Biofortified and functional food: a healthy future?

Society of Chemical Industry, London
19 May 2011

Agronomic Biofortification of Food Crops with Macro- and Micro- Mineral Elements

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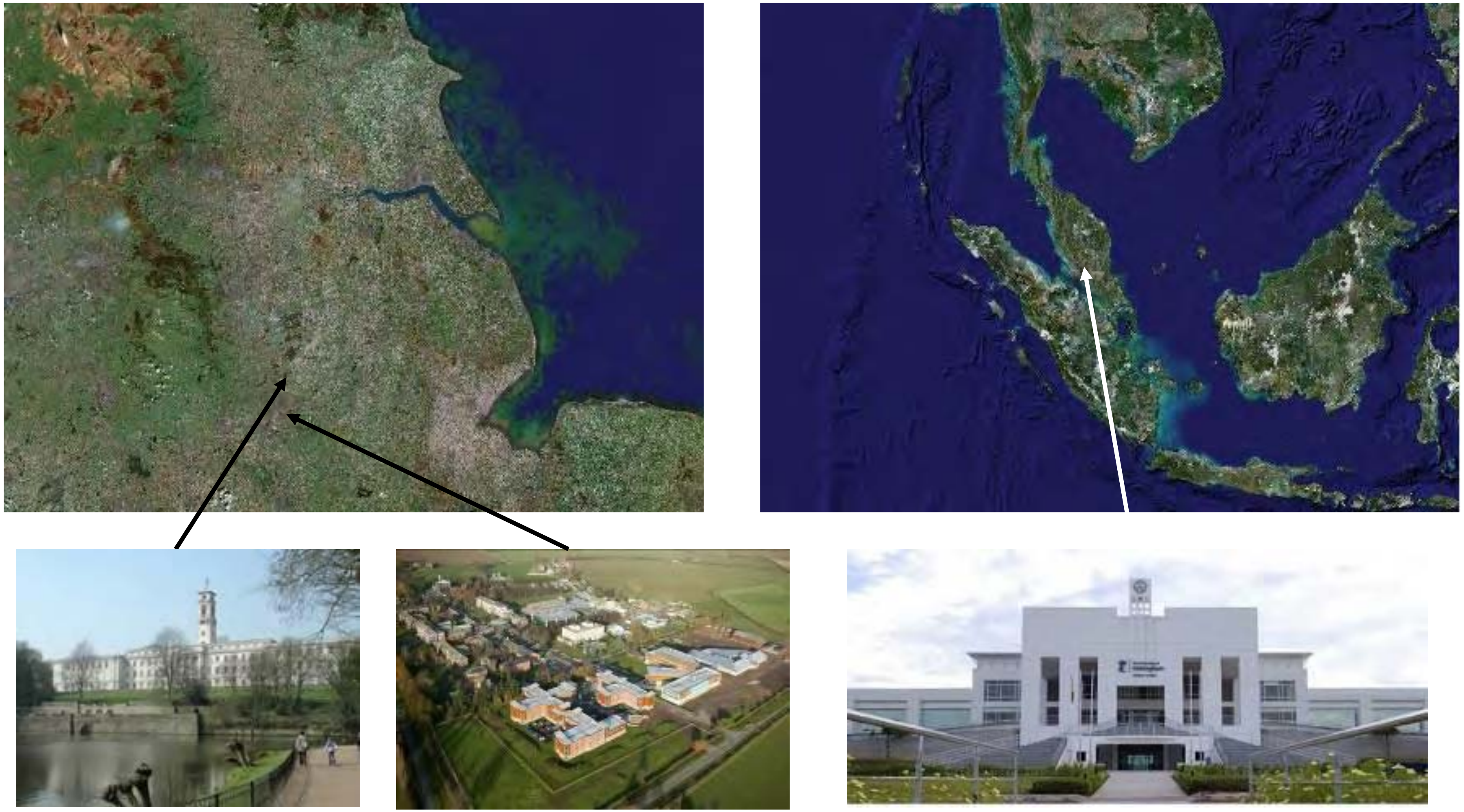
School of Biosciences - UoN



University Park (UP) | Sutton Bonington (SB) | Semenyih, Malaysia (UNMC)

Food security

"Sufficient, safe and nutritious food to meet dietary needs and food preferences for an active and healthy life for all"

(www.fao.org)

***Hungry (2006)*:**

872.9m energy-malnourished <1825 kcal d^{-1}

13.4% globally*

"Hidden hungry" (i.e. higher risk of physiological disorders):

Vitamins and minerals, e.g.

~50% Fe

~30% Zn

+ Se, Ca, Mg, I, Cu…

***Minimum daily energy requirement (MDER) assuming light work; FAO, 2006: http://faostat.fao.org/**

Biofortification of food crops

The process of increasing the bioavailable nutritional content of the edible portion of crop through:

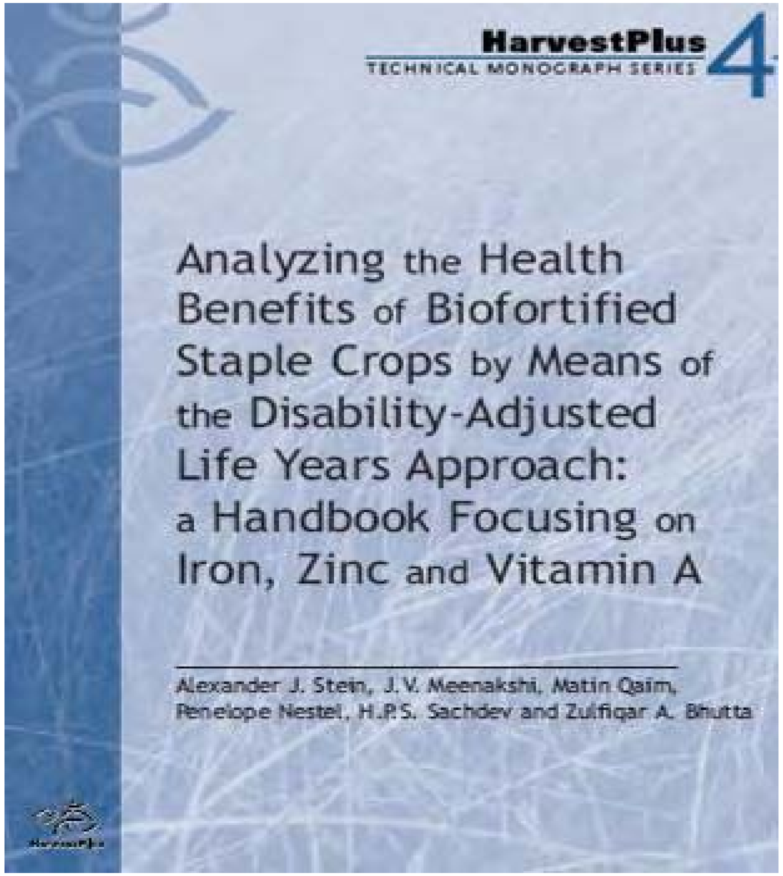
breeding (*genetic biofortification*)

agronomy (*agronomic biofortification*)

Biofortification of food crops

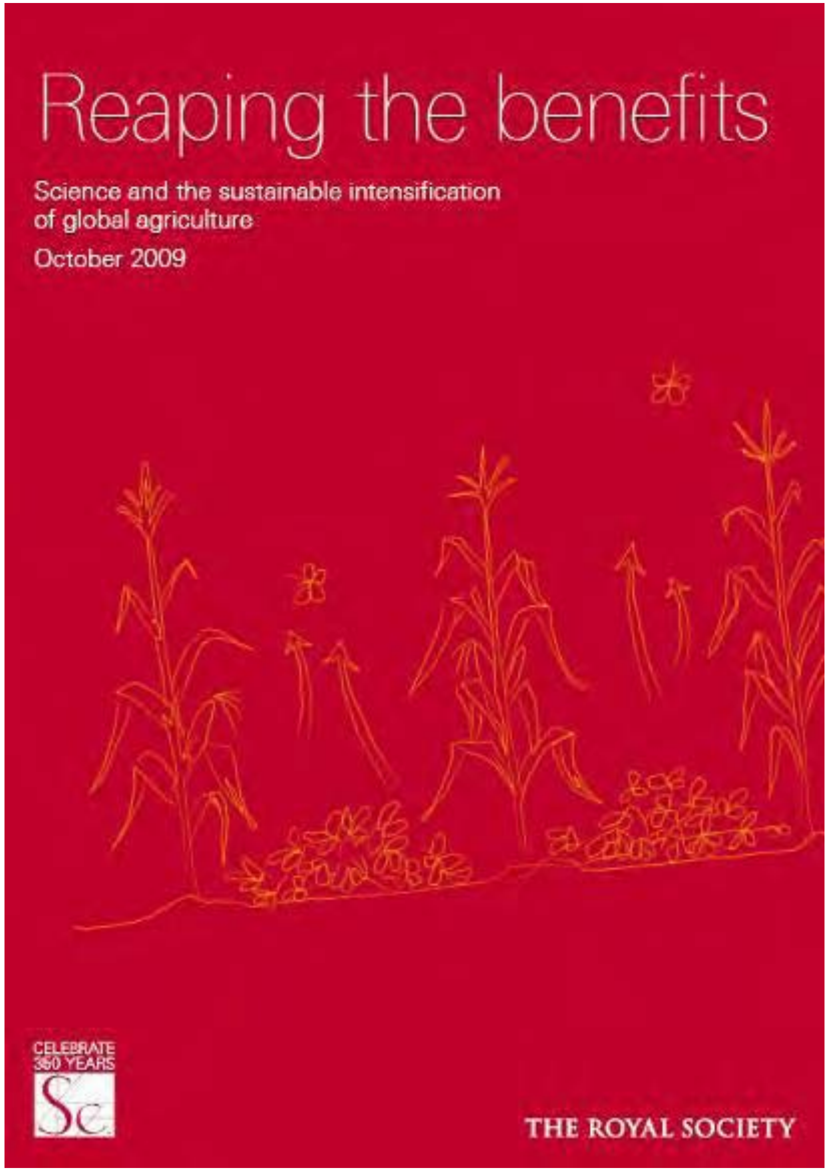
HarvestPlus
Breeding Crops for Better Nutrition

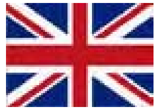
Harvest Zinc
Exploring Fertilizer Use to Increase Zinc in Cereals



www.harvestplus.org

Biofortification of food crops





Oct. 2009

"*The preferred strategy to eliminate hidden hunger… [is to] increase the diversity of diet with increased access to fruit and vegetables…*

***where the lack of infrastructure or other factors prevents [this], biofortified varieties may provide a good <u>short-term</u> solution*"**

Biofortification of food crops

HOUSES OF PARLIAMENT
PARLIAMENTARY OFFICE OF SCIENCE & TECHNOLOGY

POSTNOTE

Number 367 November 2010

Biofortification of Foods

Overview

- Undernutrition is a significant global health burden.
- Biofortification uses selective breeding and/or genetic modification to increase the

