EPSO Workshop
The Feed Value Chain, June 26-27 2007
Faculty of Life Sciences, University of Copenhagen

Improving the micronutrient content of crops using agronomic and genetic approaches: selenium (Se) as a case study

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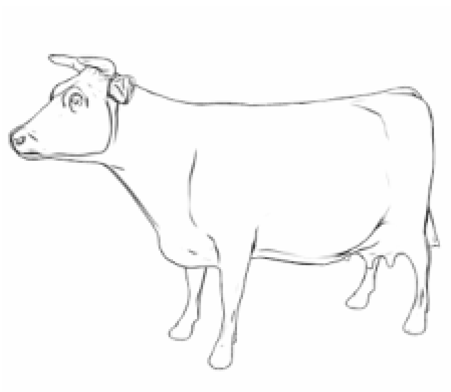
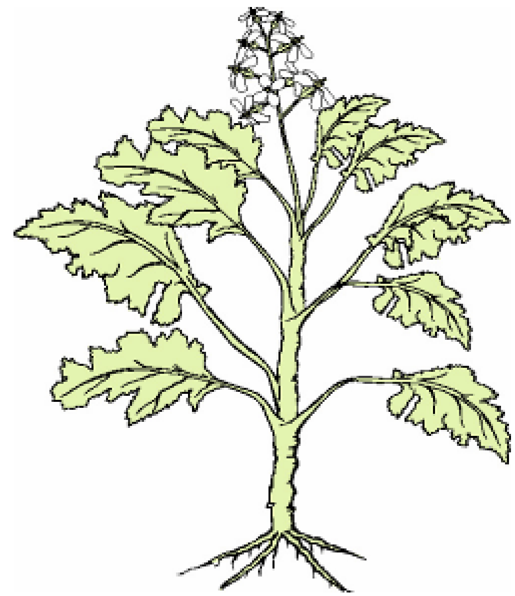
The University of Nottingham

scri living technology

Essential mineral elements in mammals and plants



(>)25 essential mineral elements



(>)17 essential mineral elements

Essential mineral elements in humans

Table 1. Essential mineral elements required by humans[a]

Element	RDA	RNI	UL	SUL	Antinutrients	Promoters
N	NS	NS	NS	NS		
S	NS	NS	NS	NS		
K (mg)	1600–3500	3500	NS	3700[b]		
Cl (mg)	750–3400	2500	NS	NS		
Ca (mg)	1000–1200	700	2500	1500[b]	Oxalate, phytate, tannins, fiber	Inuline
P (mg)	700	550	4000	250[b]		
Na (mg)	500–2400	1600	<2400	NS		
Mg (mg)	310–420	300	350[b]	400[b]	Phytate	
Fe (mg)	8.0–18.0	11.4	45.0	17.0[b]	Phytate, tannins, oxalate, fiber, hemaglutinins	Phytoferritin, riboflavin, ascorbate, β-carotene, cysteine, histidine, lysine, fumarate, malate, citrate
Zn (mg)	8.0–11.0	9.5	40.0	25.0[b]	Phytate, tannins, fiber, hemaglutinins	Palmitic acid, riboflavin, ascorbate, cysteine, histidine, lysine, methionine, fumarate, malate, citrate
Mn (mg)	1.8–2.3	>1.4	11.0	4.0[b]		
Cu (mg)	0.9	1.2	10.0	10.0		
I (μg)	150	140	1100	500[b]	Goitrogens	Selenium
Se (μg)	55	75	400	450		
Mo (μg)	45	50–400	2000	NS		
Cr (μg)	25–35	>25	NS	NS		
F (mg)	3–4	NS	10	NS		
B (mg)	NS	NS	20.0	9.6		
Ni (μg)	NS	NS	1000	260		
V (mg)	NS	NS	1.8	NS		
Si (mg)	NS	NS	NS	1500		
As	NS	NS	NS	NS		

Abbreviations: NS, none specified.

[a]The US recommended daily allowances (RDA, or adequate intakes), the UK guidance daily reference nutrient intakes (RNI), the US tolerable upper intake levels (UL), and the UK guidance safe upper levels (SUL) for adults (http://www.food.gov.uk/multimedia/pdfs/vitmin2003.pdf, [96]). The required amounts of N and S can be obtained if the recommended daily protein intake is achieved.

[b]Non-food.

White PJ, Broadley MR (2005). Biofortifying crops with essential mineral elements. *Trends in Plant Science*, 10, 586-593.

Human mineral malnutrition is widespread

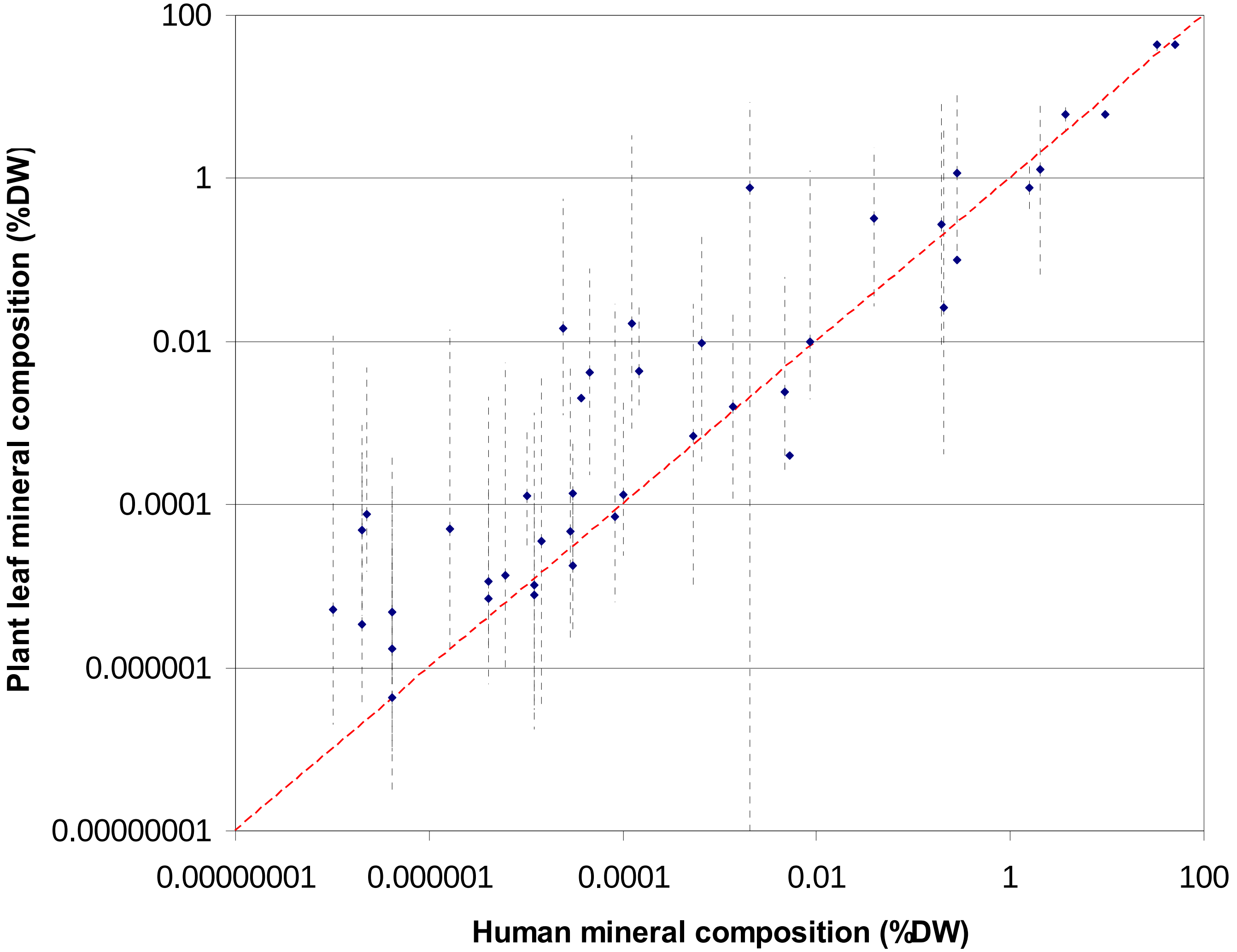
60-80% of world's population is Fe deficient

>30% Zn and I deficient

>15% Se / Mg / Ca / Cu deficient

White PJ, Broadley MR (2005). Biofortifying crops with essential mineral elements. *Trends in Plant Science*, 10, 586-593.

Concentration of 43 mineral elements in humans and plants



Sources:

Broadley MR, Bowen HC, Cotterill HL, Hammond JP, Meacham MC, Mead A, White PJ. (2004). Phylogenetic variation in the shoot mineral concentration of angiosperms. *Journal of Experimental Botany*, 55, 321-336.

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Marschner H. (1995). *Mineral Nutrition of Higher Plants, 2nd Edition*. Academic Press, London, UK.

