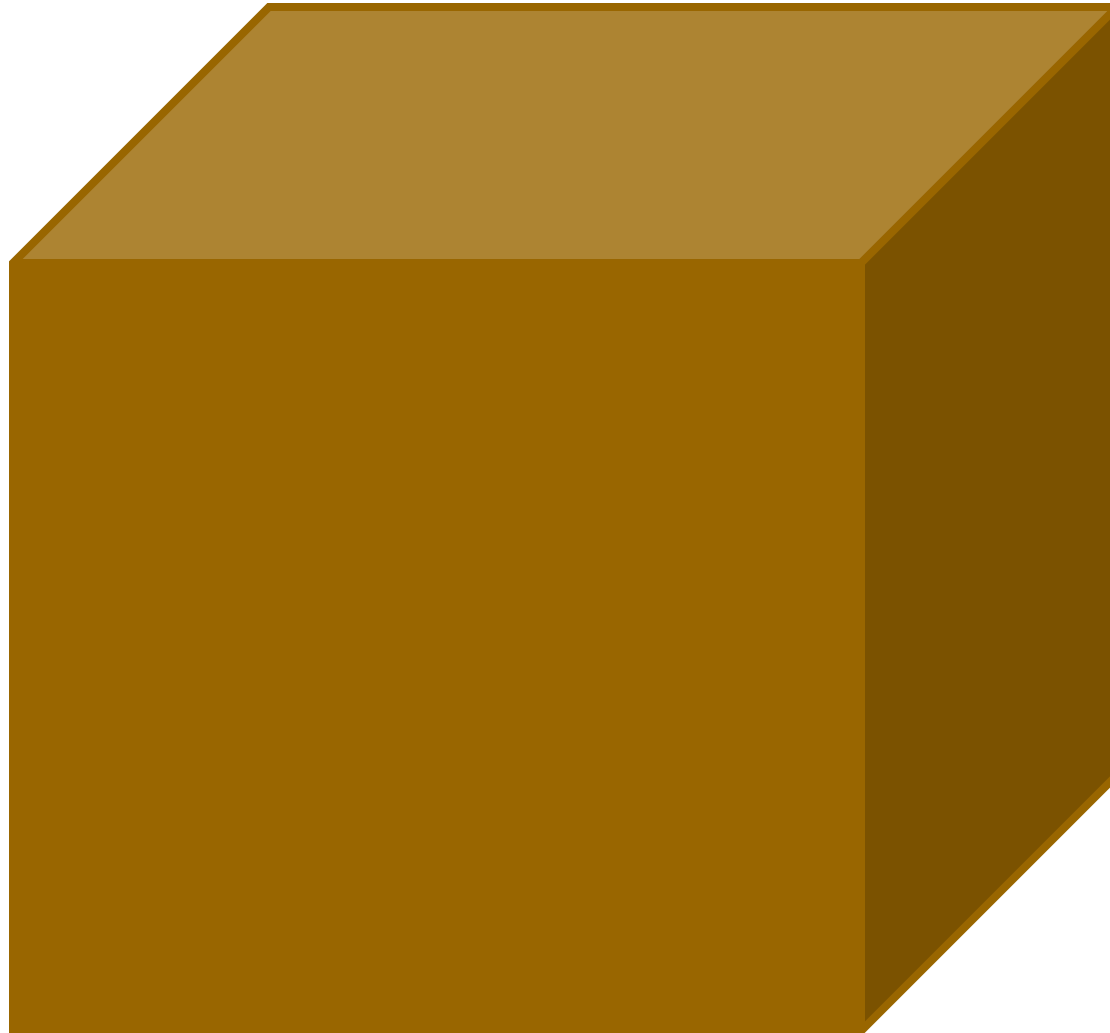
# Is Sustainable Resource Management Possible?