http://www.parliament.uk/documents/post/postpn367_biofortification.pdf

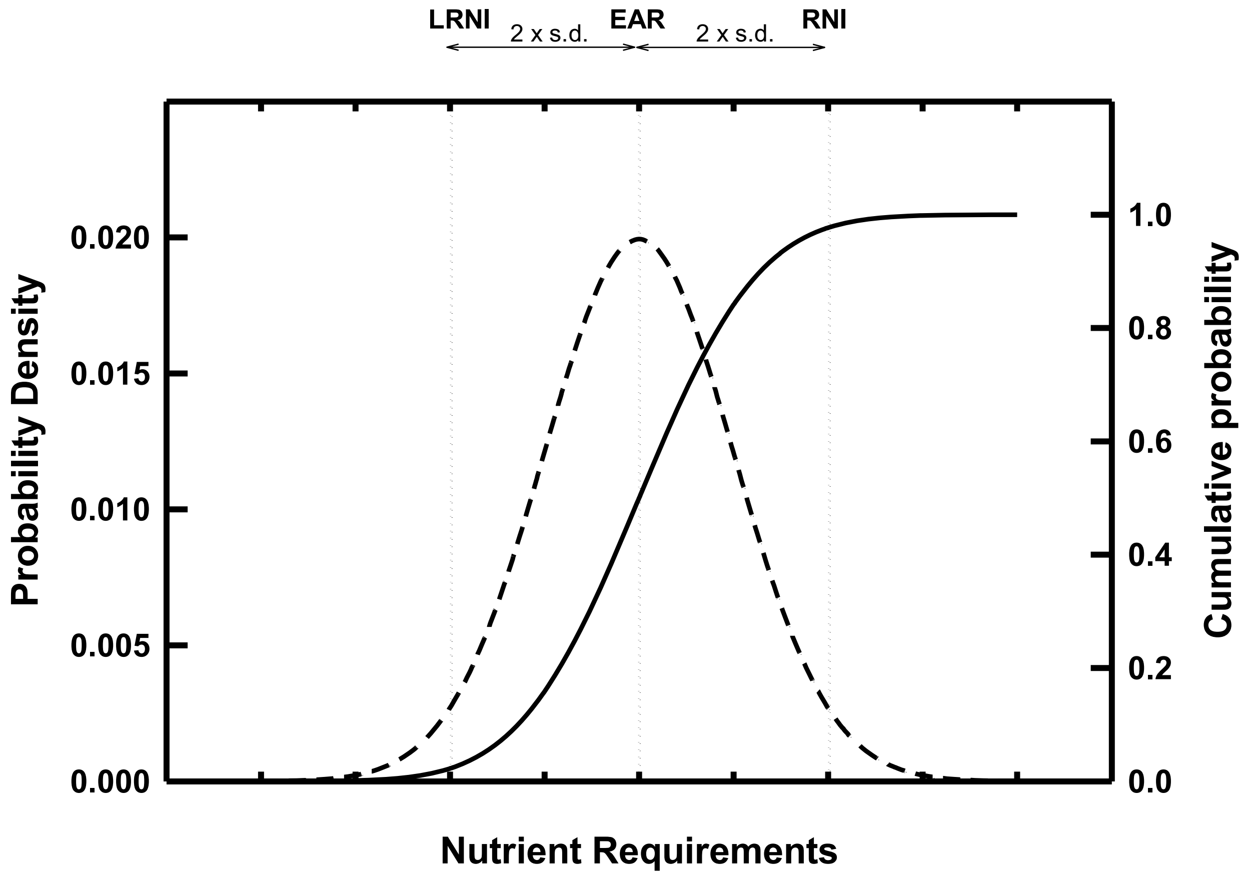
Mineral biofortification of food crops

Evidence of widespread mineral deficiencies in <u>all</u> countries

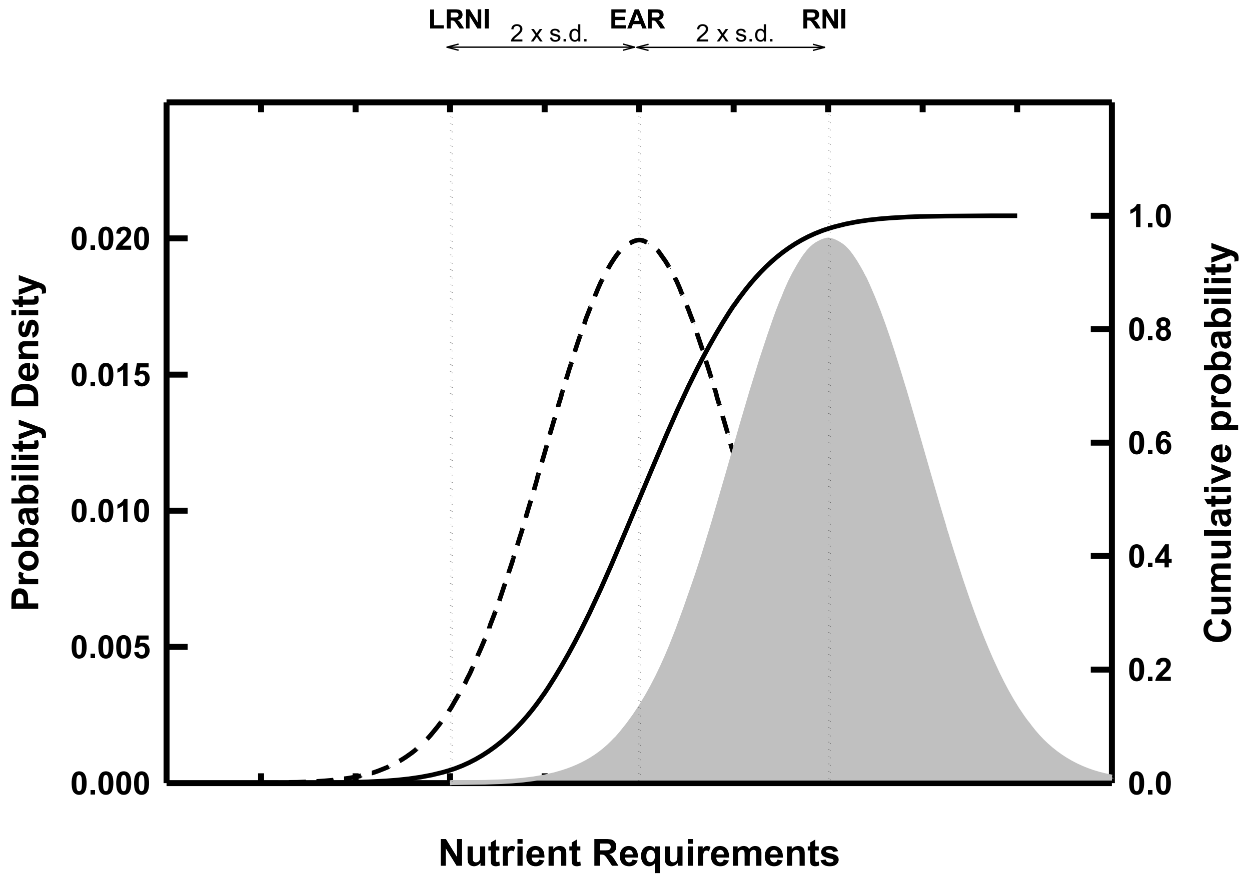
Dietary surveys (*vs* recommended intakes)

Tissue analysis (e.g. blood plasma, toenails etc.)

UK Dietary Reference Value (DRV) framework



UK Dietary Reference Value (DRV) framework



US Dietary Reference Intake (DRI) framework

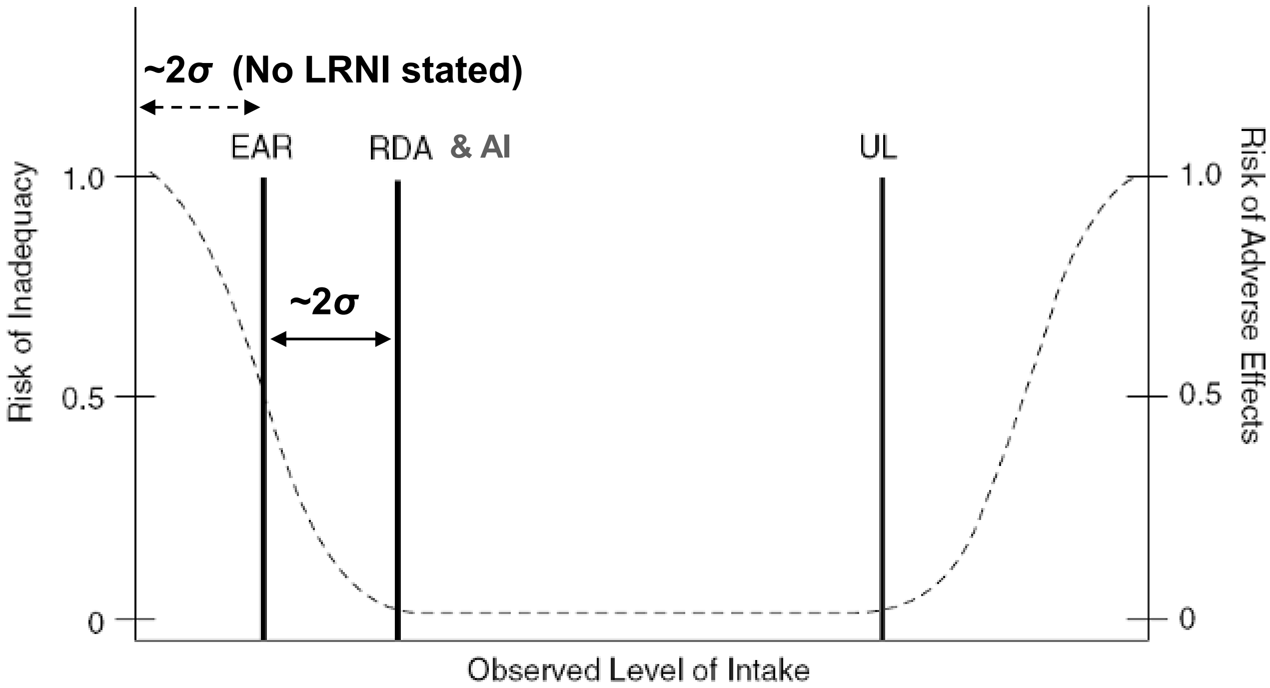
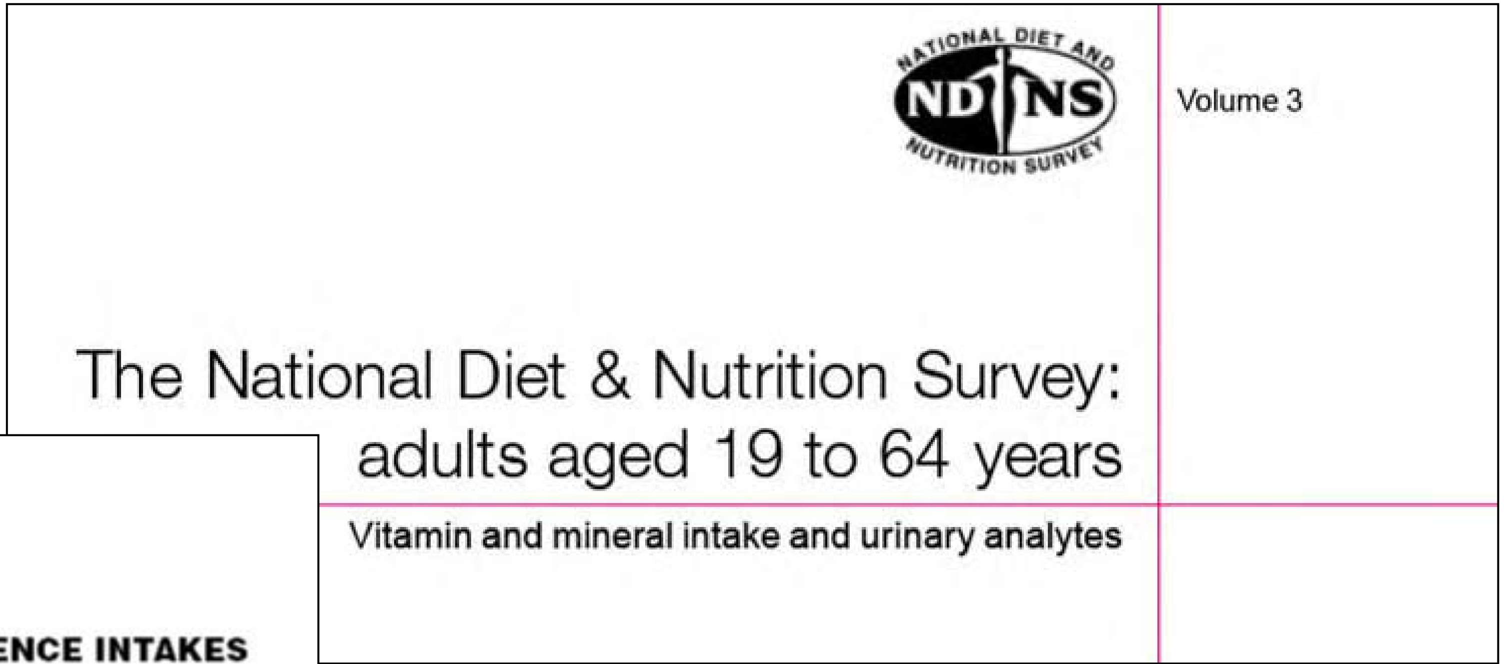


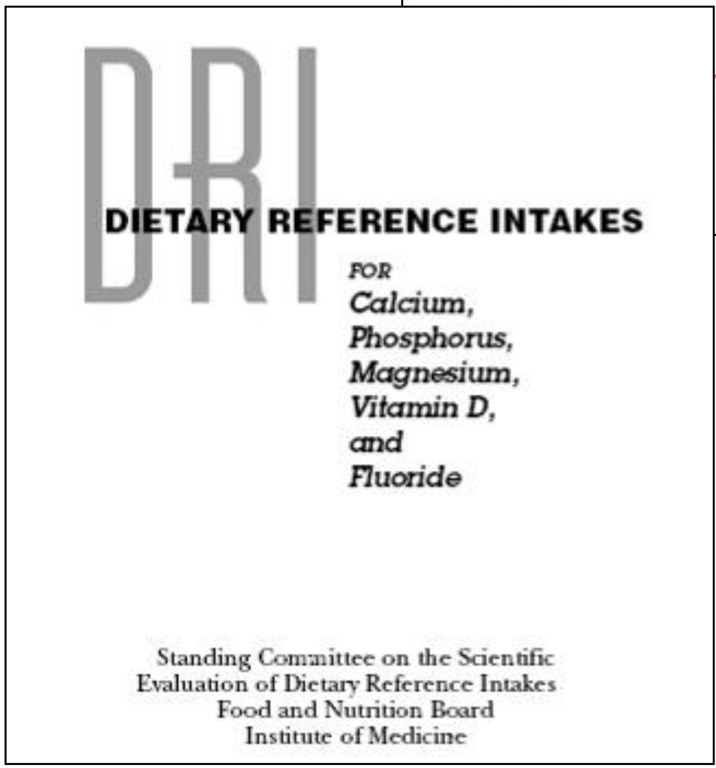
FIGURE S-1 Dietary reference intakes. This figure shows that the Estimated Average Requirement (EAR) is the intake at which the risk of inadequacy is 0.5 (50%) to an individual. The Recommended Dietary Allowance (RDA) is the intake at which the risk of inadequacy is very small—only 0.02 to 0.03 (2 to 3%). The Adequate Intake (AI) does not bear a consistent relationship to the EAR or the RDA because it is set without being able to estimate the average requirement. It is assumed that the AI is at or above the RDA if one could be calculated. At intakes between the RDA and the Tolerable Upper Intake Level (UL), the risks of inadequacy and of excess are both close to 0. At intakes above the UL, the risk of adverse effect may increase.