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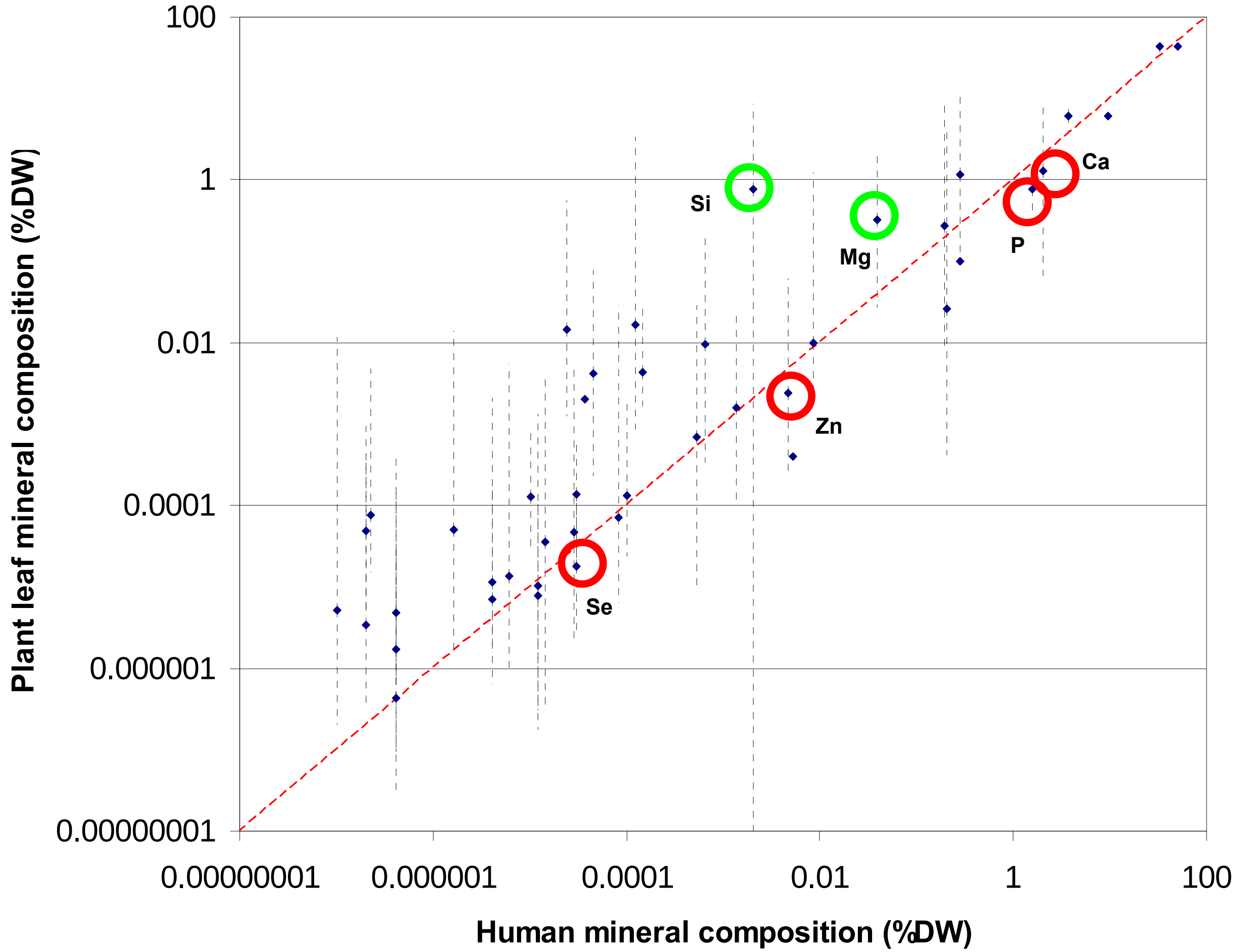

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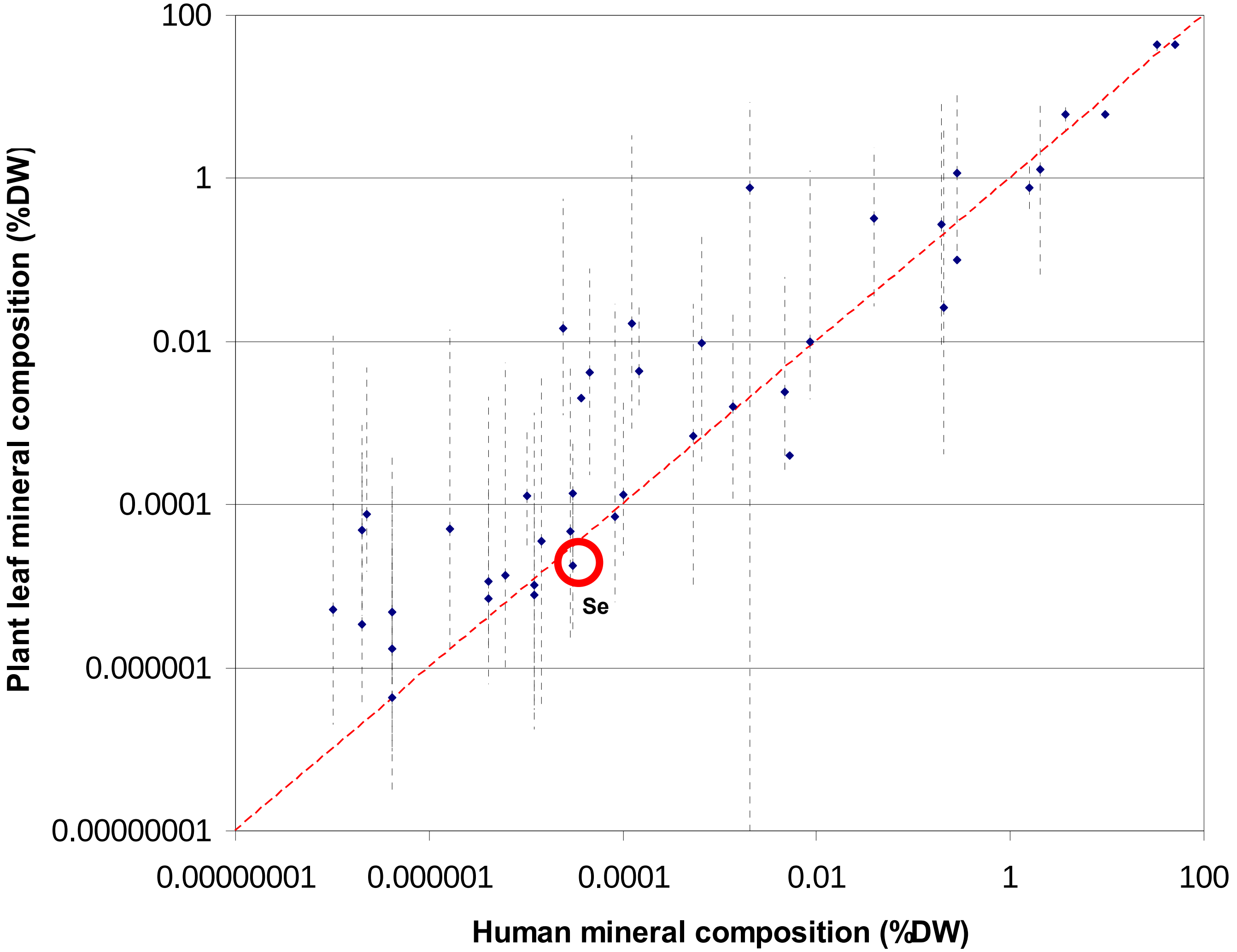
Selenium as a case study



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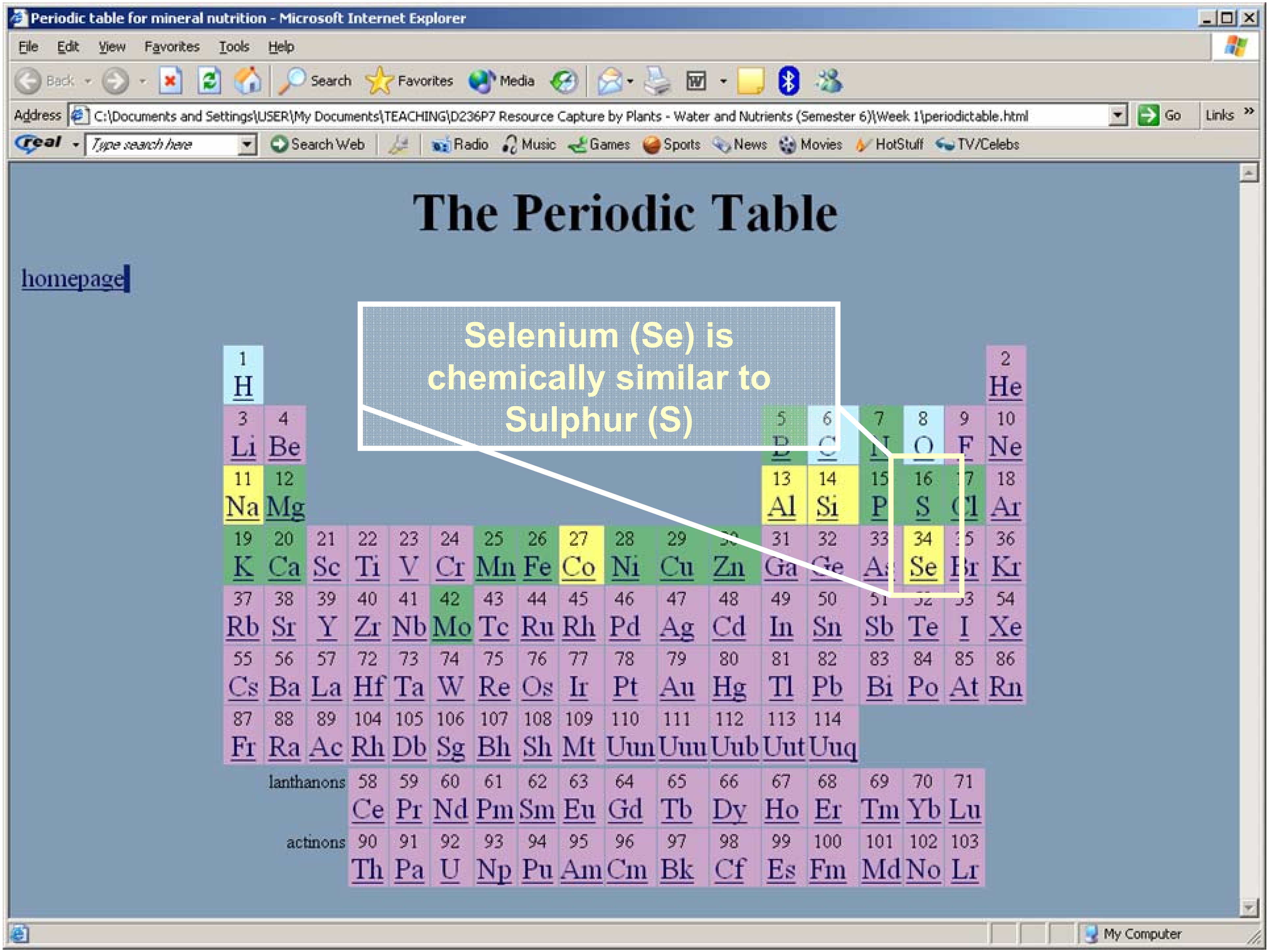
A brief history of selenium (Se)

Discovered in 1817

70th most abundant element on earth (out of 88)

Chemically similar to sulphur (S)