Thomas E. Graedel

Yale University

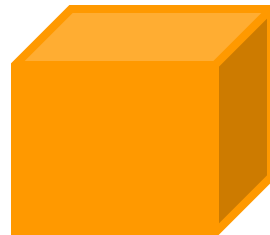


# The World's Annual Production of Iron



940 million  
metric tons

# The World's Annual Production of Copper



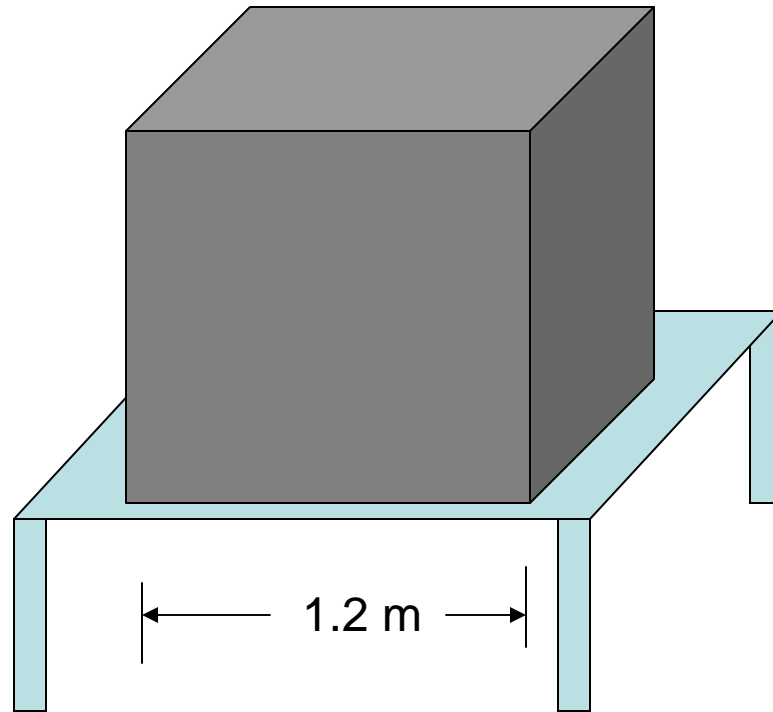
15.6 million  
metric tons

# The World's Annual Production of Tungsten



90 thousand  
metric tons

# The World's Annual Production of Rhenium



# Aircraft Engine Combustors



# Aircraft Engine Combustors



Rhenium: Only element whose alloys can withstand modern combustor temperatures



# International Panel for Sustainable Resource Management

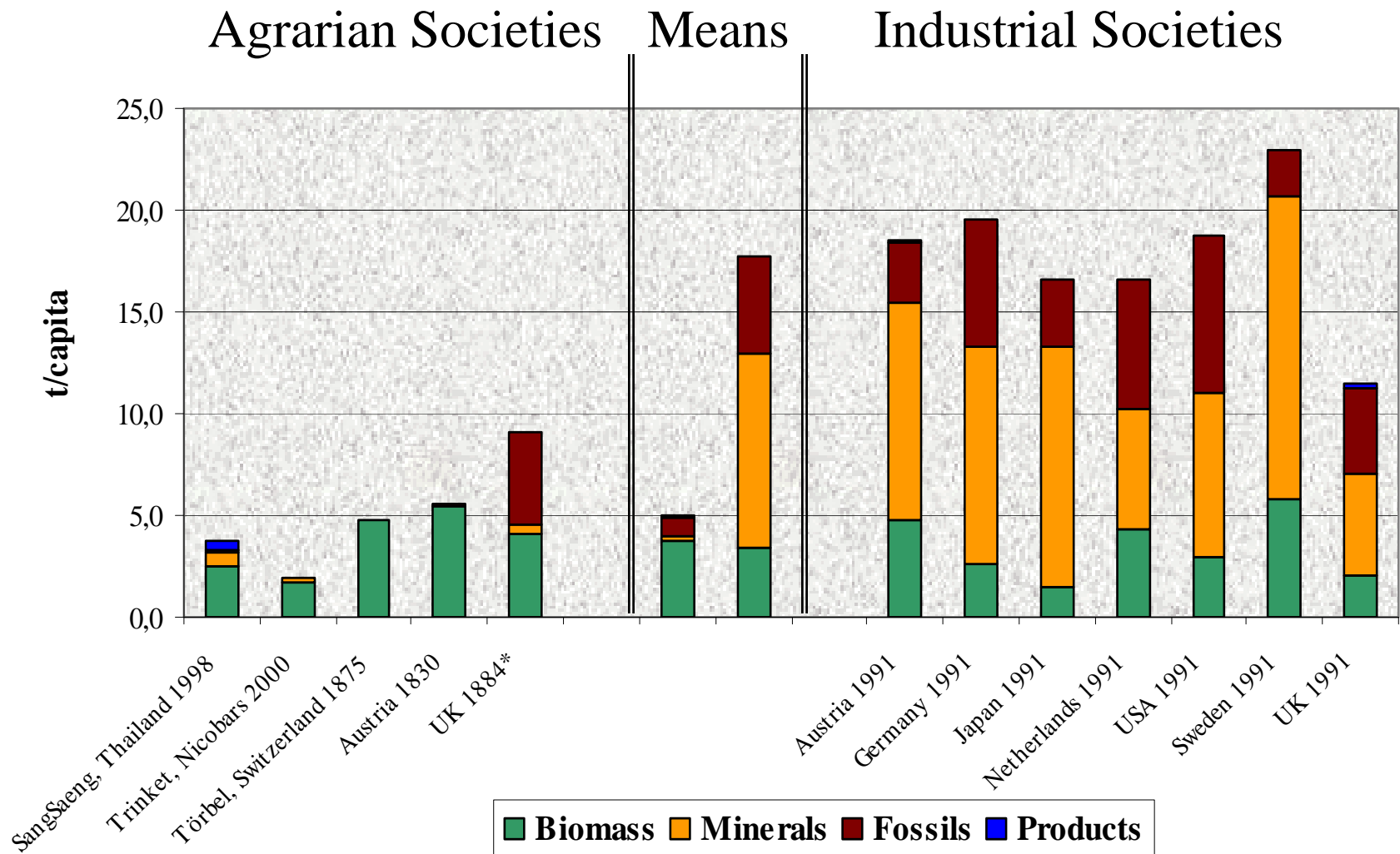
# Mission of the Panel

To provide independent scientific assessments on the sustainability of resources and on the environmental impacts from the use of resources (renewable and non-renewable) over the full life cycle