Standing Committee on the Scientific Evaluation of Dietary Reference Intakes, Food & Nutrition Board, Institute of Medicine (1997). Dietary reference intakes for calcium, phosphorus, magnesium, vitamin D, and fluoride. Washington DC: USA, *NATIONAL ACADEMY PRESS. P. 24.*

Compare DRV/DRIs with UK & US dietary intake surveys

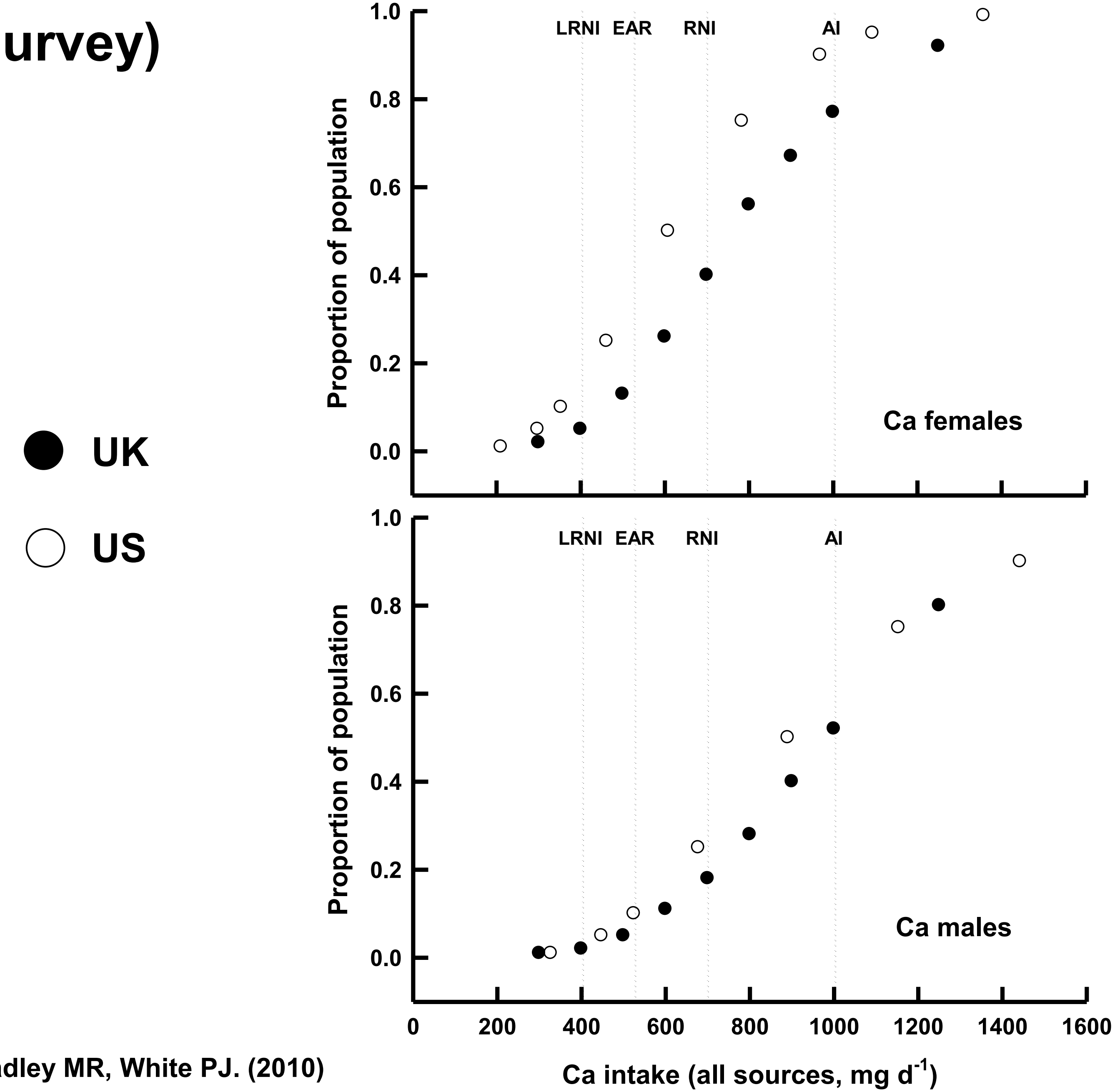


2003/2004



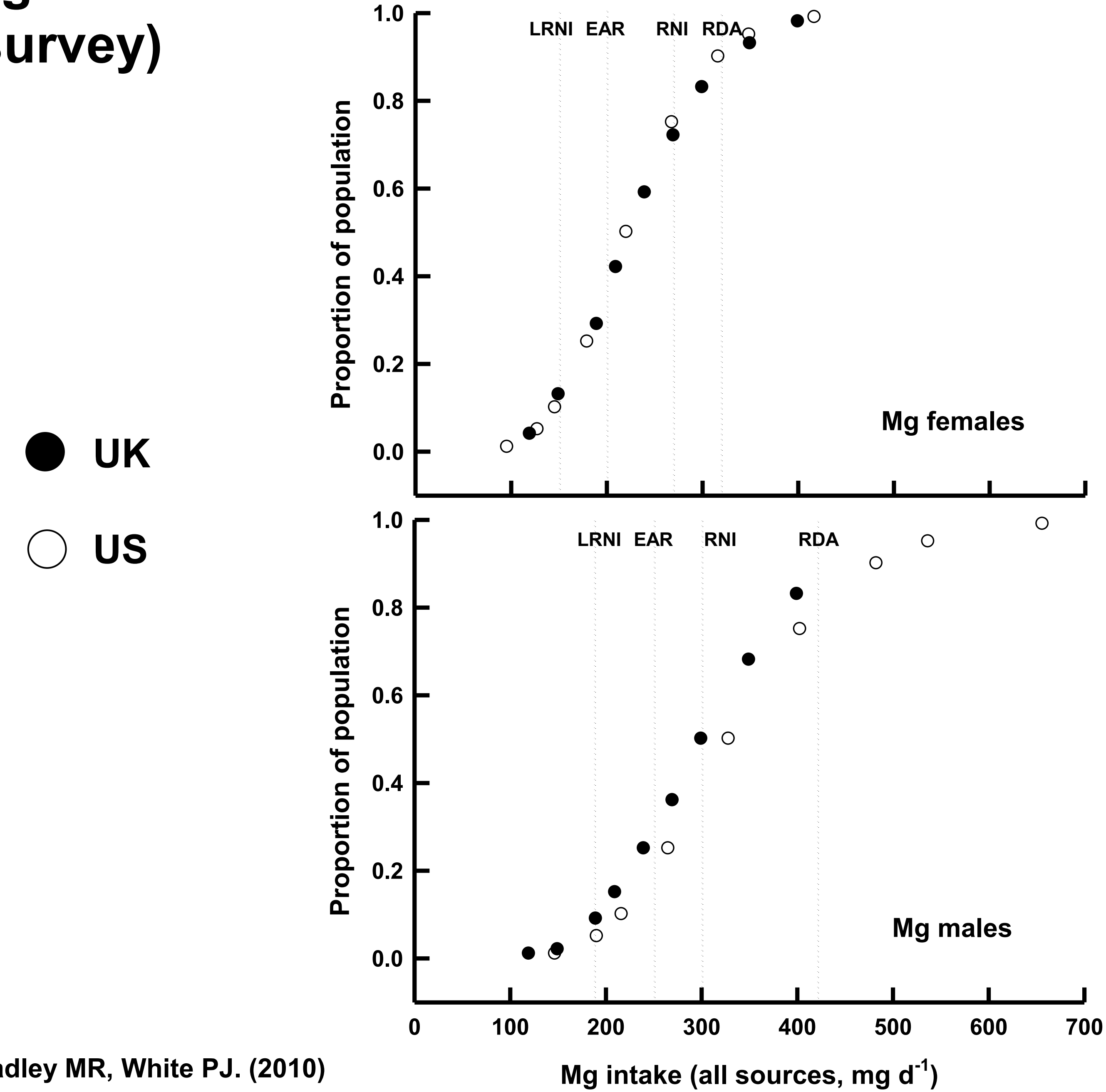
1997/2005

Ca intake (survey)



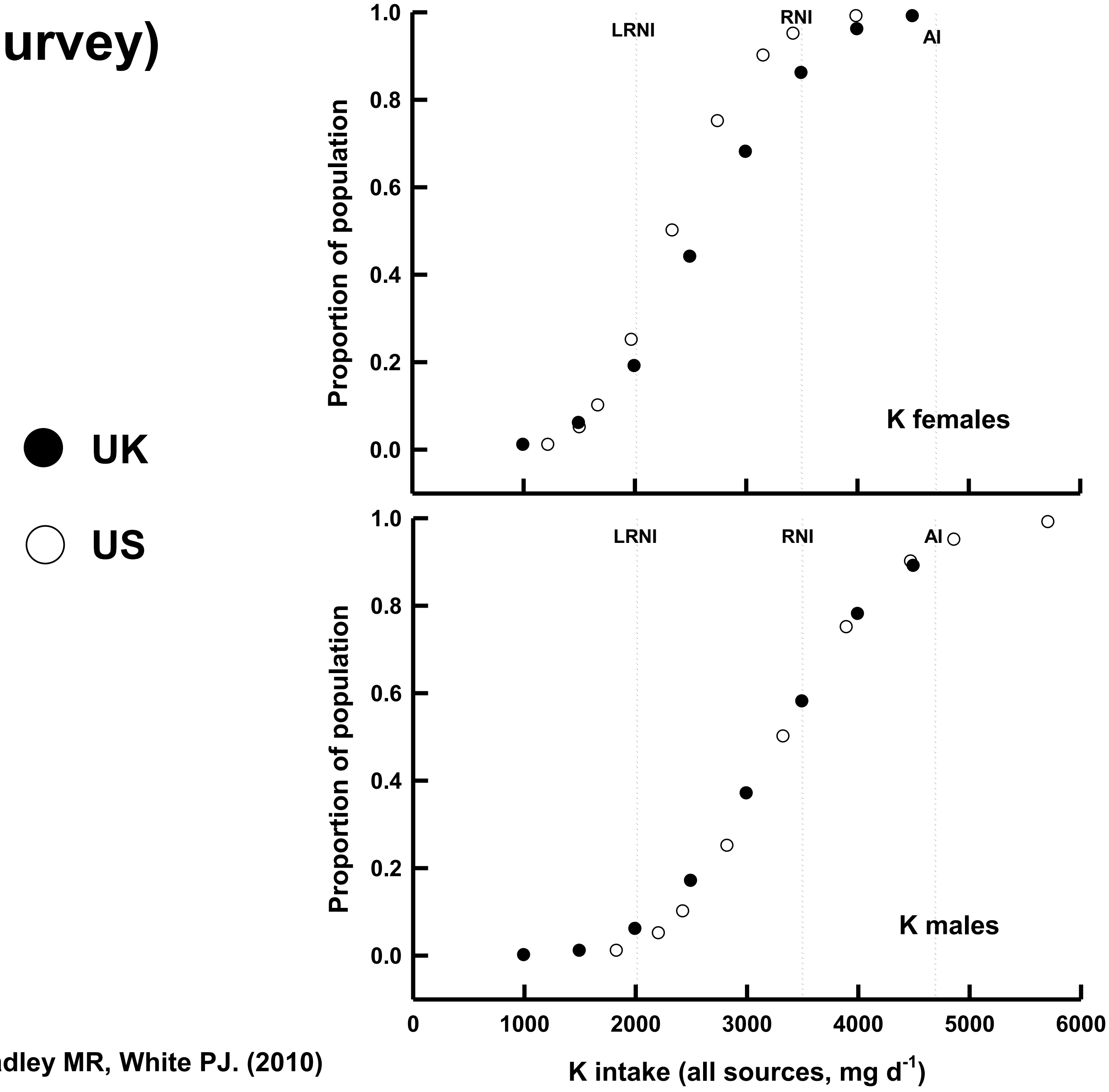
Broadley MR, White PJ. (2010)

Mg intake (survey)



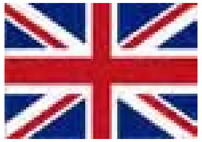
Broadley MR, White PJ. (2010)

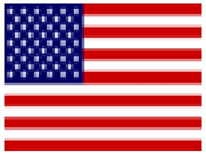
K intake (survey)



Broadley MR, White PJ. (2010)

Suboptimal mineral intake is widespread





Ca-deficient: 25.5m UK & US adults (esp. US women) = 8.8%

Mg-deficient: 25.5m UK & US adults (esp. women) = 8.8%

K-deficient: 40.2m UK & US adults (esp. women) = 14.6%

Broadley MR, White PJ. (2010). Eats roots and leaves. Can edible horticultural crops address dietary calcium, magnesium and potassium deficiencies? *Proceedings of the Nutrition Society*, **69**, 601-612.