Periodic table for mineral nutrition - Microsoft Internet Explorer
The Periodic Table
homepage
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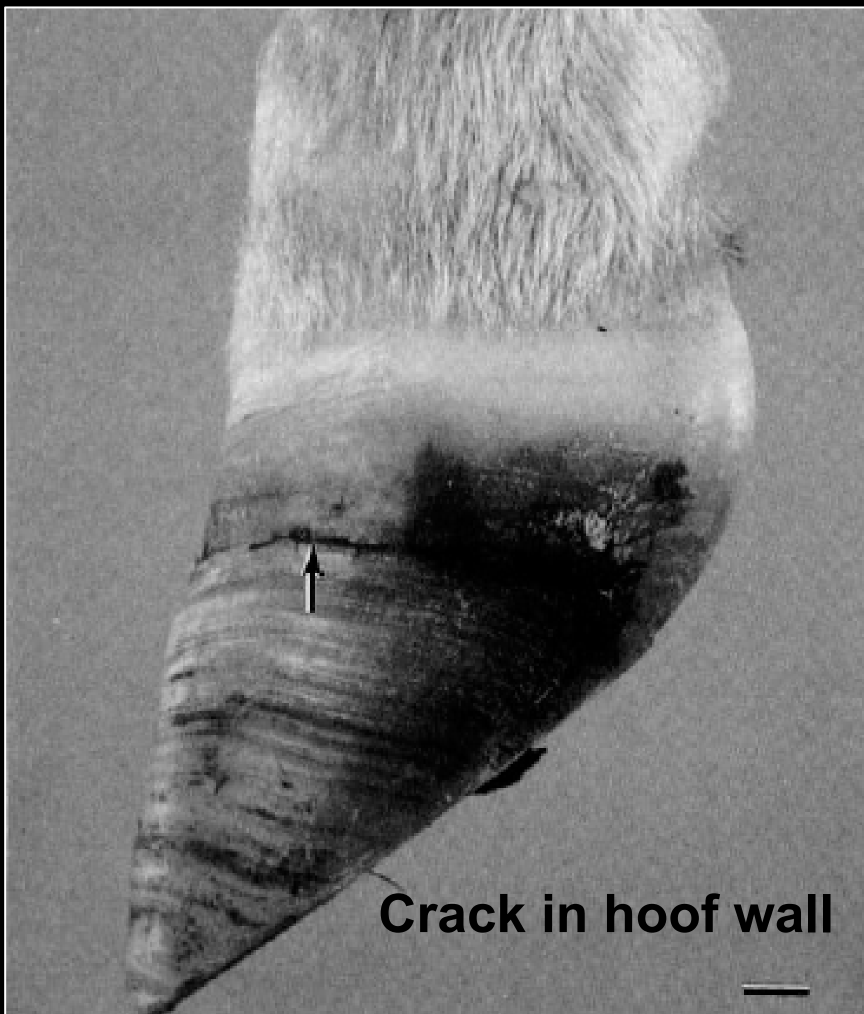

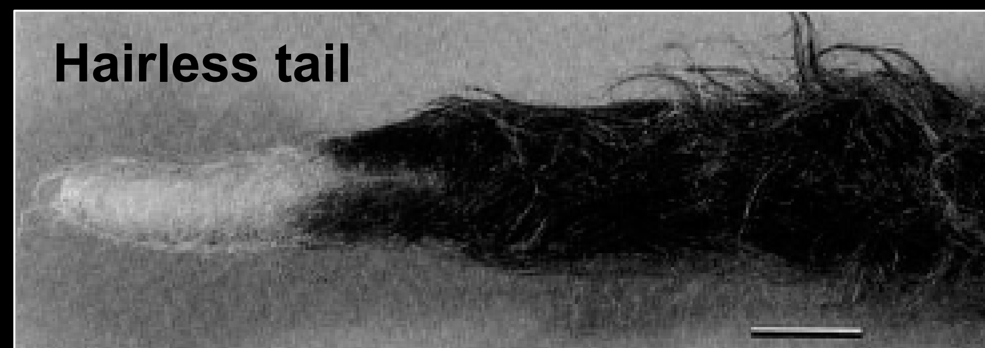

O'Toole & Raisbeck (1995) J. Vet. Diagn. Invest. 7: 364-373

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1930 - associated with toxicity in cattle (blind staggers, alkali disease)

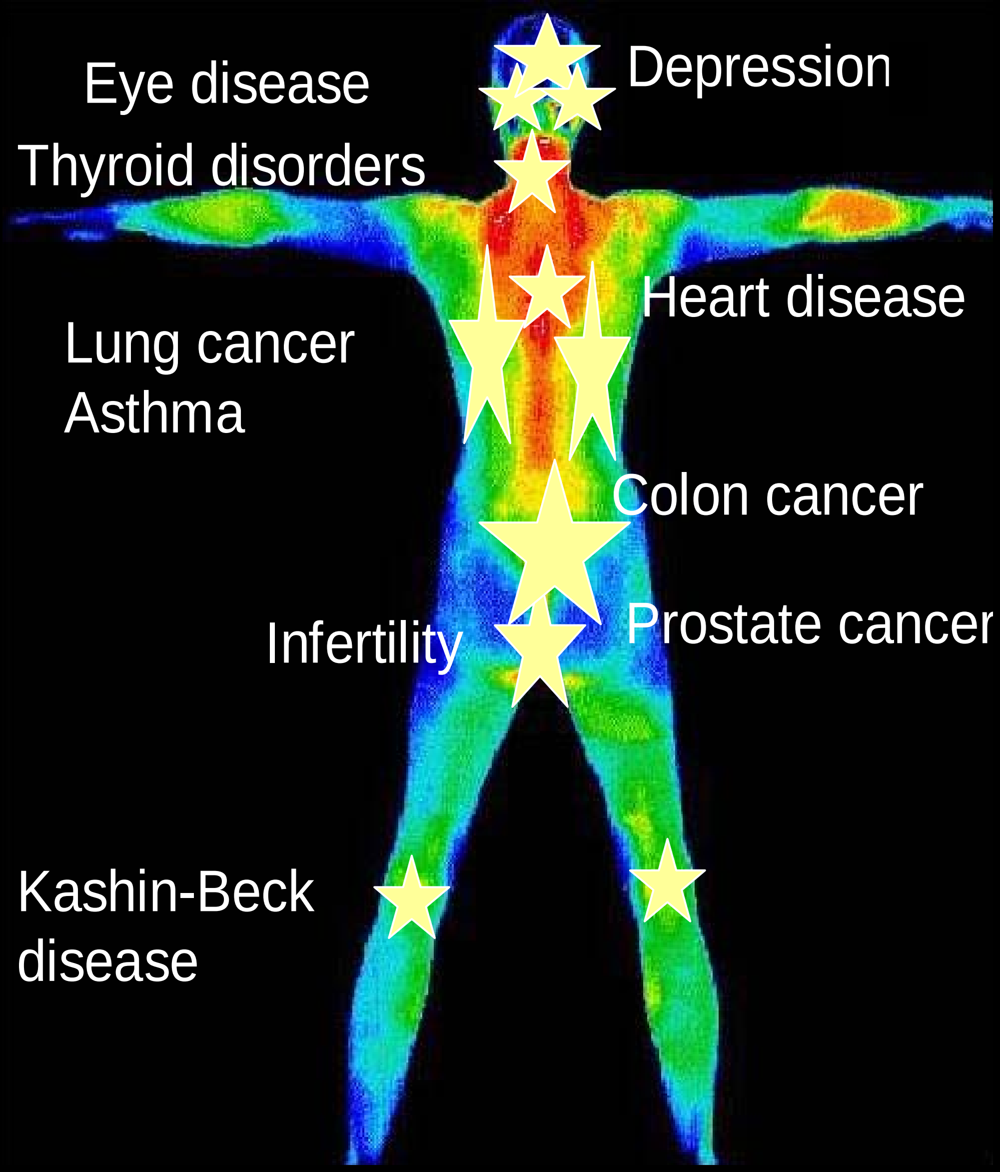
1957 - Se identified as an essential nutrient in rats

1971 - glutathione peroxidase identified as a selenoprotein

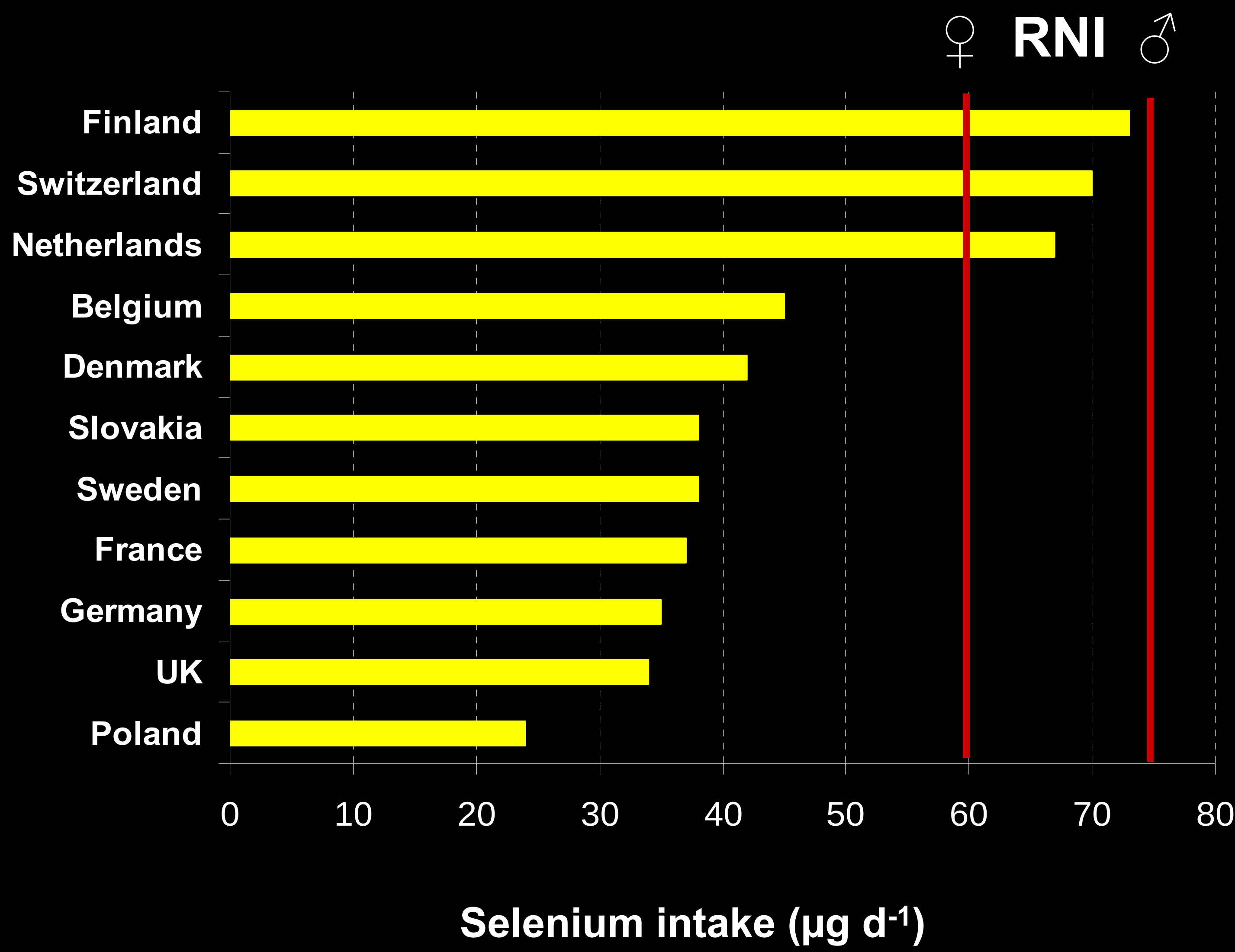
~35 mammalian selenoproteins identified to date