# Working Groups of the Panel

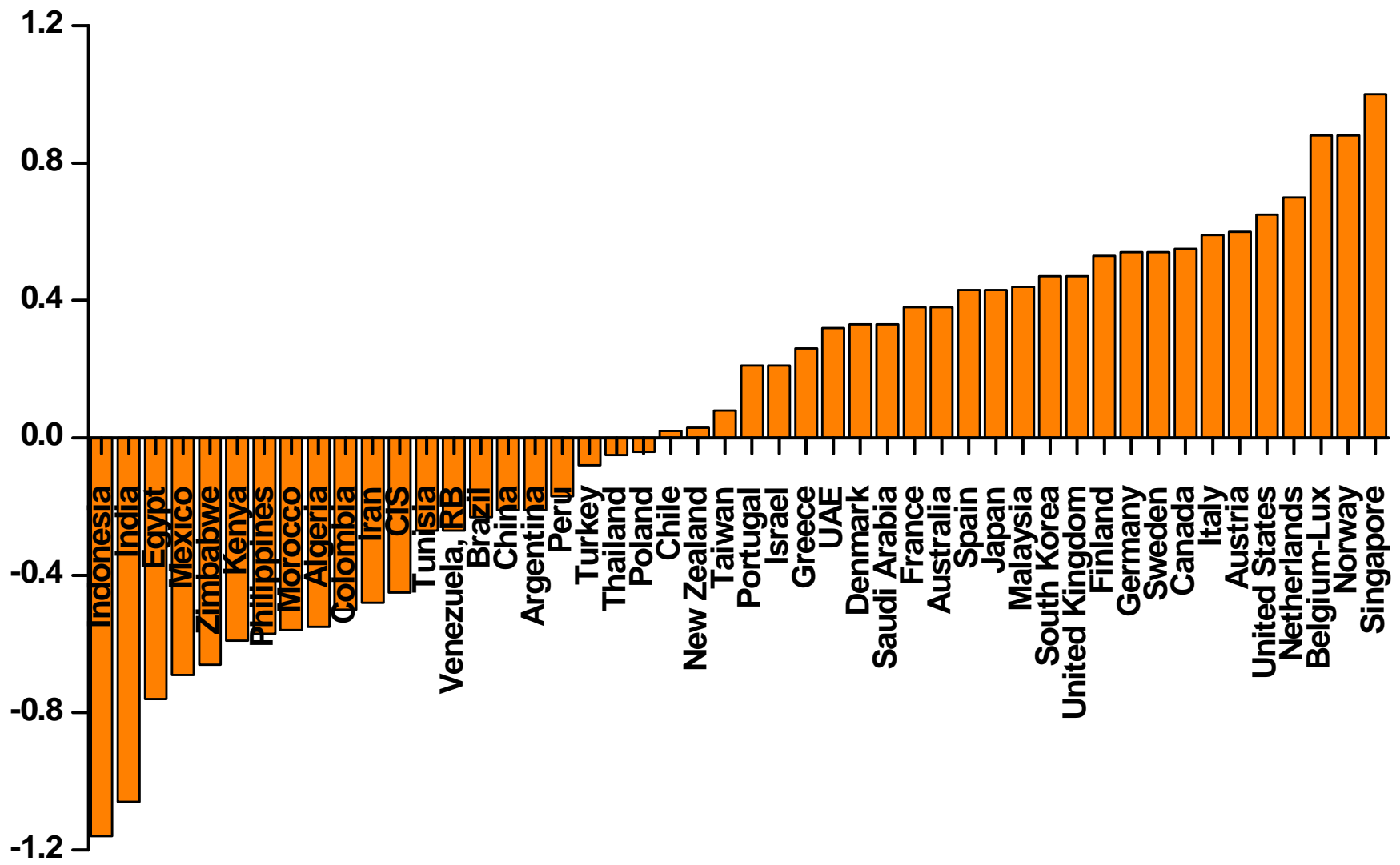
- Metal stocks and flows
- Biofuels
- Water supplies
- Prioritization of flows
- Decoupling
- Innovations
- Institution building