Mineral deficiencies are widespread

Table 2. UK and US adults at risk of sub-optimal Ca, Mg and K intake based on dietary surveys[5–8]

	Intakes <UK LRNI		Intakes <UK RNI	
	%	$\times 10^6$*	%	$\times 10^6$
Ca				
UK females	5	1·2	40	9·6
UK males	2	0·5	18	4·3
US females	16	19·7	63	75·7
US males	3	4·1	28	33·1
Total		25·4		122·8
Mg				
UK females	13	3·1	72	17·3
UK males	9	2·2	50	12·0
US females	12	14·0	76	90·6
US males	5	6·0	39	46·3
Total		25·3		166·2
K				
UK females	19	4·6	86	20·6
UK males	6	1·4	58	13·9
US females	27	32·0	96	114·6
US males	3	3·4	58	69·0
Total		41·4		218·2

RNI, reference nutrient intake; LRNI, lower RNI.
*Assuming 48 and 240 million UK and US adults, respectively, 50:50 males: females.

Mineral deficiencies are widespread… why?

UK / US not energy restricted (trade and production)

US = 1st (3830 kcal d^{-1})
UK = 16th (3440 kcal d^{-1})

UK / US diets “diverse” in theory (non-starchy foods)

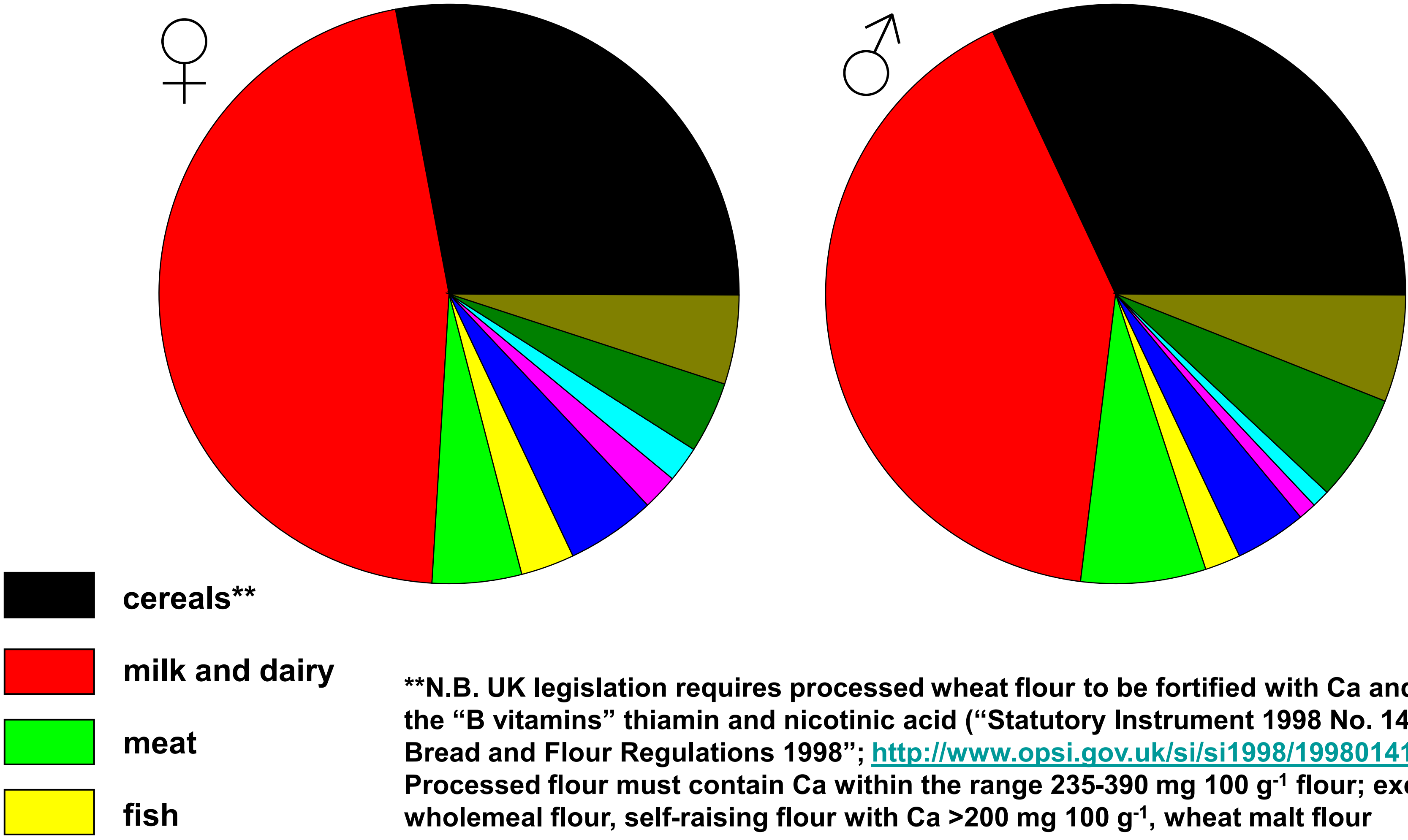
…but UK mean (median) fruit + veg. portions d^{-1}

♀ = 2.9 (2.4)
♂ = 2.7 (2.2)

http://faostat.fao.org/

Dietary sources of minerals

Calcium intake (UK)

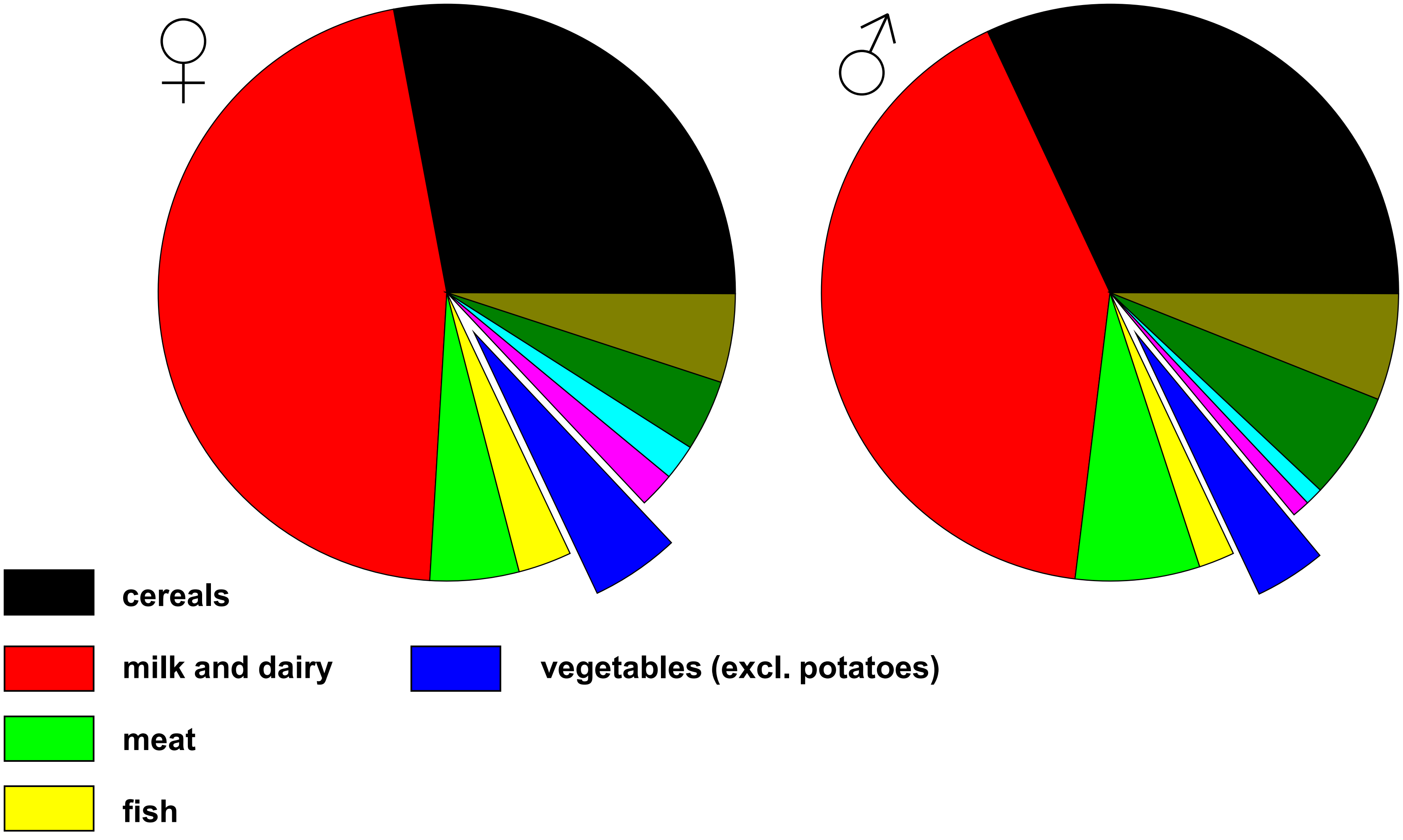


Broadley MR, White PJ. (2010)

**N.B. UK legislation requires processed wheat flour to be fortified with Ca and Fe, and the "B vitamins" thiamin and nicotinic acid ("Statutory Instrument 1998 No. 141, The Bread and Flour Regulations 1998"; http://www.opsi.gov.uk/si/si1998/19980141.htm). Processed flour must contain Ca within the range 235-390 mg 100 g^{-1} flour; exceptions for wholemeal flour, self-raising flour with Ca >200 mg 100 g^{-1}, wheat malt flour

Dietary sources of minerals

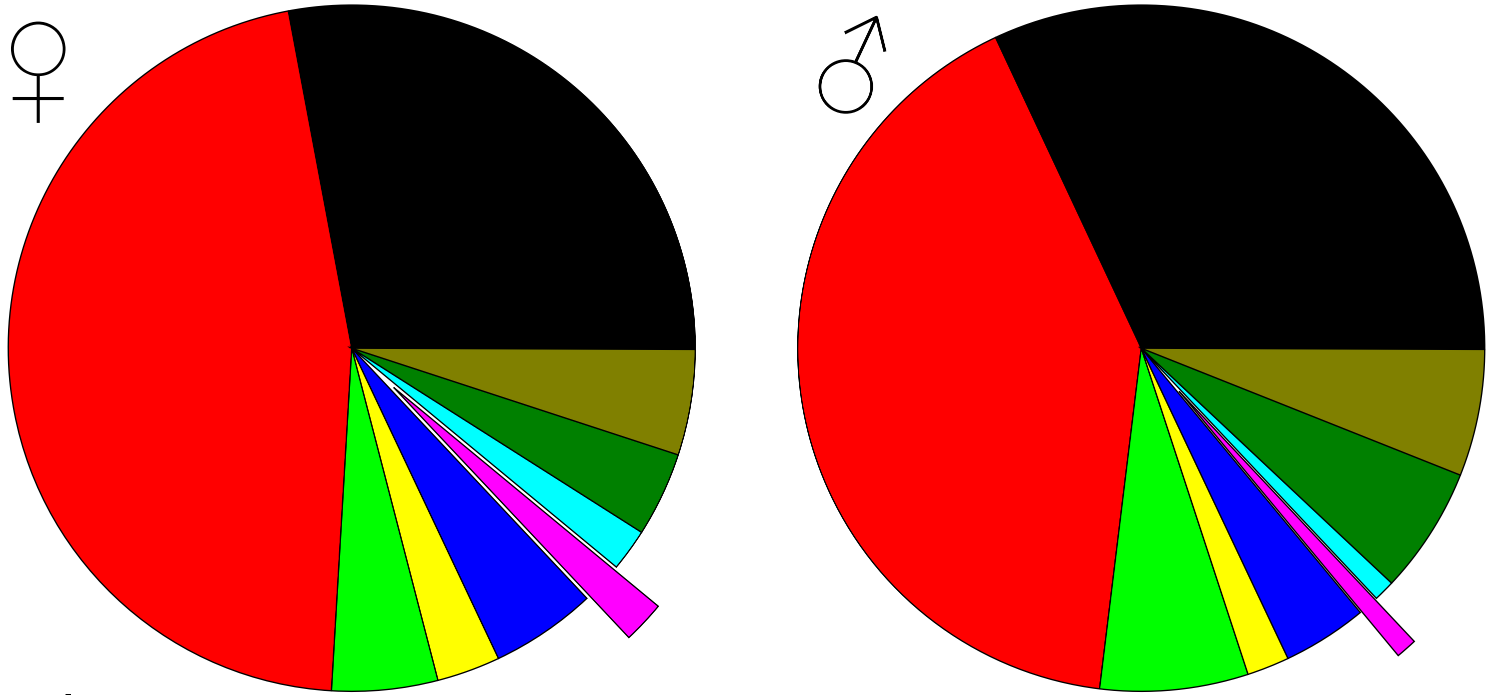
Calcium intake (UK)