Low Se status associated with increased health risks

- **Impaired immune function**
- **Impaired thyroid function**
- **Cardiovascular disorders**
  (e.g. Keshan disease)
- **Male infertility**
- **Increased risk of cancer**
- **Animals:**
  fertility, white muscle disease

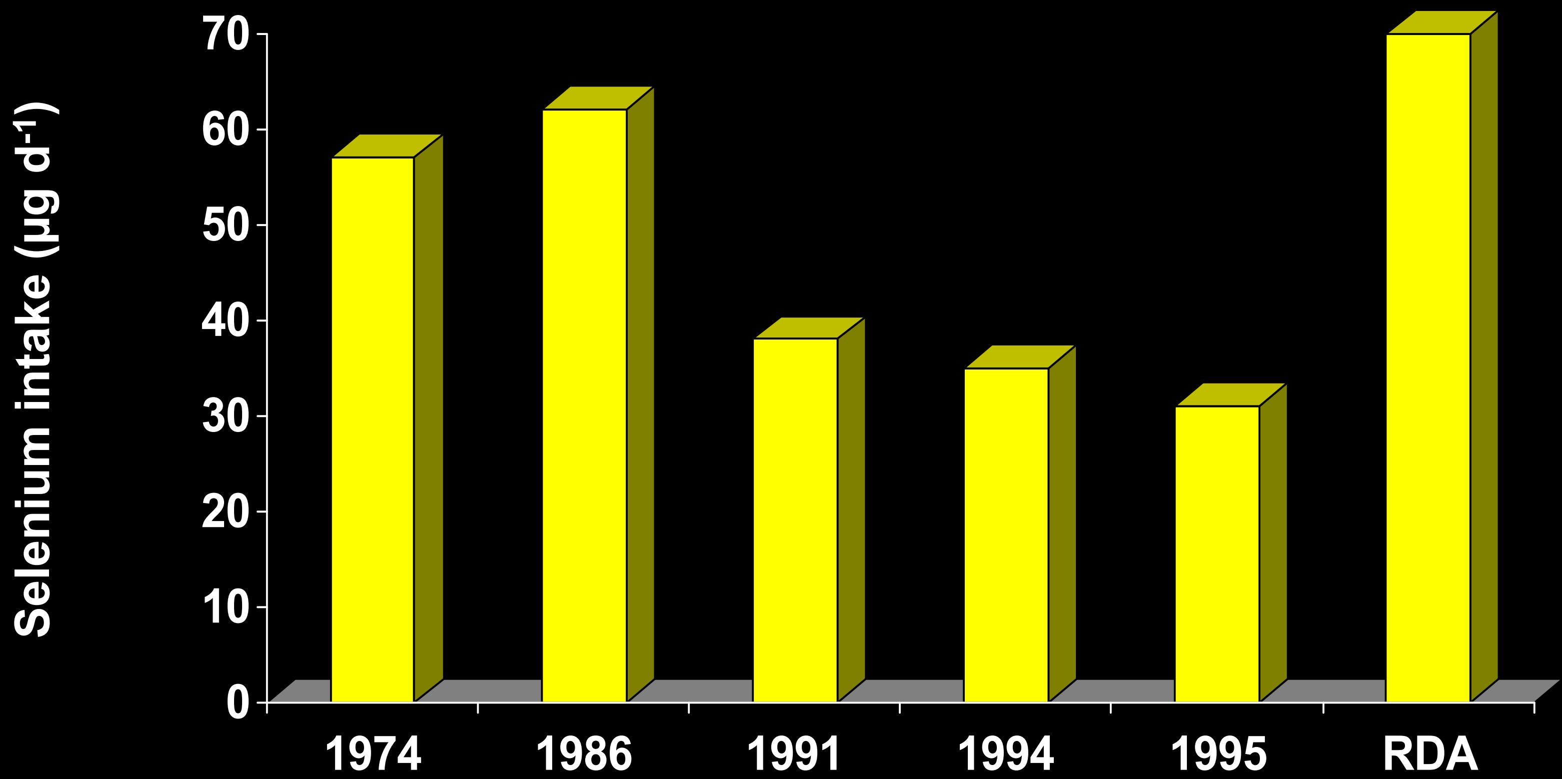


European dietary Se intakes



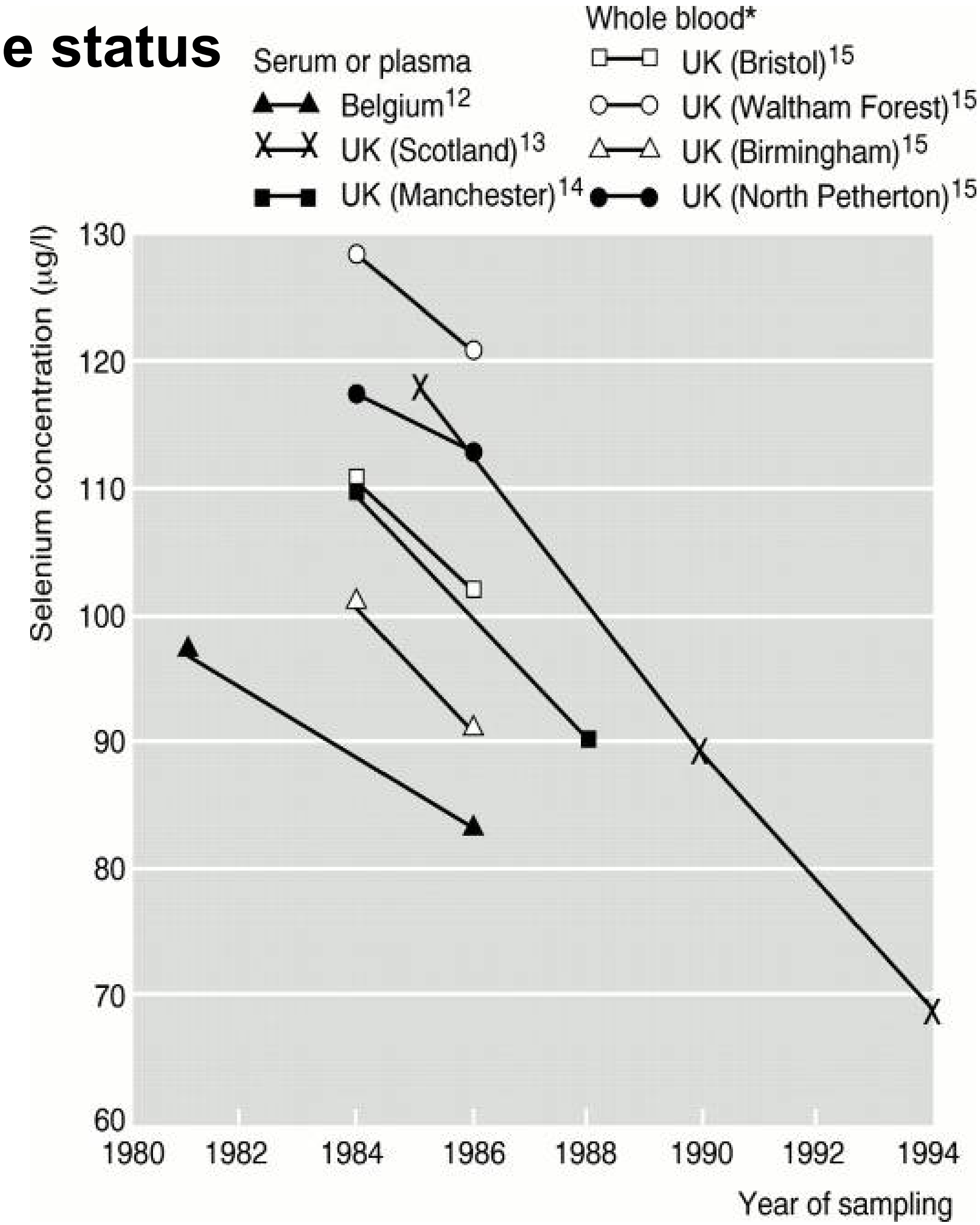
Rayman MP 2000. *The Lancet*, 356, 233-241.

UK Se intake has declined



UK Ministry of Agriculture, Fisheries and Food (MAFF), Food Surveillance Information Sheet, 1999

Decline in UK Se status



Rayman MP 1997. *British Medical Journal*, 314, 387-388.

Why has UK Se intake (& status) declined ?

UK wheat in milling blends 15% in 1950s, >80% in 2005. Replacing American and Canadian wheat (*Arable Farming*, 6th June, 2005)

Se in UK bread-making wheat up to 40x lower than American and Canadian wheat…

Haygarth PM et al., 1993. *Journal of Geophysical Research-Atmospheres* 98, 16769-16776.
Lyons G et al., 2003. *Nutrition Research Reviews* 16, 45-60.
Broadley MR et al., 2006. *Proceedings of the Nutrition Society*, 65, 169-181.