# Metabolic profiles by socio-ecological regimes (DMC/capita)

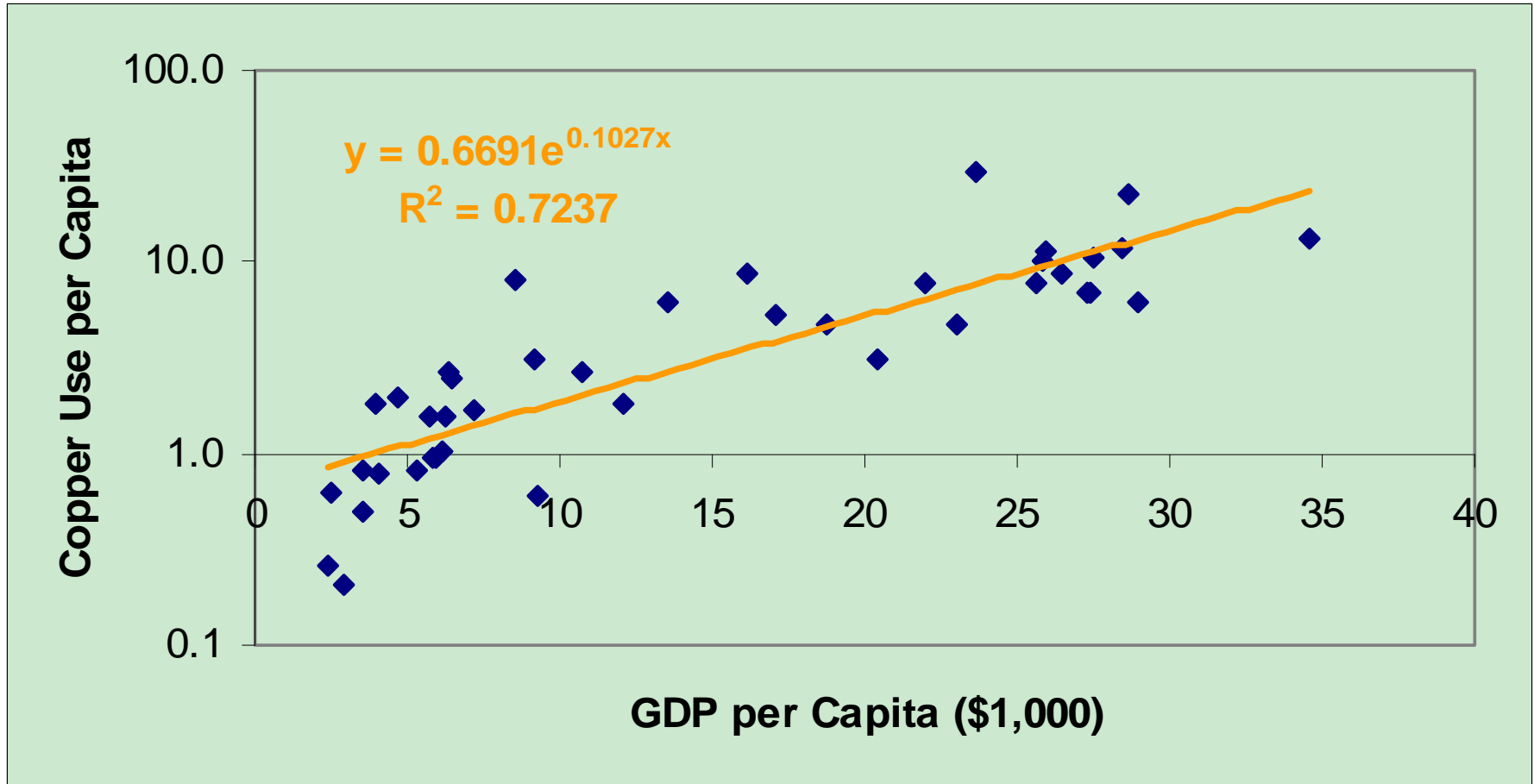


Source: M. Fischer-Kowalski, Vienna

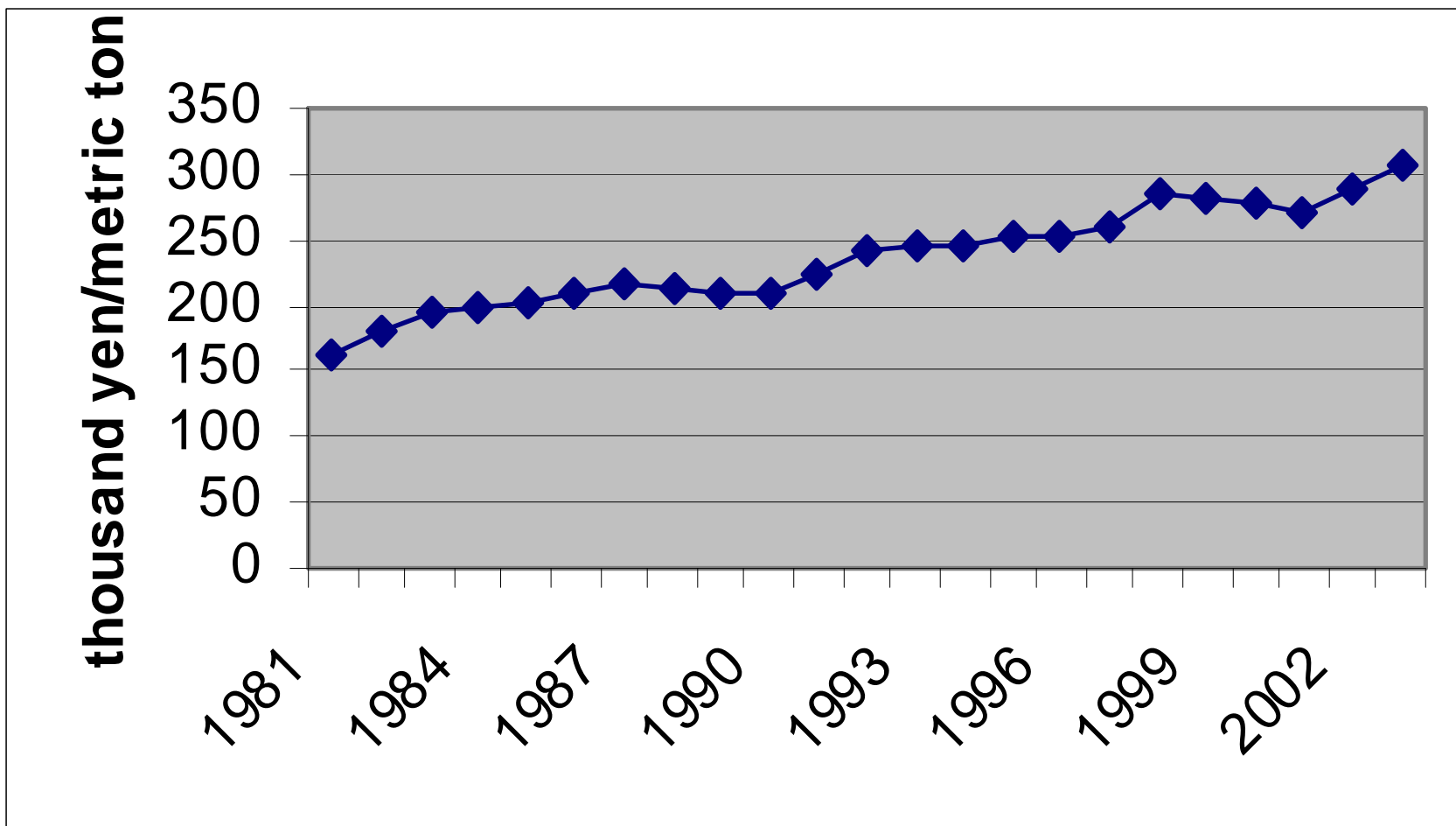
Copper Use per Capita (compared to world average, on log scale)



# Copper Use per Capita Vs GDP per Capita



# “Resource Productivity” in Japan



Source: Y. Moriguchi, NIES, Japan, 2008

# Information on Metal Flow Cycles

IA																	VIIIA																												
1 <b>H</b>	IIA										III A	IV A	VA	VIA	VII A	2 <b>He</b>																													
3 <b>Li</b>	4 <b>Be</b>											5 <b>B</b>	6 <b>C</b>	7 <b>N</b>	8 <b>O</b>	9 <b>F</b>	10 <b>Ne</b>																												
11 <b>Na</b>	12 <b>Mg</b>	III B	IV B	V B	V I B	V II B	VIII B				IB	I I B	13 <b>Al</b>	14 <b>Si</b>	15 <b>P</b>	16 <b>S</b>	17 <b>Cl</b>	18 <b>Ar</b>																											
19 <b>K</b>	20 <b>Ca</b>	21 <b>Sc</b>	22 <b>Ti</b>	23 <b>V</b>	24 <b>Cr</b>	25 <b>Mn</b>	26 <b>Fe</b>	27 <b>Co</b>	28 <b>Ni</b>	29 <b>Cu</b>	30 <b>Zn</b>	31 <b>Ga</b>	32 <b>Ge</b>	33 <b>As</b>	34 <b>Se</b>	35 <b>Br</b>	36 <b>Kr</b>																												
37 <b>Rb</b>	38 <b>Sr</b>	39 <b>Y</b>	40 <b>Zr</b>	41 <b>Nb</b>	42 <b>Mo</b>	43 <b>Tc</b>	44 <b>Ru</b>	45 <b>Rh</b>	46 <b>Pd</b>	47 <b>Ag</b>	48 <b>Cd</b>	49 <b>In</b>	50 <b>Sn</b>	51 <b>Sb</b>	52 <b>Te</b>	53 <b>I</b>	54 <b>Xe</b>																												