Broadley MR, White PJ. (2010)

Dietary sources of minerals

Calcium intake (UK)



- cereals
- milk and dairy
- meat
- fish
- vegetables (excl. potatoes)
- potatoes

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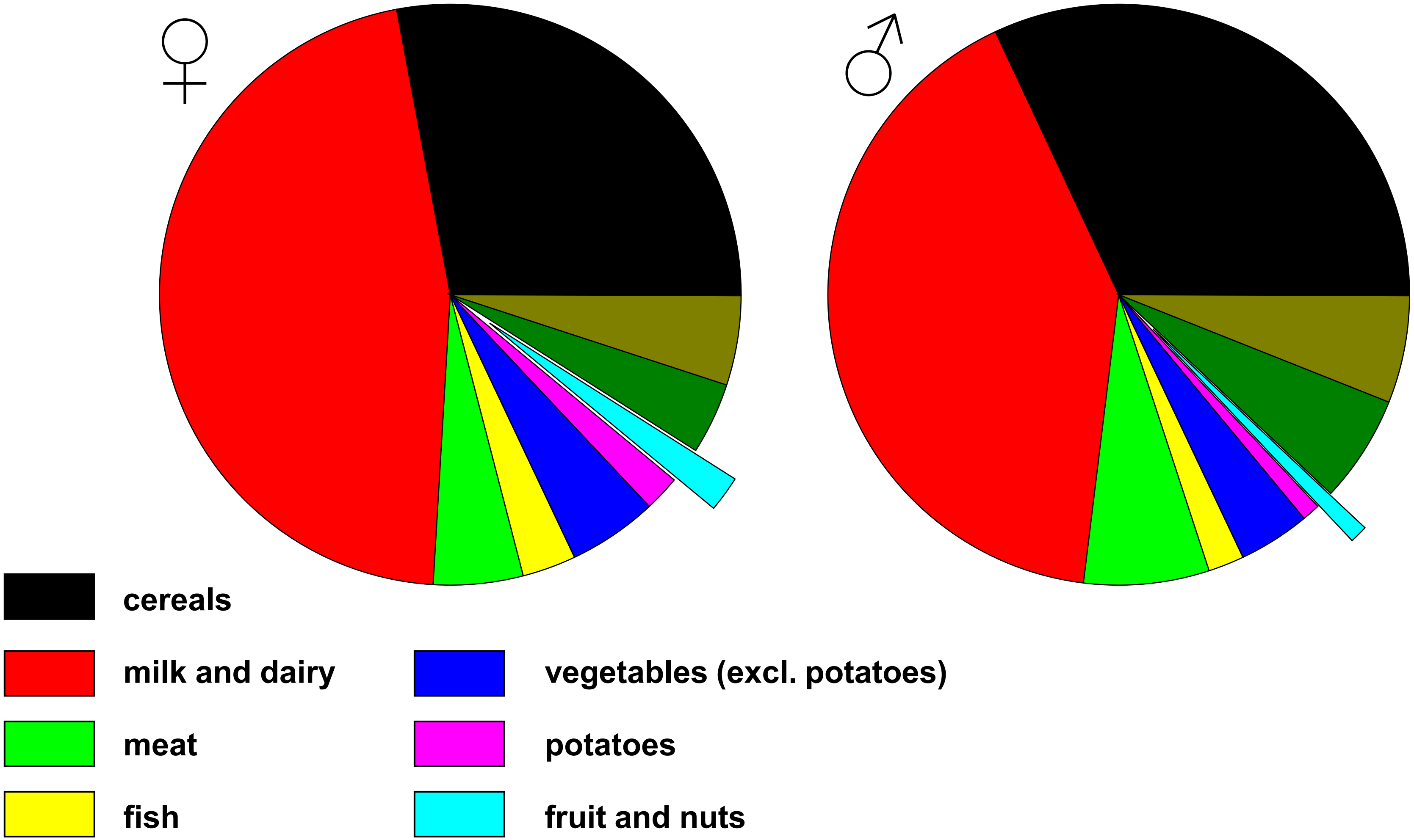
Dietary sources of minerals

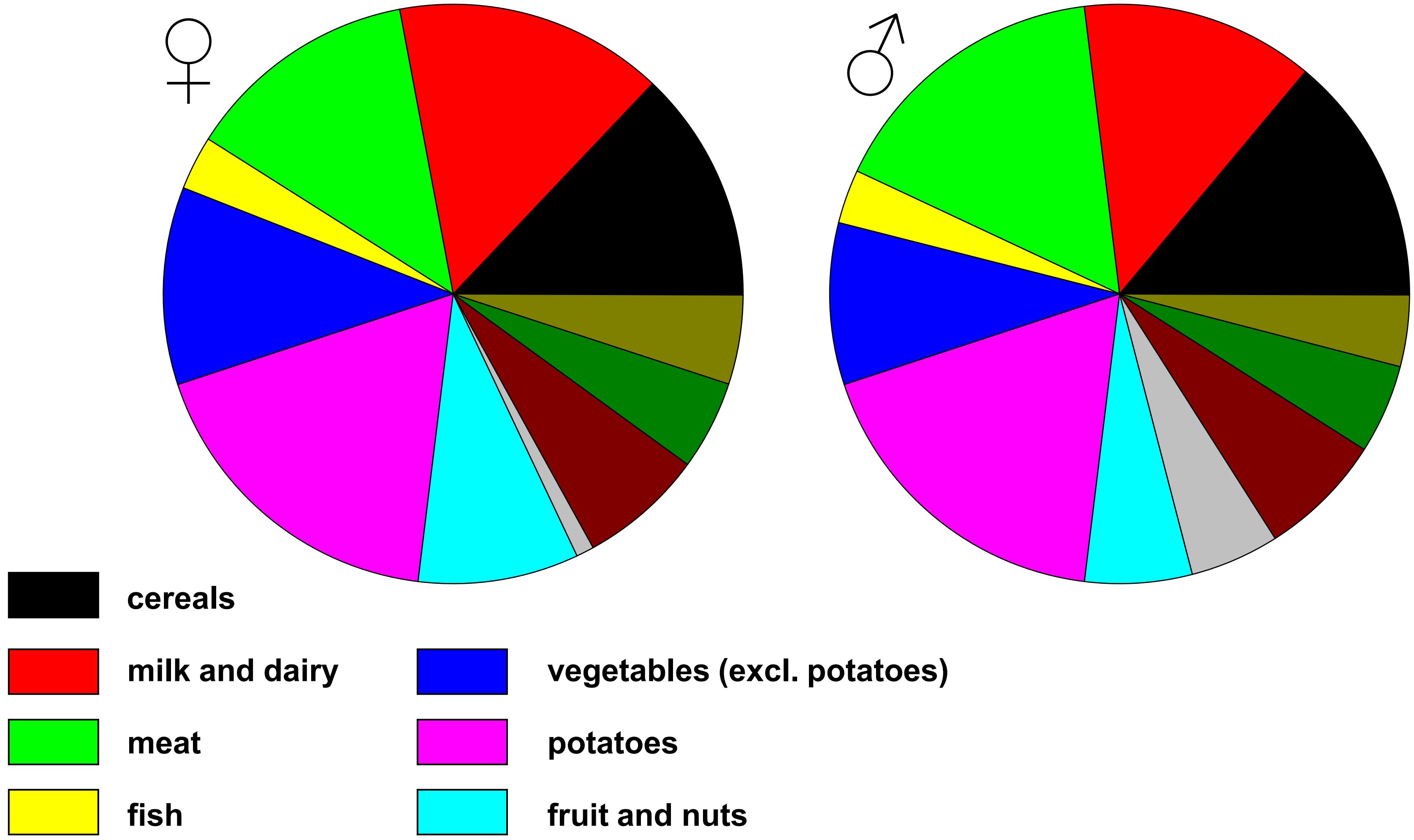
Calcium intake (UK)



Broadley MR, White PJ. (2010)

Dietary sources of minerals

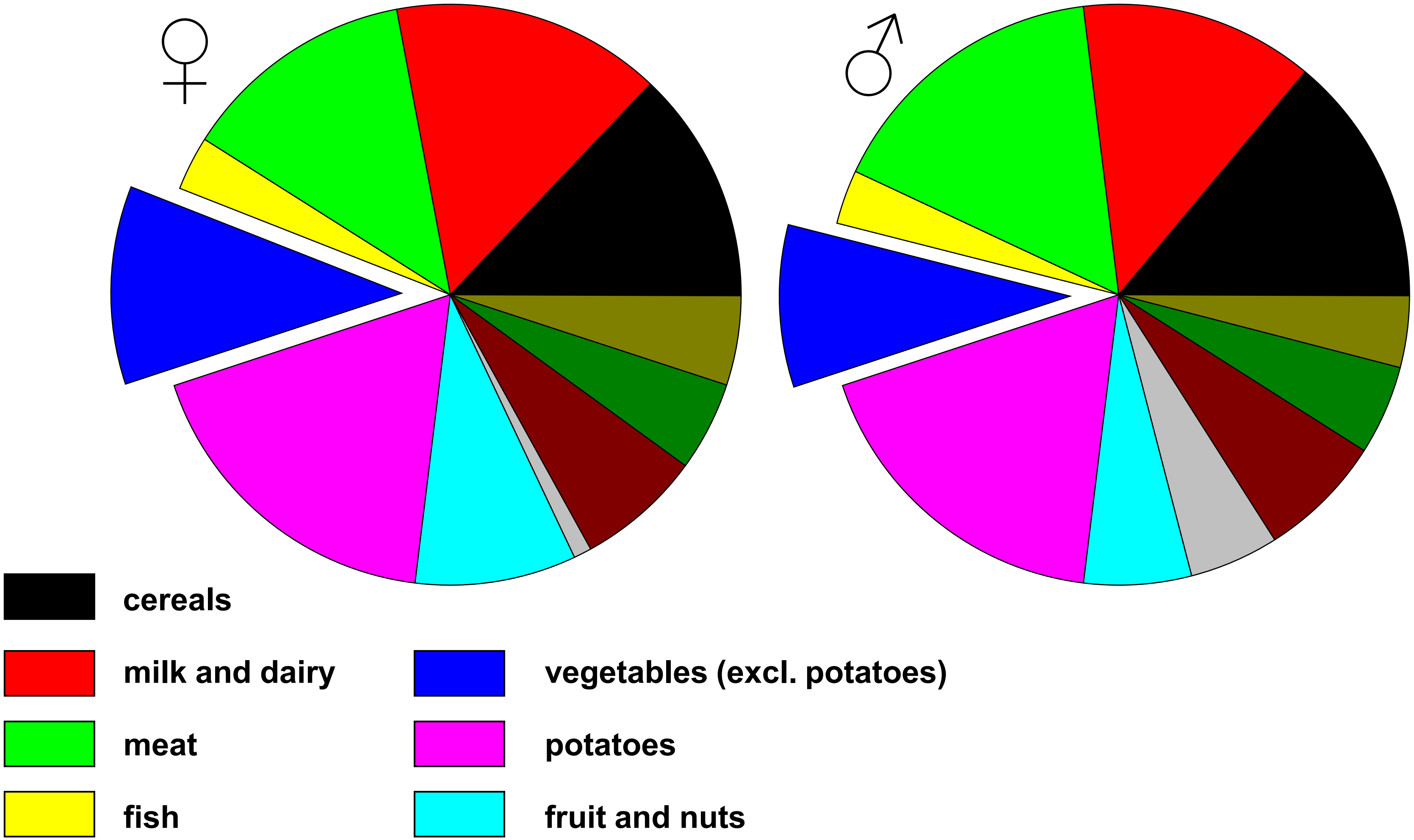
Potassium intake (UK)



Broadley MR, White PJ. (2010)