Low baseline selenium in UK wheat

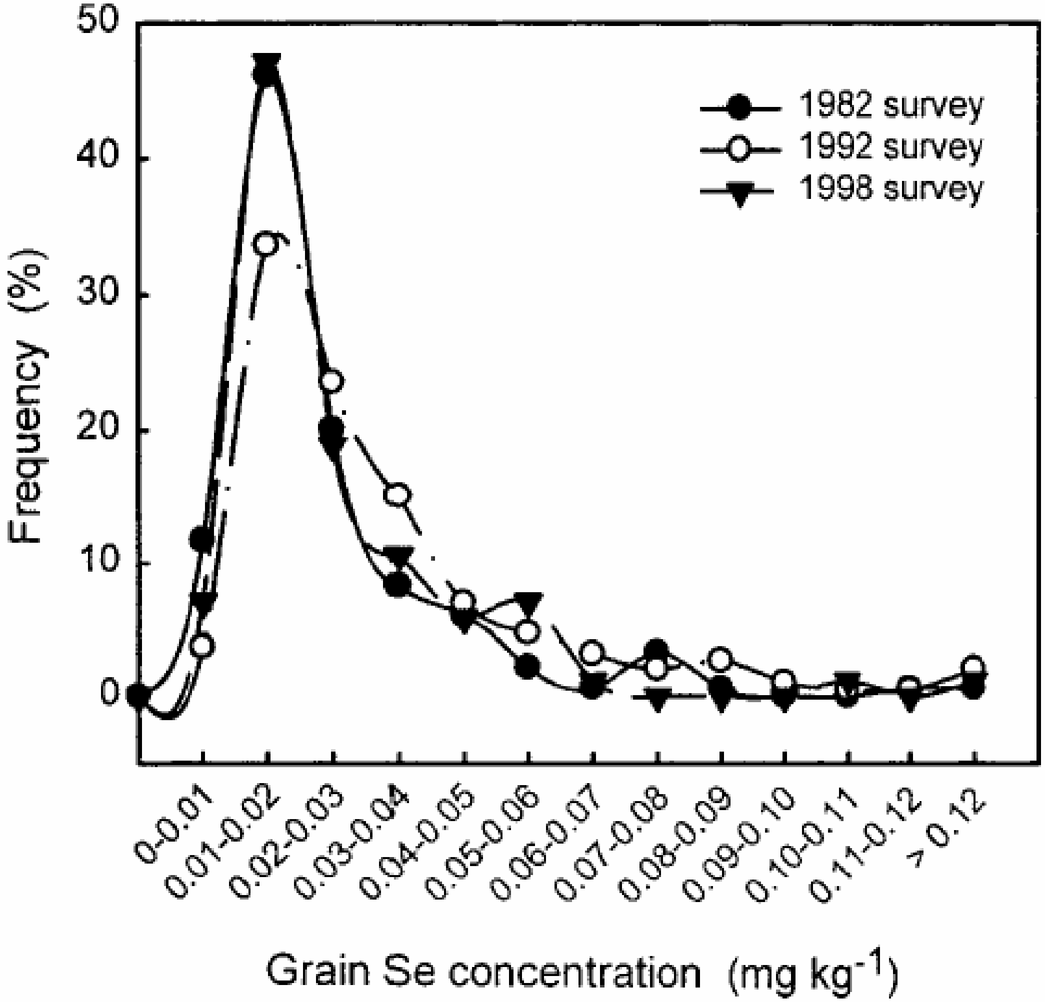


Figure 1. Distribution of selenium in bread-making wheat grain varieties collected from representative sites throughout the UK during 1982 (n=180), 1992 (n=187) and 1998 (n=85).

*****US and Canadian wheat contains 0.370-0.760 mg kg^{-1}**

Adams ML et al. 2002. *Journal of the Science of Food and Agriculture*, 82, 1160-1165.

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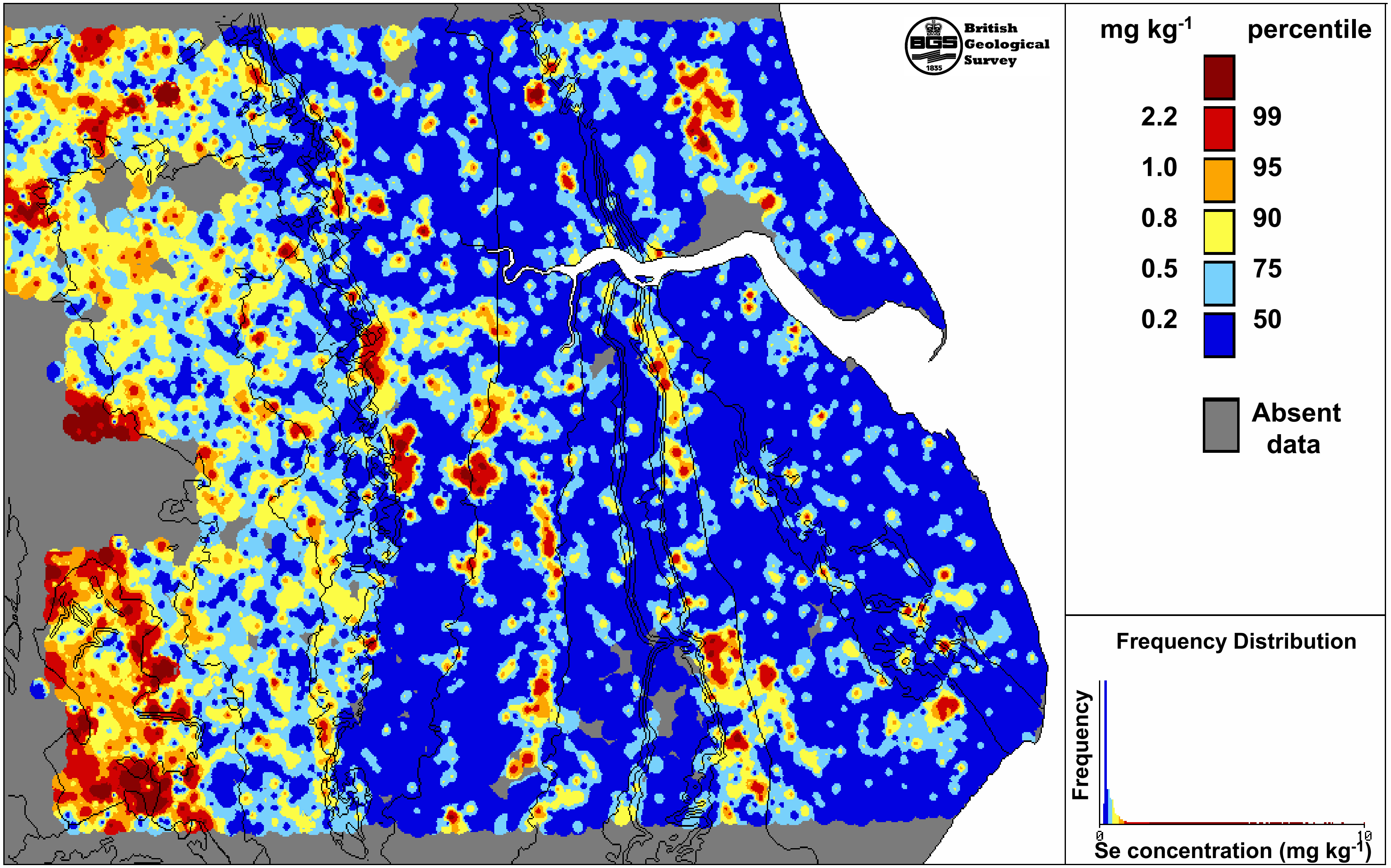
Low baseline selenium in UK soils



British Geological Survey

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Se in UK soils has declined due to cleaner (phosphate) fertilisers

Cleaner fossil fuel technologies: less Se deposited to soils and crops

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What options are currently available to rectify Se-deficient diets ?

- **Strategy 1: Flour fortification**
- **Strategy 2: Human supplements**
- **Strategy 3: Livestock supplements (licks, boluses, tablets, Sel-Plex®)**
- **Strategy 4: Se fertiliser applications (*agronomic biofortification*)**
- **Strategy 5: Breed crops with more Se in edible portions (*genetic biofortification*)**

What options are currently available to rectify Se-deficient diets ?

- Strategy 1: Flour fortification

Requires changes in legislation. Se is highly toxic >800 µg Se d^{-1} $person^{-1}$ which poses logistical problems, unlikely to be implemented

What options are currently available to rectify Se-deficient diets ?

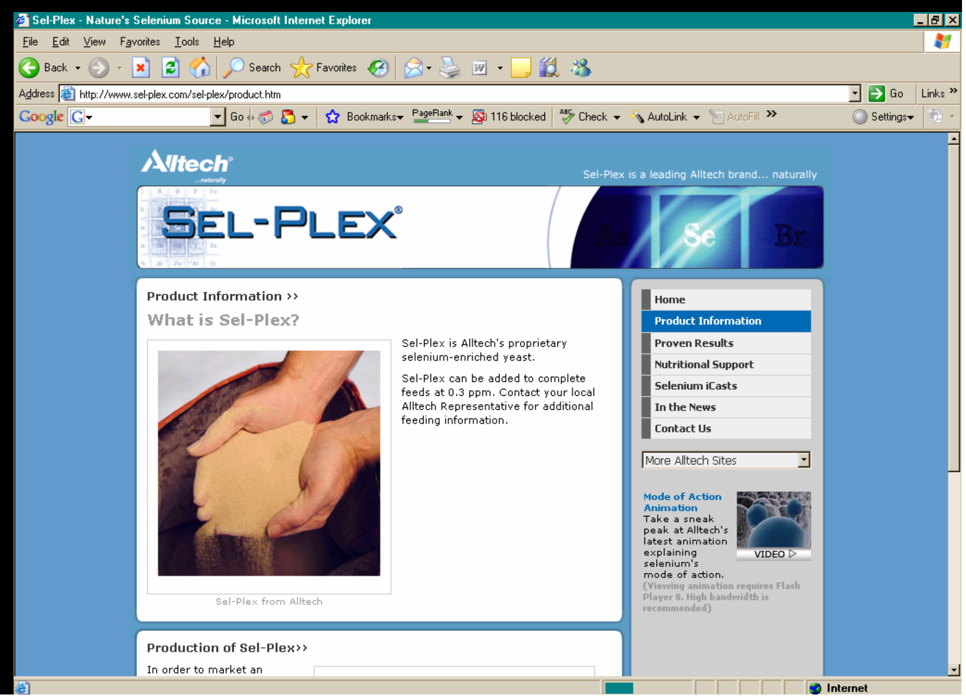
- **Strategy 2: Human supplements**

Feasible, expensive, does not penetrate most socio-economic groups. Again, Se highly toxic >800 µg Se d^{-1} $person^{-1}$ ("mega-doses" outlawed in EU)

What options are currently available to rectify Se-deficient diets ?

- **Strategy 3: Livestock supplements (licks, boluses, tablets, Sel-Plex®)**

Already used for animal health, some dietary forms are potentially expensive (e.g. 10 euros per bolus), effect of supra-optimal Se diets not known, Se-forms in different tissues not known



What options are currently available to rectify Se-deficient diets ?

- **Strategy 4: Se fertiliser applications (*agronomic biofortification*)**

Practised in Finland since 1984 (government driven), used widely elsewhere for livestock supplementation (animal health and fertility)

Increasing dietary Se by fertilising crops

In Finland, mandatory addition of Se to fertilisers (1984-1991, 16 / 6 mg kg^{-1})

1991, all lowered to 6 mg kg^{-1}

1998 it was increased to 10 mg kg^{-1}

mg Se kg^{-1} DM in retail food

	1984	1990	1992
Wheat bread	0.05	0.23	0.14
Potatoes	<0.01	0.11	0.07
Beef, steak	0.17	0.64	0.54
Pork, fillet	0.35	1.09	0.84
Milk, whole	0.06	0.23	0.17

Varn et al., 1993

Processor / consumer drivers ?