55 <b>Cs</b>	56 <b>Ba</b>	57 <b>La</b>	72 <b>Hf</b>	73 <b>Ta</b>	74 <b>W</b>	75 <b>Re</b>	76 <b>Os</b>	77 <b>Ir</b>	78 <b>Pt</b>	79 <b>Au</b>	80 <b>Hg</b>	81 <b>Tl</b>	82 <b>Pb</b>	83 <b>Bi</b>	84 <b>Po</b>	85 <b>At</b>	86 <b>Rn</b>																												
87 <b>Fr</b>	88 <b>Ra</b>	89 <b>Ac</b>	<table border="1" style="width: 100%; border-collapse: collapse; text-align: center;"> <tr> <td>58 <b>Ce</b></td> <td>59 <b>Pr</b></td> <td>60 <b>Nd</b></td> <td>61 <b>Pm</b></td> <td>62 <b>Sm</b></td> <td>63 <b>Eu</b></td> <td>64 <b>Gd</b></td> <td>65 <b>Tb</b></td> <td>66 <b>Dy</b></td> <td>67 <b>Ho</b></td> <td>68 <b>Er</b></td> <td>69 <b>Tm</b></td> <td>70 <b>Yb</b></td> <td>71 <b>Lu</b></td> </tr> <tr> <td>90 <b>Th</b></td> <td>91 <b>Pa</b></td> <td>92 <b>U</b></td> <td colspan="11"></td> </tr> </table>															58 <b>Ce</b>	59 <b>Pr</b>	60 <b>Nd</b>	61 <b>Pm</b>	62 <b>Sm</b>	63 <b>Eu</b>	64 <b>Gd</b>	65 <b>Tb</b>	66 <b>Dy</b>	67 <b>Ho</b>	68 <b>Er</b>	69 <b>Tm</b>	70 <b>Yb</b>	71 <b>Lu</b>	90 <b>Th</b>	91 <b>Pa</b>	92 <b>U</b>											
58 <b>Ce</b>	59 <b>Pr</b>	60 <b>Nd</b>	61 <b>Pm</b>	62 <b>Sm</b>	63 <b>Eu</b>	64 <b>Gd</b>	65 <b>Tb</b>	66 <b>Dy</b>	67 <b>Ho</b>	68 <b>Er</b>	69 <b>Tm</b>	70 <b>Yb</b>	71 <b>Lu</b>																																
90 <b>Th</b>	91 <b>Pa</b>	92 <b>U</b>																																											