Dietary sources of minerals

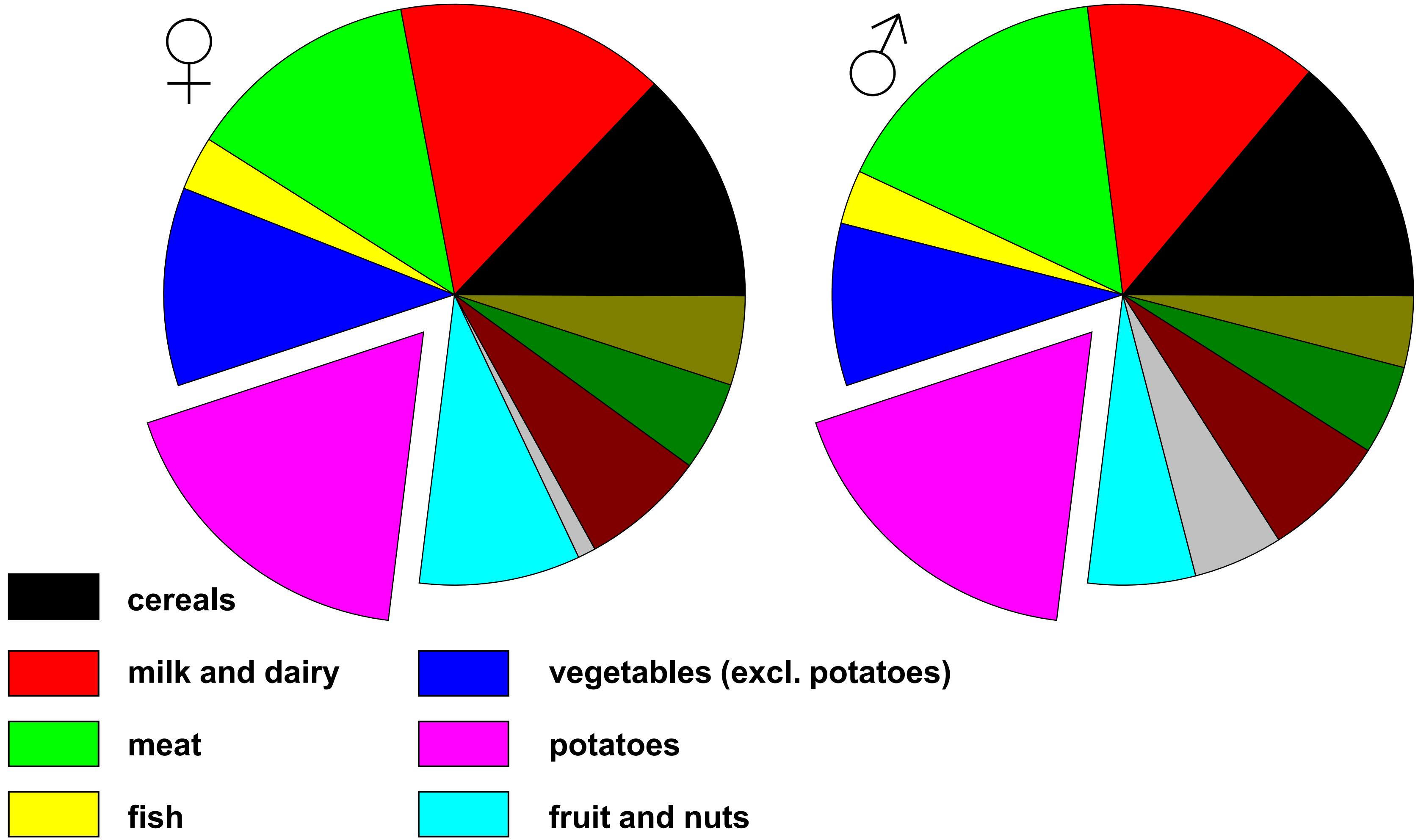
Potassium intake (UK)



Broadley MR, White PJ. (2010)

Dietary sources of minerals

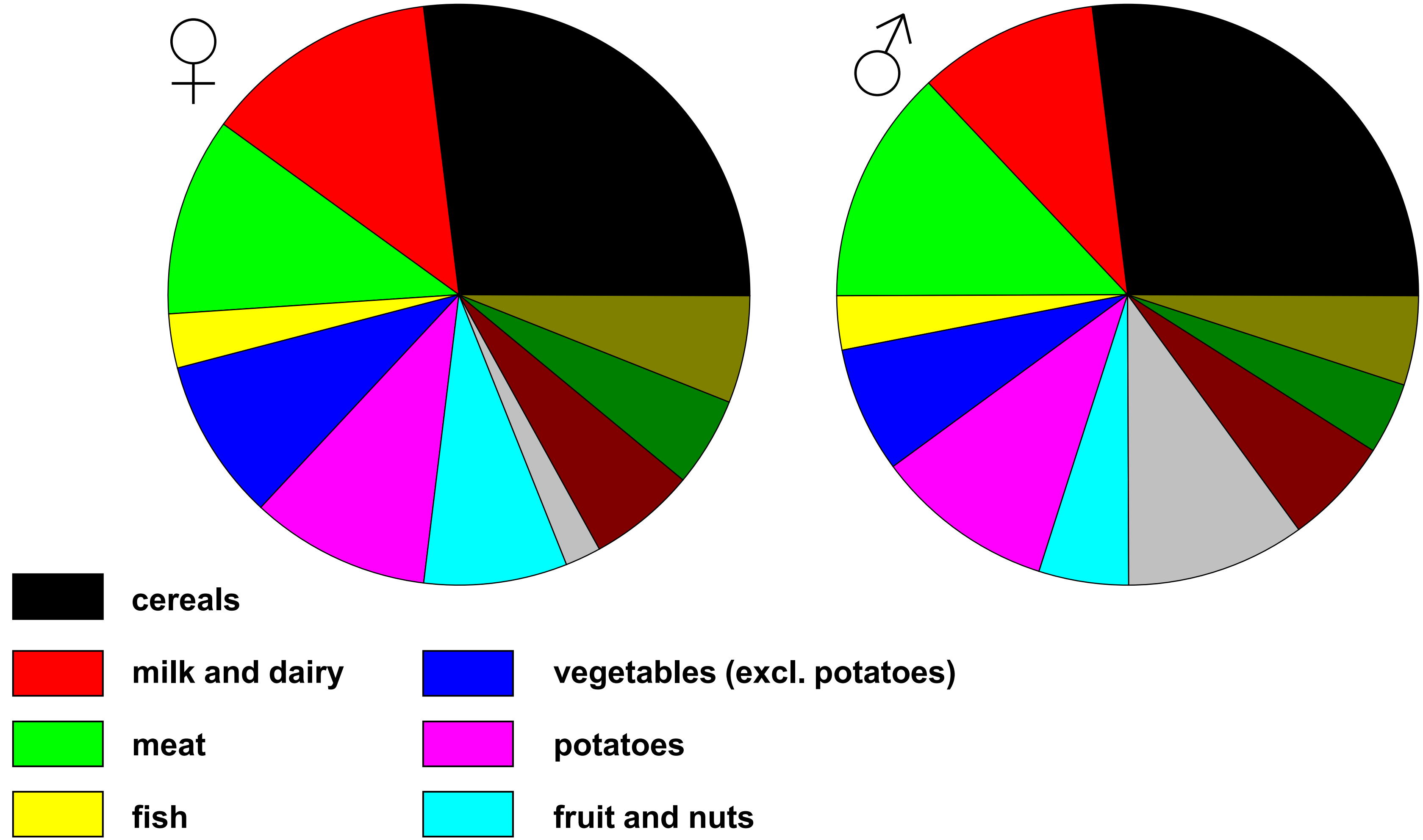
Potassium intake (UK)



Broadley MR, White PJ. (2010)

Dietary sources of minerals

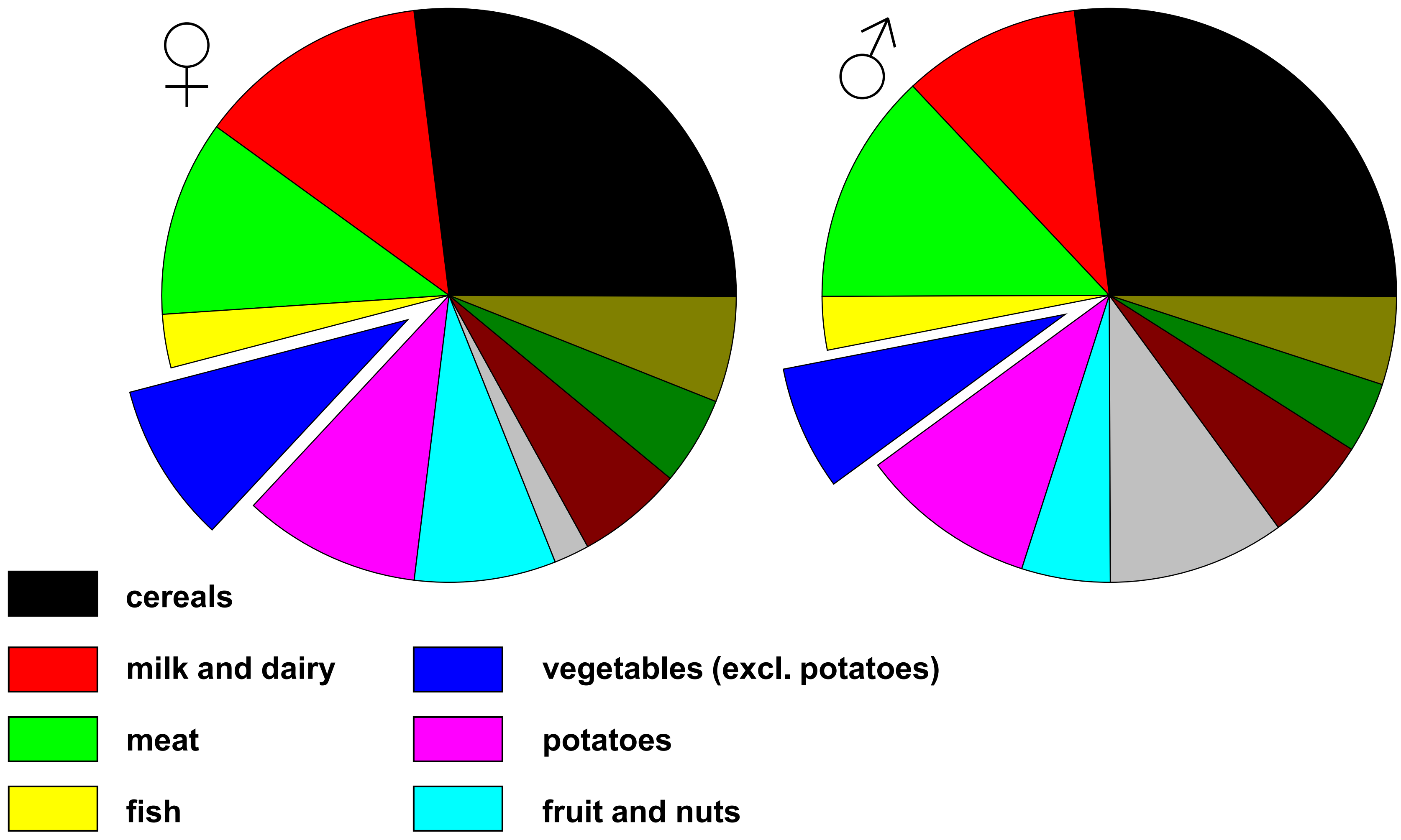
Magnesium intake (UK)



Broadley MR, White PJ. (2010)