1448 ng Se g^{-1} DW

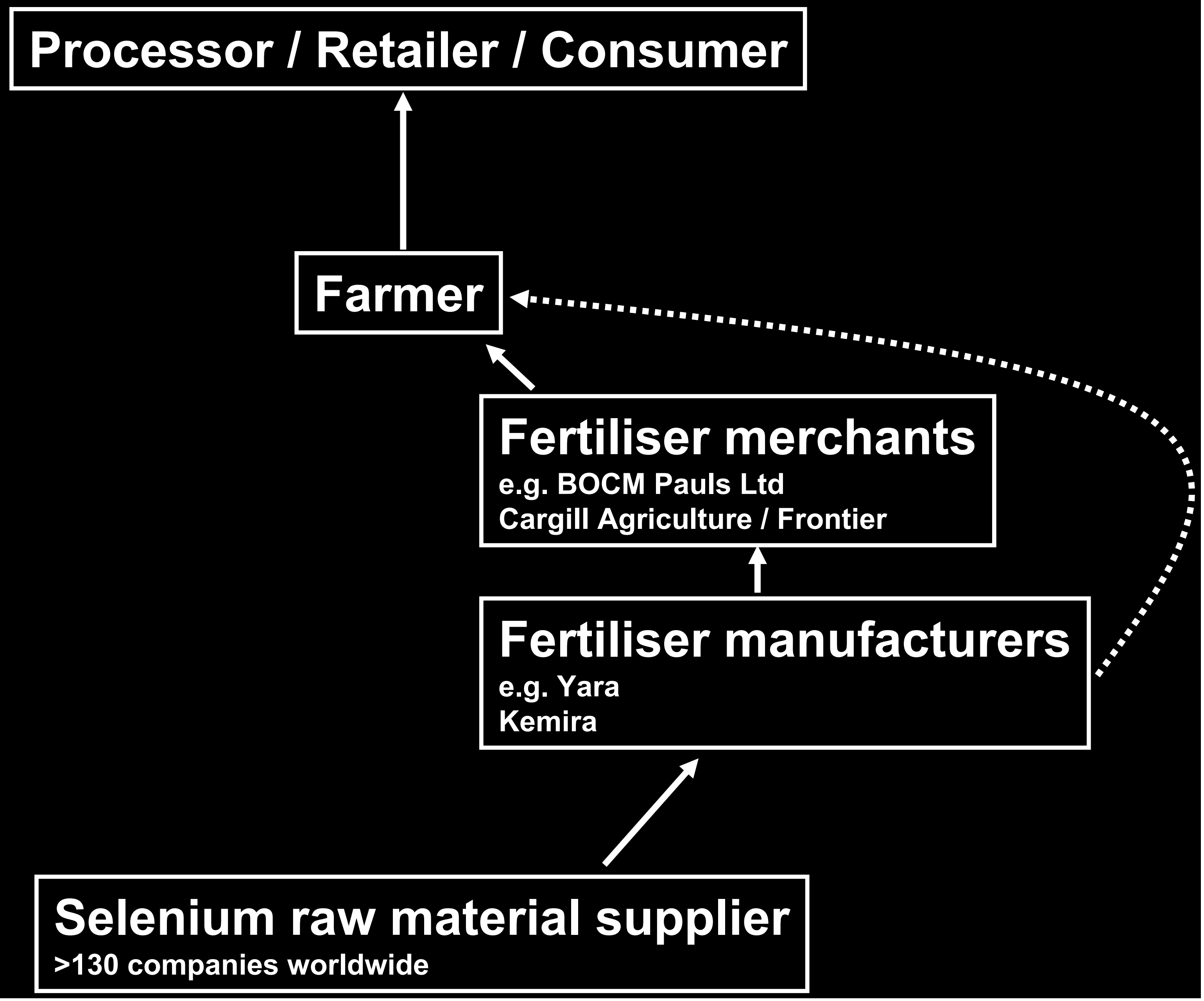
Launched in UK February 2005, discontinued November 2005, lack of consumer take-up.

What options are currently available to rectify Se-deficient diets ?

- **Strategy 5: Breed crops with more Se in edible portions (*genetic biofortification*)**

Unproven, genetic potential exists within plant kingdom [Se *hyperaccumulators*]

Current R&D: adding value to the bread-wheat chain



Current R&D: adding value to the bread-wheat chain

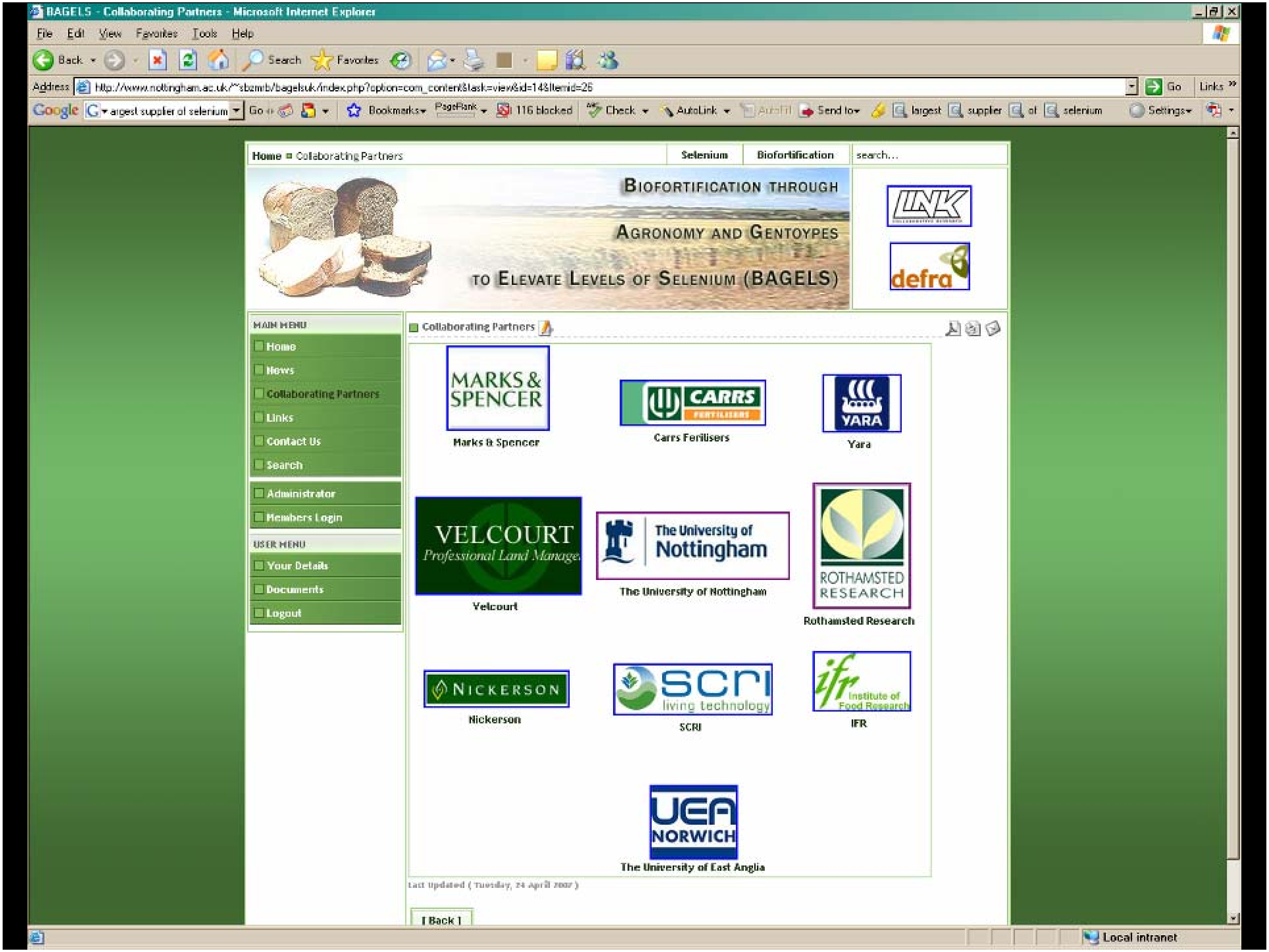
UK government / industry-funded project 2005-2009

"Biofortification through agronomy and genotypes to elevate levels of Se"

Project aims:

1. **Optimise Se fertilisation application rates and forms**
2. **Determine fate and speciation of Se in soils**
3. **Quantify genotypic variation in Se accumulation in wheat**
4. **Determine 'carry-through' of Se species (total Se, selenomethionine, Se methylselenocysteine) from raw material to final product.**

defra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Last Updated (Tuesday, 24 April 2007)
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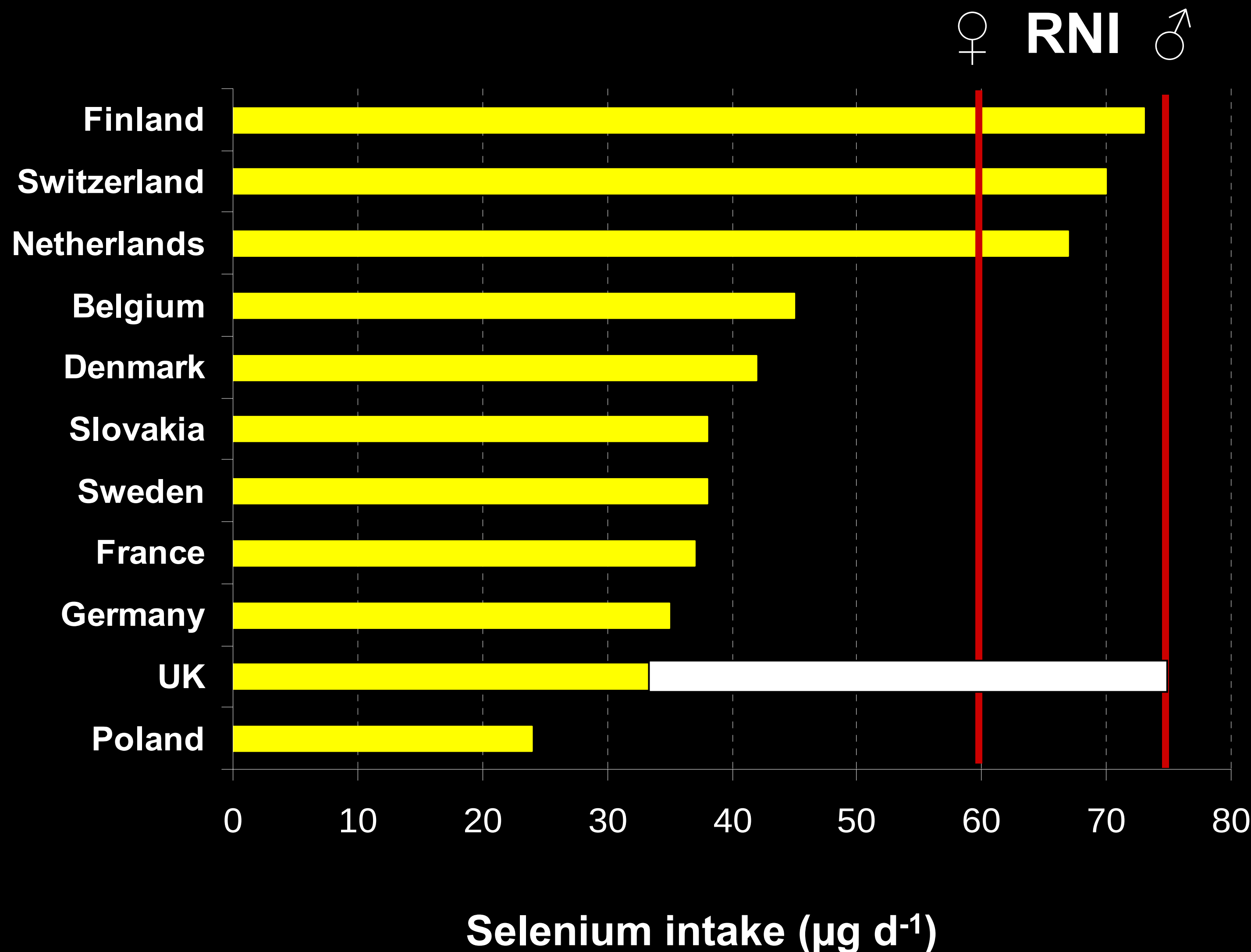
Local intranet