Complete multi-level cycle



More than one single country cycle



One single country cycle

# Metal Linkages in the New Mineralogy

[2000s]

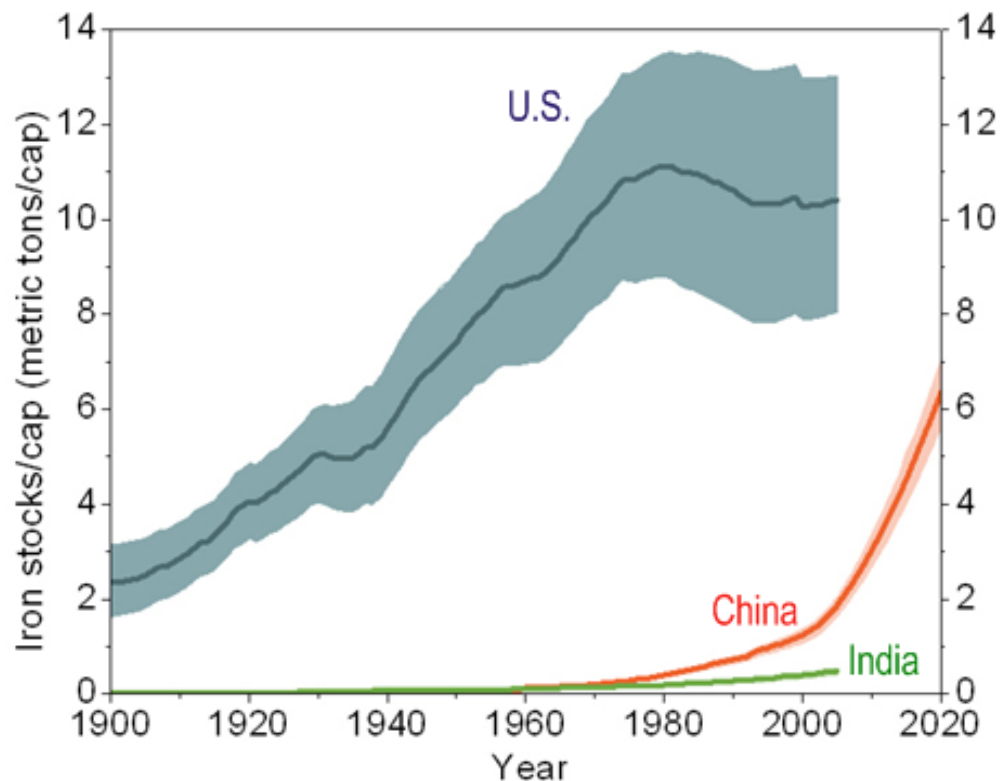
1 H 1.0079																	18 Ar 39.948																		
3 Li 6.941	4 Be 9.0122															19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.867	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.38	31 Ga 69.723	32 Ge 72.64	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.798		
11 Na 22.990	12 Mg 24.305															37 Rb 85.468	38 Sr 87.62	39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 101.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.6	53 I 126.91	54 Xe 131.29		
19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.867	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.38	31 Ga 69.723	32 Ge 72.64	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.798	37 Rb 85.468	38 Sr 87.62	39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 101.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.6	53 I 126.91	54 Xe 131.29
55 Cs 132.91	56 Ba 137.33	57-71 *	72 Hf 178.49	73 Ta 180.95	74 W 183.84	75 Re 186.21	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)	87 Fr (223)	88 Ra (226)	89-103 Ac	104 Rf (261)	105 Db (262)	106 Sg (263)	107 Bh (264)	108 Hs (265)	109 Mt (266)	110 Ds (267)	111 Rg (268)	112 Cn (269)	113 Nh (270)	114 Fl (271)	115 Mc (272)	116 Lv (273)	117 Ts (274)	118 Og (276)
87 Fr (223)	88 Ra (226)	89-103 Ac	104 Rf (261)	105 Db (262)	106 Sg (263)	107 Bh (264)	108 Hs (265)	109 Mt (266)	110 Ds (267)	111 Rg (268)	112 Cn (269)	113 Nh (270)	114 Fl (271)	115 Mc (272)	116 Lv (273)	117 Ts (274)	118 Og (276)																		
57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.05	71 Lu 174.96	89 Ac (227)	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)						
89 Ac (227)	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)																					