Dietary sources of minerals

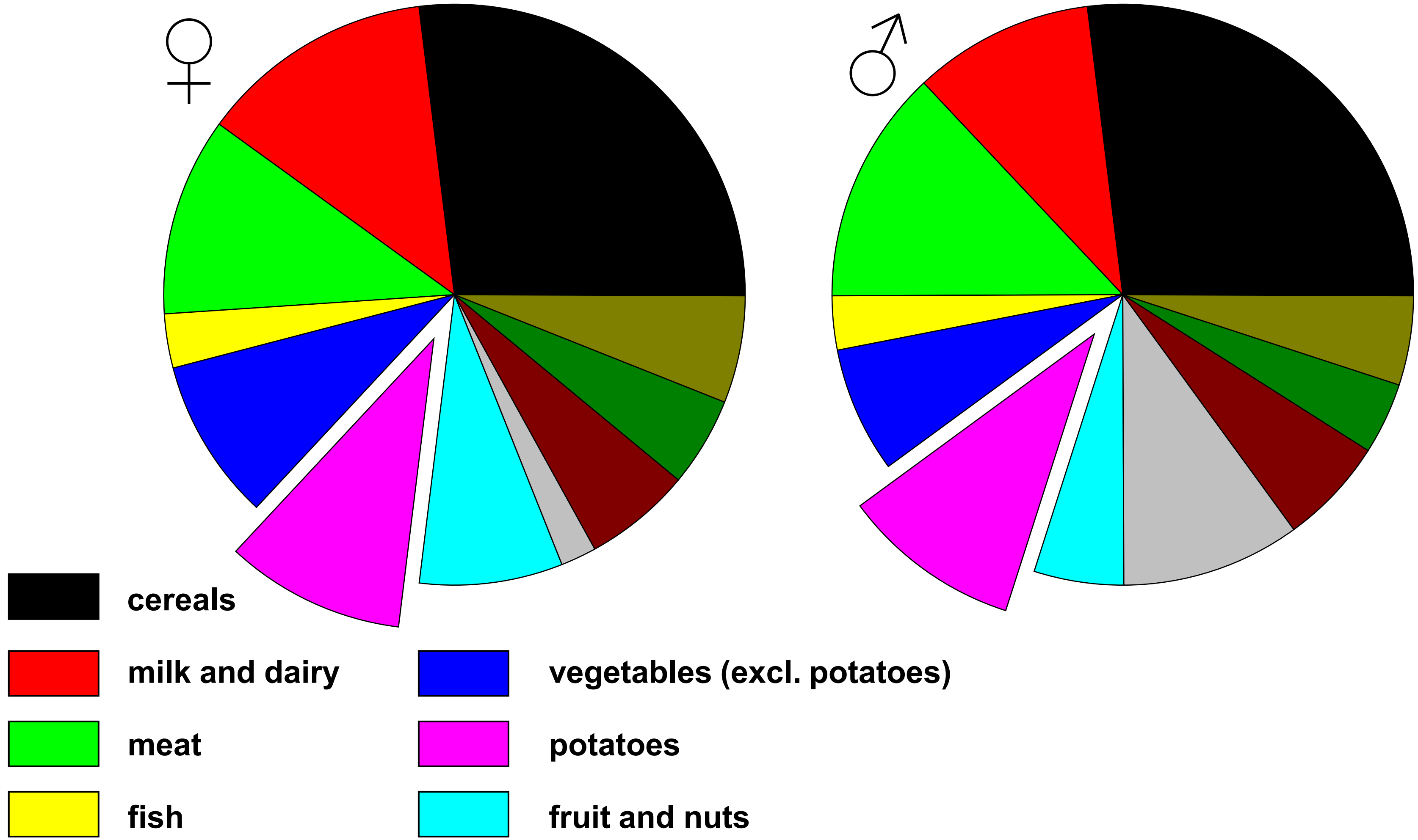
Magnesium intake (UK)



Broadley MR, White PJ. (2010)

Dietary sources of minerals

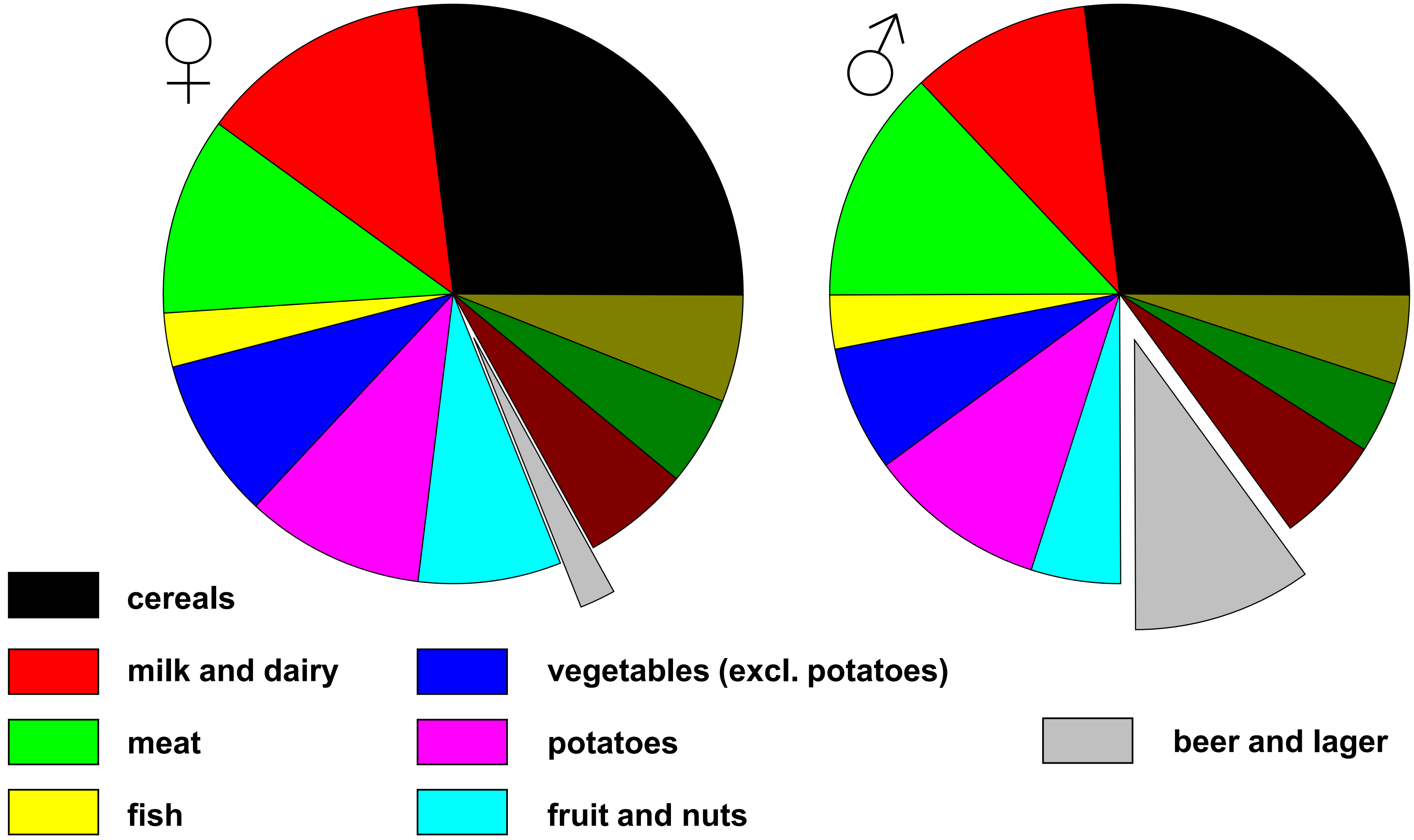
Magnesium intake (UK)



Broadley MR, White PJ. (2010)

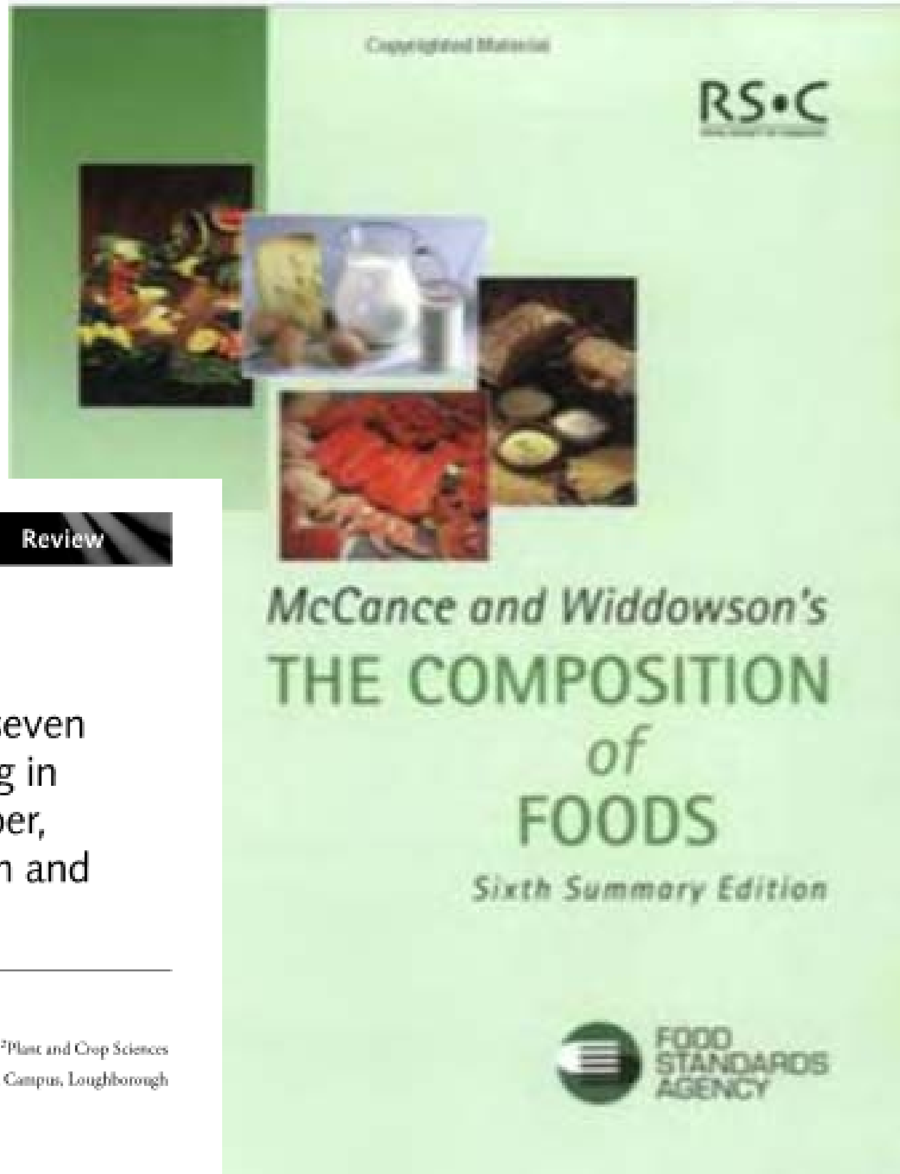
Dietary sources of minerals

Magnesium intake (UK)



Broadley MR, White PJ. (2010)

Simulate altered food consumption and composition



New Phytologist

Review

Research review

Biofortification of crops with seven mineral elements often lacking in human diets – iron, zinc, copper, calcium, magnesium, selenium and iodine

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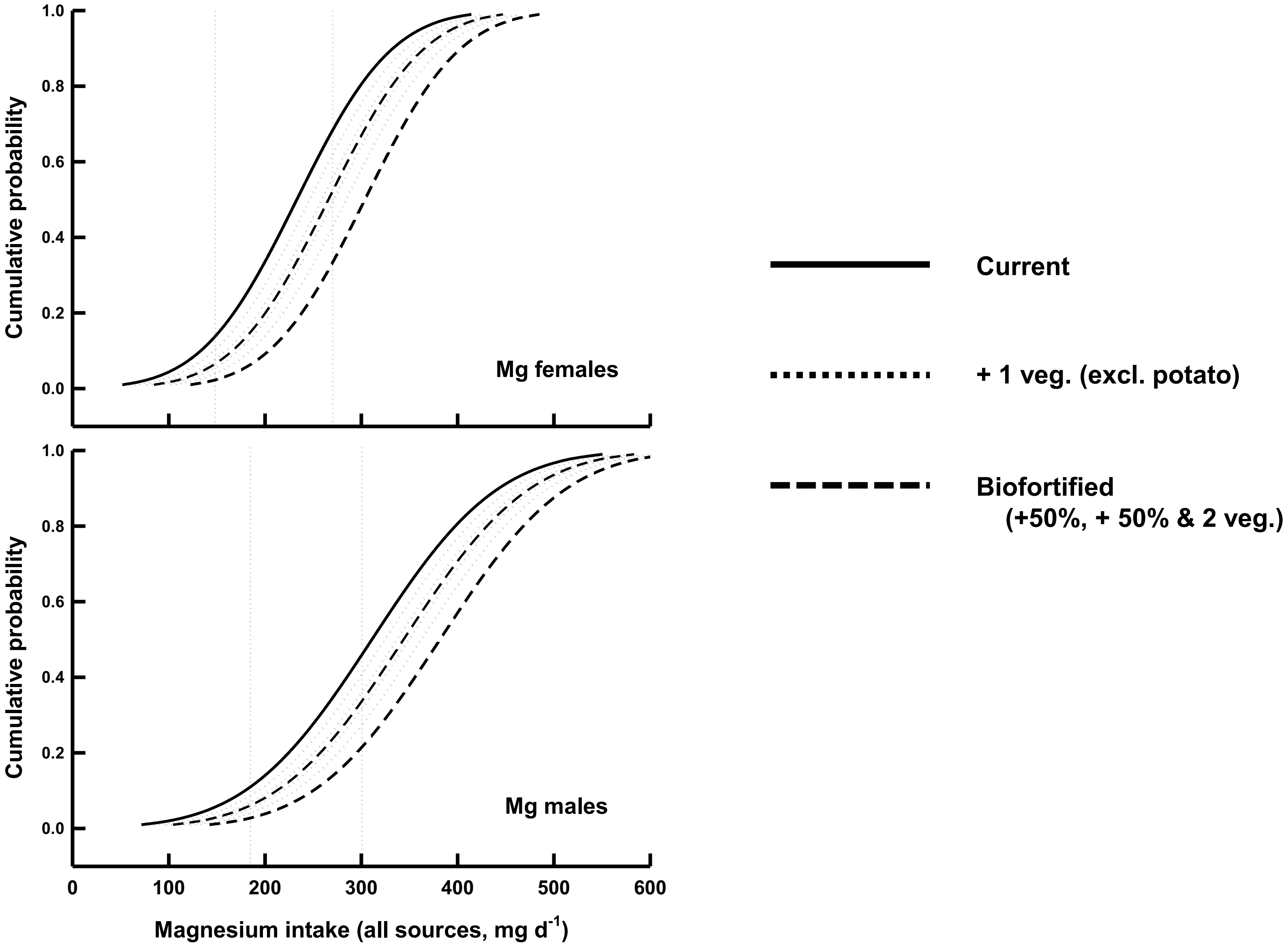
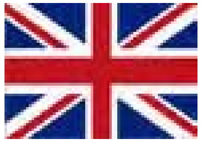
Received: *15 September 2008*
Accepted: *10 November 2008*

Impact of horticultural biofortification



Broadley MR, White PJ. (2010)

Impact of horticultural consumption / biofortification



	+2 veg.	*+50% biofort.*	*both*
Calcium	**0.5m**	**0.3m**	**1.0m (60%)**
Magnesium	**1.4m**	**2.0m**	**4.0m (75%)**
Potassium	**3.0m**	**4.1m**	**4.2m (70%)**

Proceedings of the Nutrition Society (2010), **69**, 601–612 doi:10.1017/S0029665110001588
 First published online 28 May 2010

The Winter meeting of the Nutrition Society supported by the Society for Experimental Biology and the British Society of Animal Science was held at the University of Reading on 15 December 2009

Symposium on 'Food supply and quality in a climate-changed world'

Eats roots and leaves. Can edible horticultural crops address dietary calcium, magnesium and potassium deficiencies?