Winter-wheat experiments at five UK sites: 2005-2009
University of Nottingham, Sutton Bonington Farm, 2006

European dietary Se intakes



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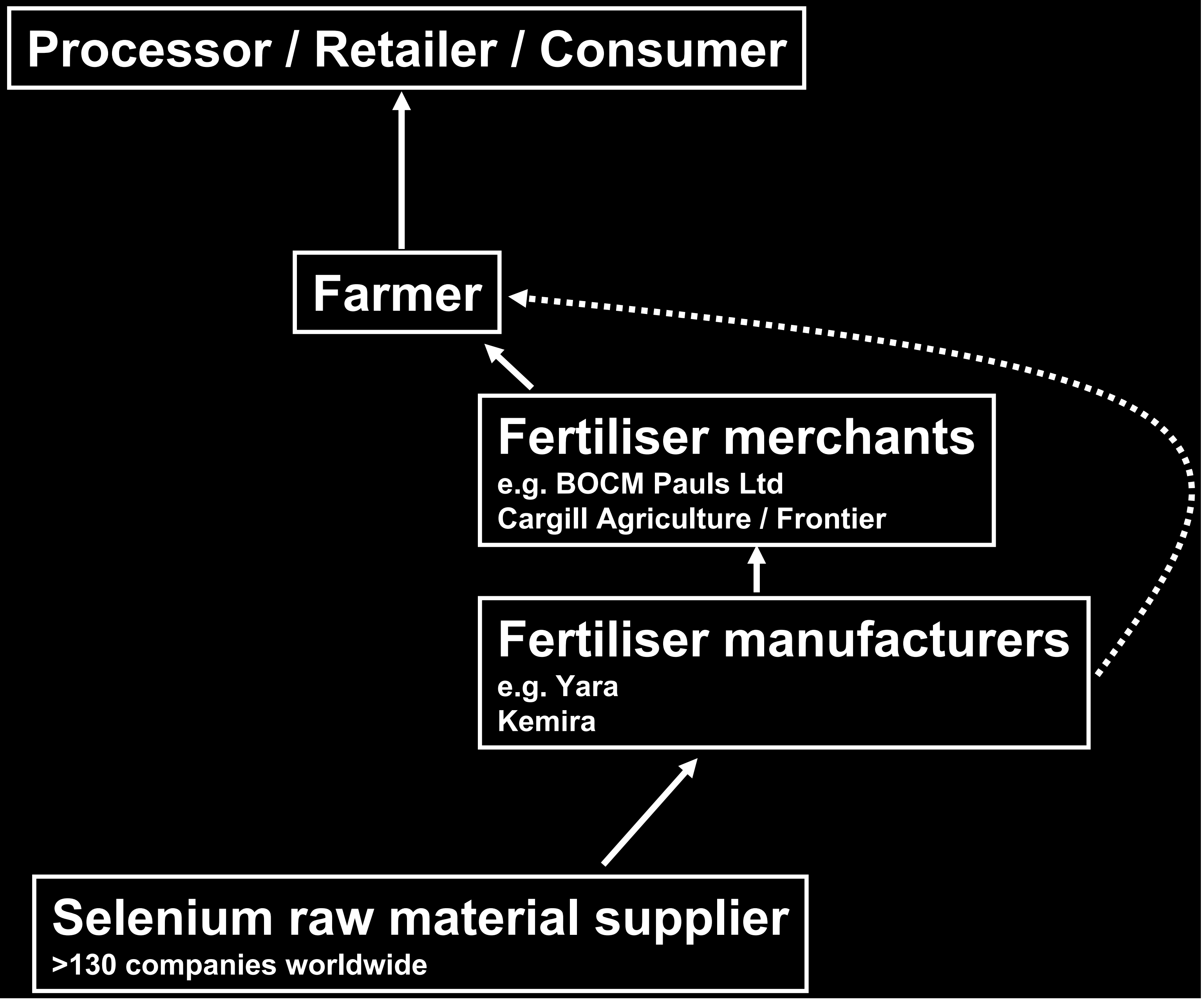
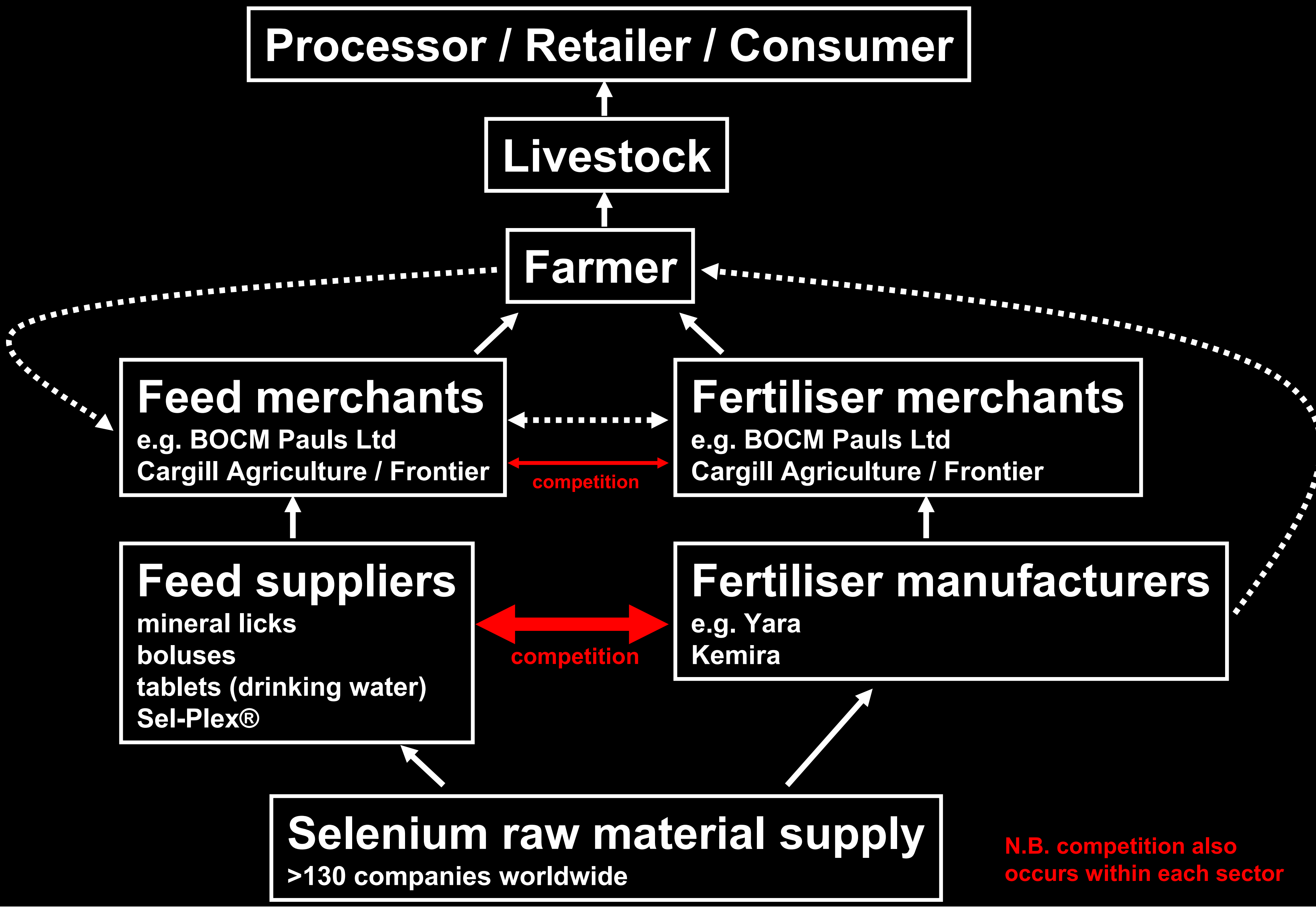


Adding value to the livestock food chain ???



R&D priorities: adding value to the livestock food chain through mineral supplementation

Aim: Optimal delivery of Se (+ other minerals) through livestock feedchains

Key R&D questions:

1. **Can biofortification via livestock deliver sufficient quantities of Se compared to biofortification of bread-wheat (and in suitable forms) ?**

2. **Is supra-optimal mineral nutrition of livestock needed / safe / ethical ?**

3. **Is biofortification via livestock economic for farmers / processors [..and in which form. …e.g. pasture improvement *vs* feeds] ?**

4. **What are environmental impacts of different mineral delivery routes ?**
    - **CO_2 emissions**
    - **Efficient use of scarce mineral resources**
    - **Mineral pollution**

5. **Can value be added to non-food (e.g. biomass / -ethanol / -diesel) crops ?**

6. **Opportunities for crop breeding ?**

R&D priorities: biofortification via livestock ?

Quantify mineral delivery via different sectors (dairy, meat etc.)

Bioavailability / intervention studies required in animals and humans

Longer-term cohort-studies required in low-Se-status humans.