Source: T. McManus, Intel Corp., 2006

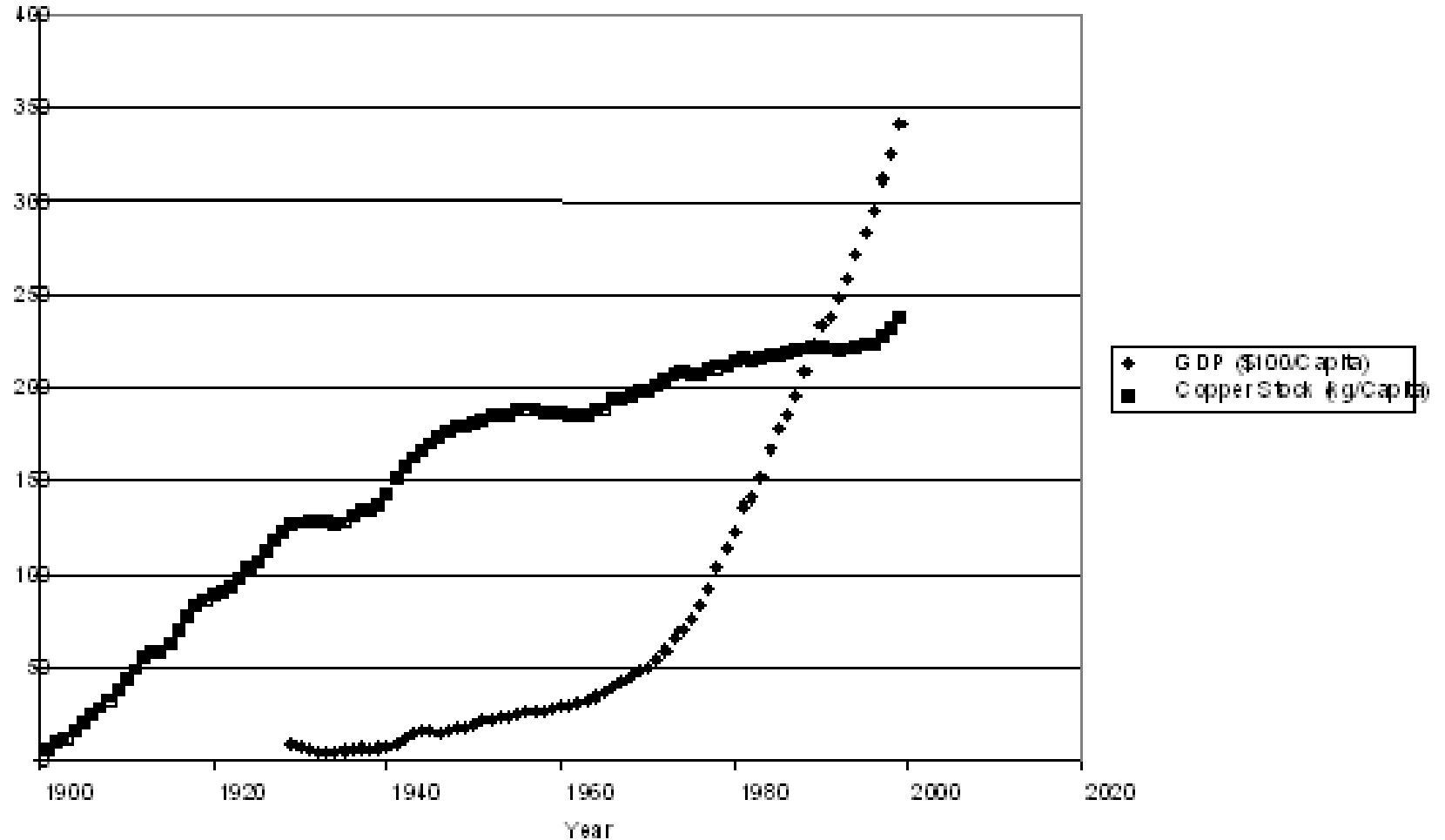
A Key Question for the Future:  
How Much Material Will People Use?

# Dynamics of in-use stocks provide clues about future iron use

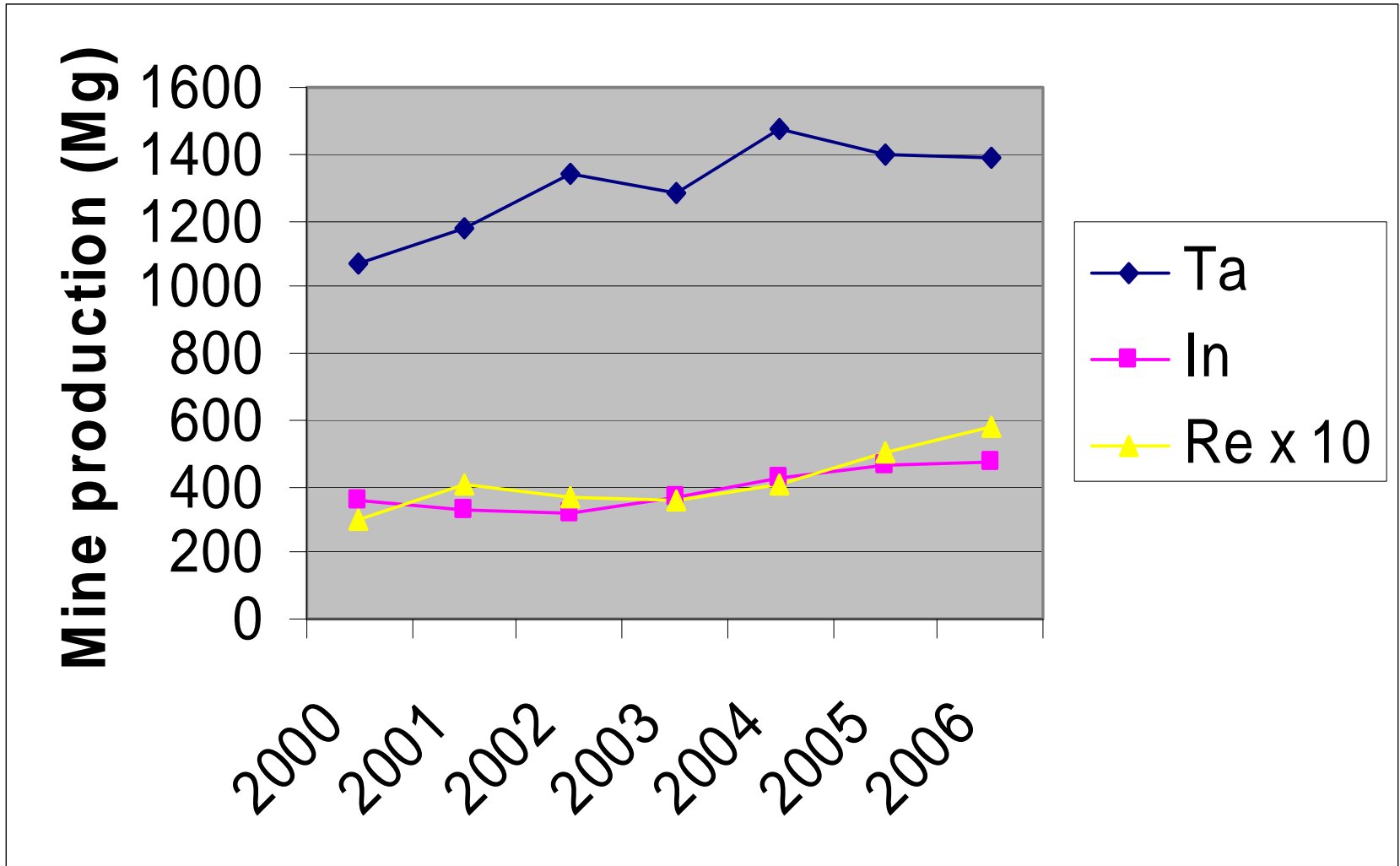
- Saturation hypothesis of in-use stocks proposed by Müller et al., *PNAS*, **44**, 16111-16116, 2006
- Per capita iron stocks in industrialized countries are predictors of metal stock increase and use in developing countries



# Copper per capita stock in the US



# World Use of Specialty Metals



Data source: U.S. Geological Survey

# Summary

- We can probably estimate how much of the base metals (Fe, Al, Cu, Ni, Cr, Pb) we will need in the coming decades
- We do not have the information to do the same for most other resources
- Sustainable resource management required statistics are not yet adequate
- Nonetheless, we suspect that supplies of some widely used materials (Pt, Cu, Co, In?) may be severely challenged in the next decade or two