> ***N.B. evidence for genotype-specific responses to supra-optimal Se in humans (…based on human transcript profiling)***

R&D priorities: economic analyses

E.g. for Se [N.B. economic analyses are lacking for all delivery routes]:

– In feed	- mineral supplements	£???
– Via tablets / water	- dissolved in drinking water	£5.30/cow
– Via a bolus	- animal treatment	£7.00/cow
– Via fertilisers	- forage treatment	£4.68/cow

Source: Yara, personal communication, June 2007

R&D priorities: environmental impact

I. CO_2 emissions ?

Not known, requires life-cycle analysis of different delivery routes

R&D priorities: environmental impact

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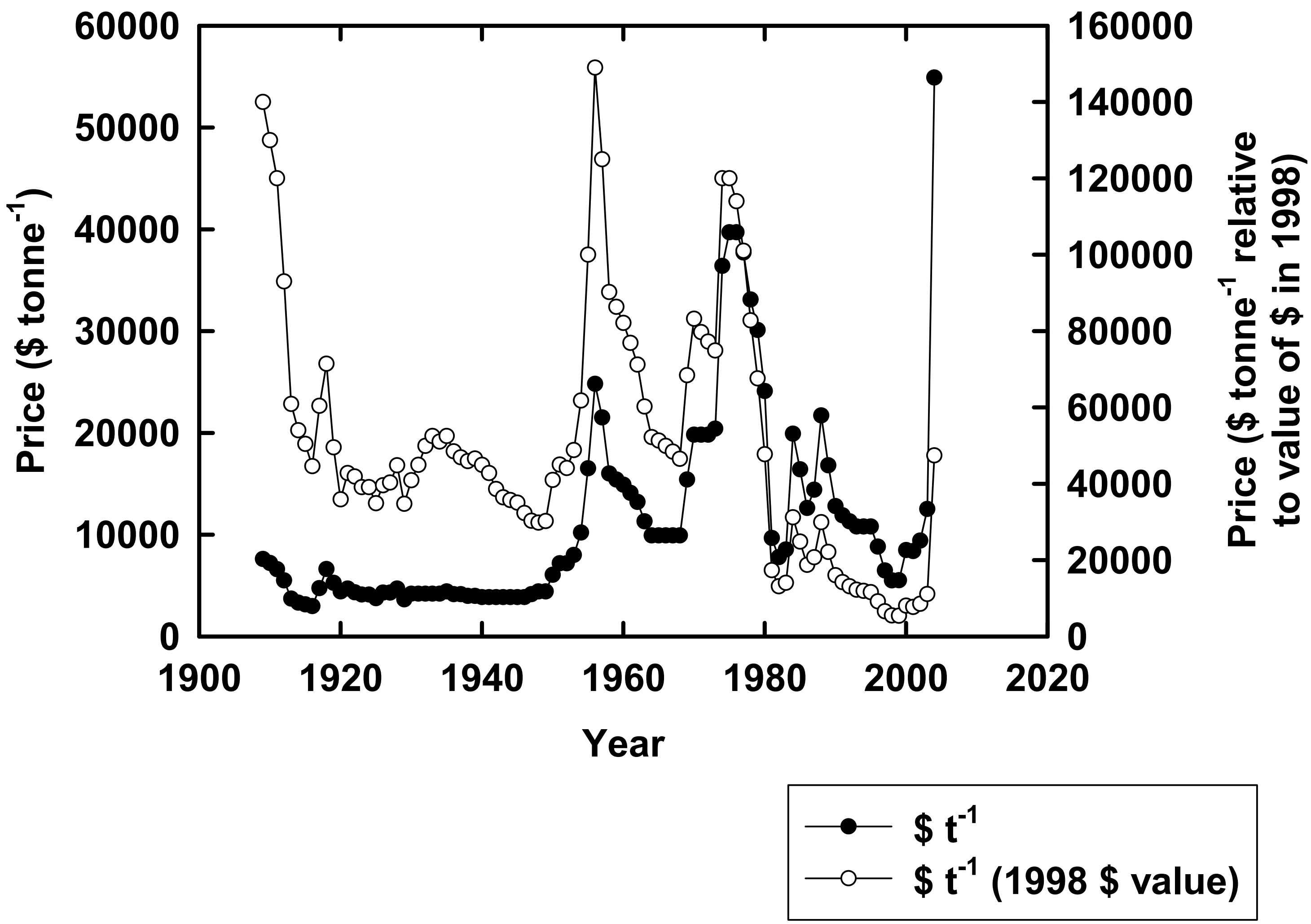
Not known, requires life-cycle analysis of different delivery routes

II. Efficient use of scarce resources ?

170,000 tonnes of world Se reserves, current US usage = *ca.* 500 t yr^{-1}
If all of 1.8 Mha of UK wheat fertilised at 10 g Se ha^{-1}, = 18 t Se yr^{-1}

Selenium: price of raw material



Source: US Geological Survey: http://minerals.usgs.gov/ds/2005/140/

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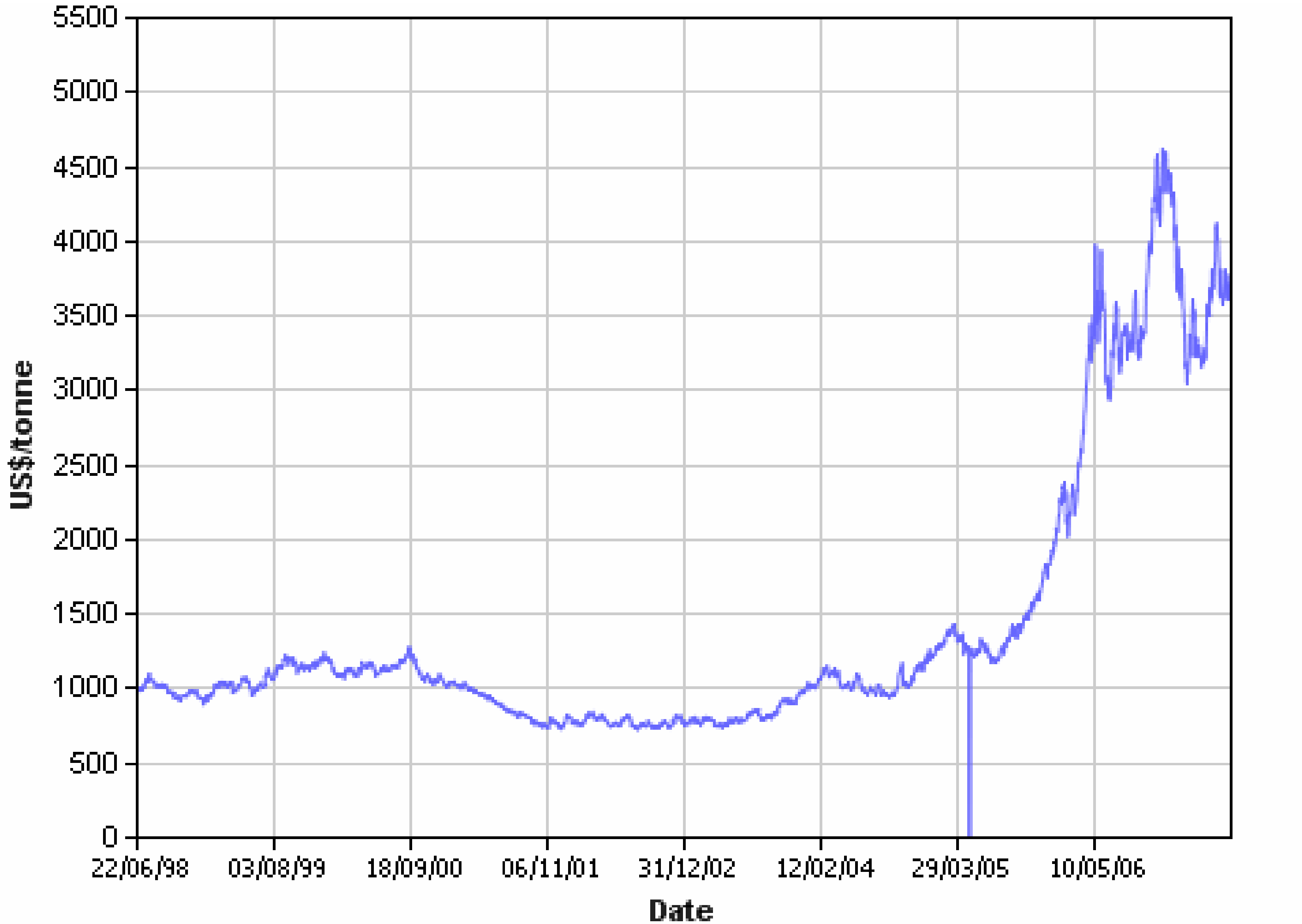
For other minerals, resources may become limiting:
e.g. Zn is becoming very scarce (<50 years supply remaining)

See New Scientist “Earth Stripped Bare” 26/05/2007

Zinc: price of raw material



Source: London Metals Exchange 22nd June 2007: https://secure.lme.com/Data/community/Dataprices_pricegraphs.aspx

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III. Mineral pollution ?

Unlikely for Se [10 / 20 g Se ha^{-1} increases soil Se by 2.6 / 5.1 ppb in 30 cm soil layer if none removed]. Other minerals ?

R&D priorities: adding value to non-(human) food crops

Increased non-food crop usage in EU (e.g starch, biomass, bioethanol)

Add value to meals, e.g. is it possible to enrich with bioavailable minerals (e.g. oilseed rape cake), without compromising processing ?

Opportunities for crop breeding…?

R&D priorities: crop breeding

Comparatively-little ongoing R&D (…N.B. HarvestPlus)

1. Relatively difficult trait to score (…mineral analysis = £5 per sample)
2. High E and G*E (…many replicates)
3. Inter-specific genetic variation (hyperaccumulators)
4. High-accumulating genotypes still need Se in the soil

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Copenhagen Consensus 2004:

Research priorities "for advancing global welfare" as ranked by eight of the World's top economists (inc. three Nobel Laureates)

Project rating		Challenge	Opportunity
Very Good	1	Diseases	Control of HIV/AIDS
	2	Malnutrition	Providing micro nutrients
	3	Subsidies and Trade	Trade liberalisation
	4	Diseases	Control of malaria
Good	5	Malnutrition	Development of new agricultural technologies
	6	Sanitation & Water	Small-scale water technology for livelihoods
	7	Sanitation & Water	Community-managed water supply and sanitation
	8	Sanitation & Water	Research on water productivity in food production
	9	Government	Lowering the cost of starting a new business
Fair	10	Migration	Lowering barriers to migration for skilled workers
	11	Malnutrition	Improving infant and child nutrition
	12	Malnutrition	Reducing the prevalence of low birth weight
	13	Diseases	Scaled-up basic health services
Bad	14	Migration	Guest worker programmes for the unskilled
	15	Climate	Optimal carbon tax
	16	Climate	The Kyoto Protocol
	17	Climate	Value-at-risk carbon tax

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What do the dinosaurs, Marco Polo's Pack Horses and General Custer have in common?