Martin R. Broadley[1*] and Philip J. White[2]
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Biofortifying *Brassica* with Ca and Mg (2009-2013)

BBSRC bioscience for the future

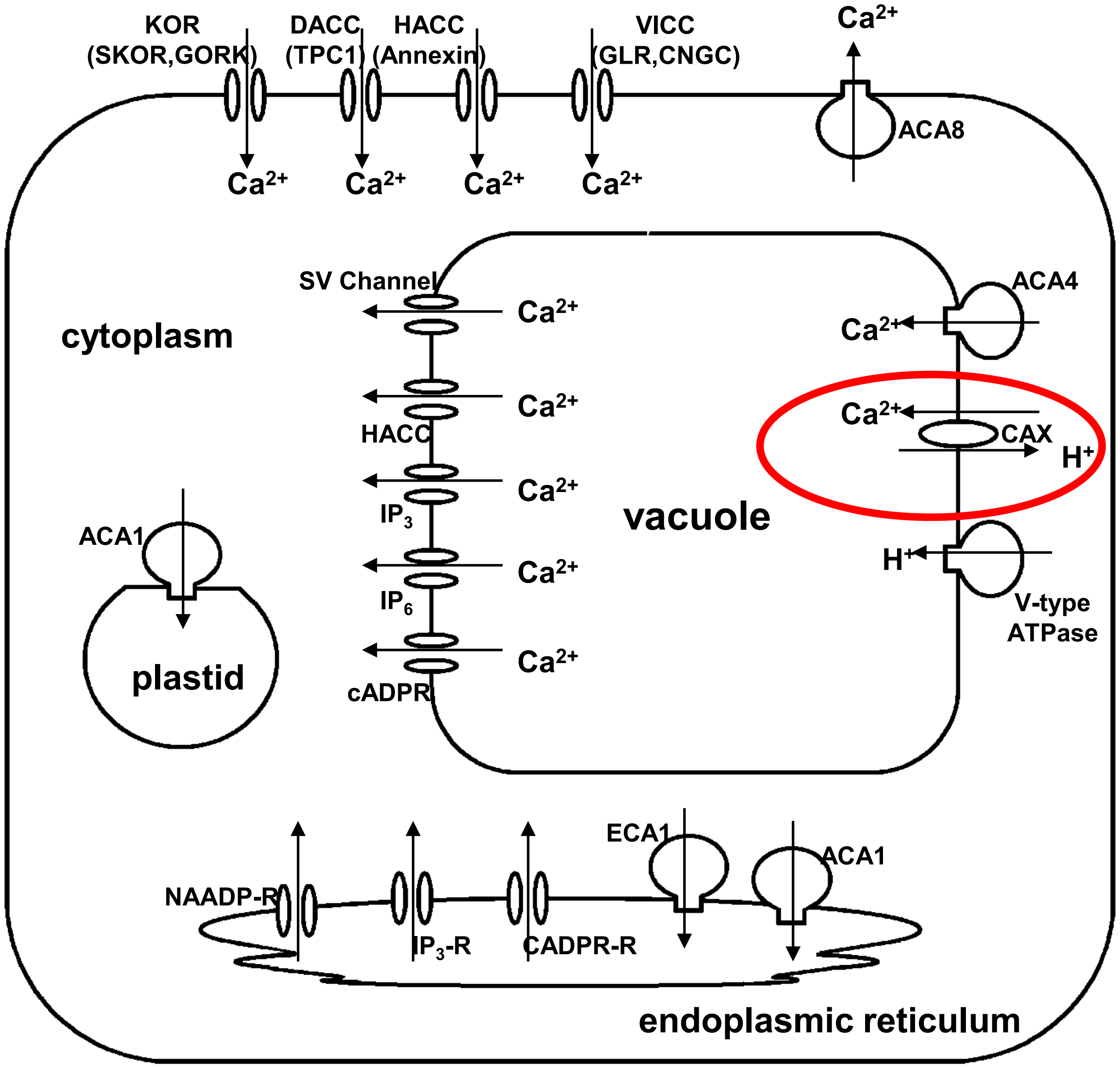
YARA

The University of Nottingham

ROTHAMSTED RESEARCH

The James Hutton Institute

Candidate genes



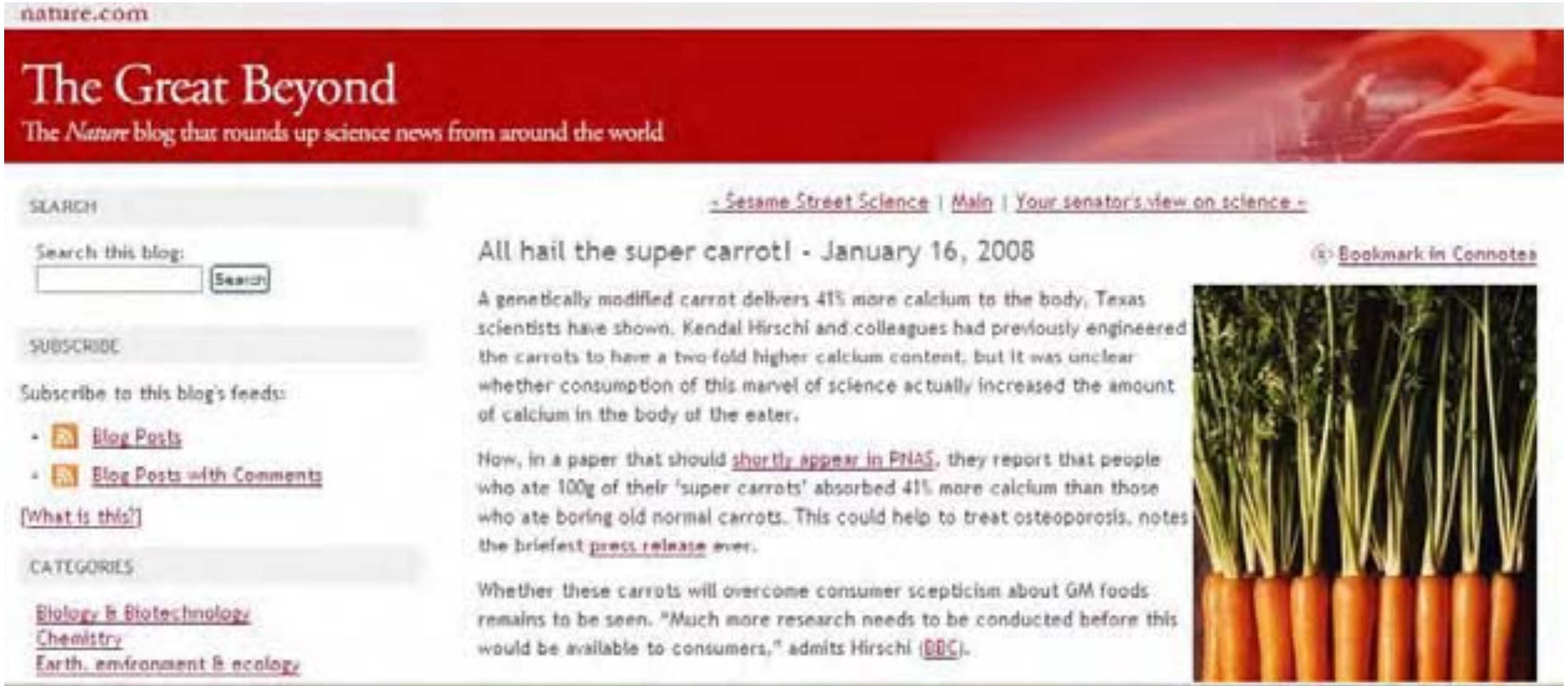
Vacuolar Ca accumulation via P_{2B}-ATPases (*ECA*/*ACA*), Ca^{2+}/H^{+} antiporters (*CAX*)

White PJ & Broadley MR (2003). *Annals of Botany*, 92, 487-511

Candidate genes

Overexpression of modified CAX1 (sCAX1) increases bioavailable Ca in:

Carrot:	***100% increase in Ca***	**Morris J et al. (2008).** ***PNAS*** **105, 1431-1435**
Lettuce:	***25-32% increase in Ca***	**Park S et al. (2009).** ***Plant Biotechnol. J.*** **7, 106-117**
Tomato:	***>20% increase in Ca***	**Park S et al. (2005).** ***Plant Physiol. 139, 1194-1206***
Potato:	***>100% increase in Ca***	**Park S et al. (2005).** ***J. Ag. Food Chem.*** **53, 5598-5603**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All hail the super carrot! - January 16, 2008

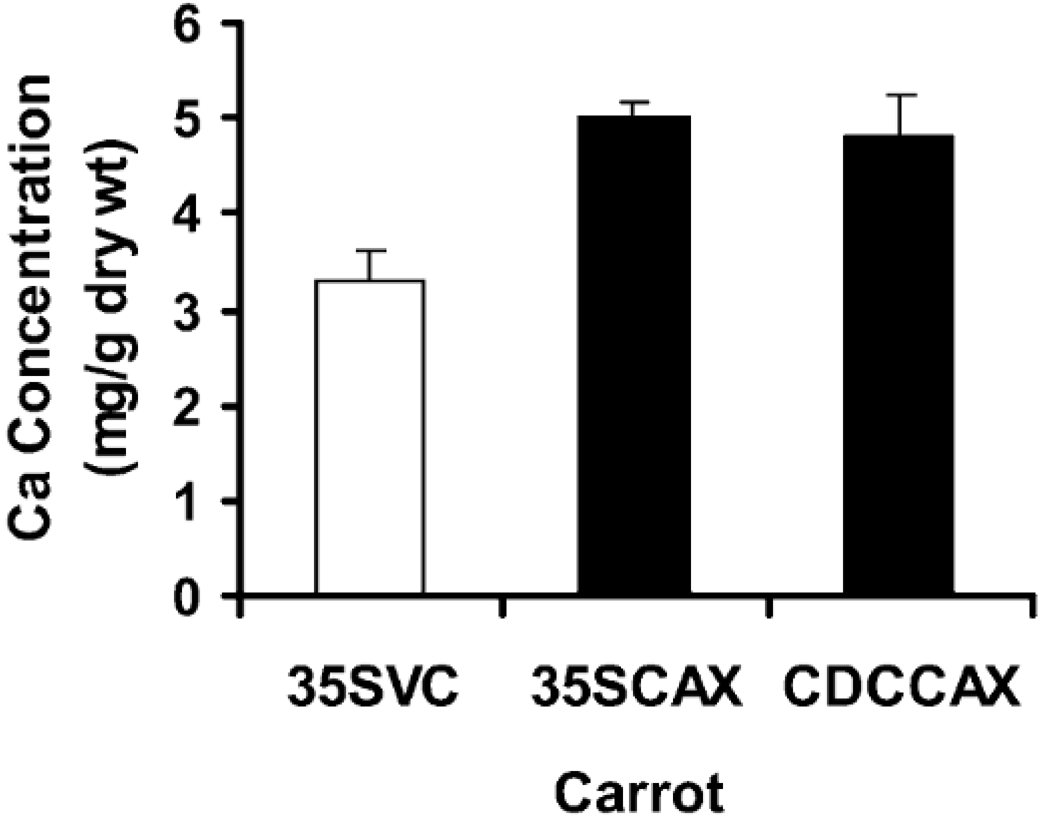
Bookmark in Connotea

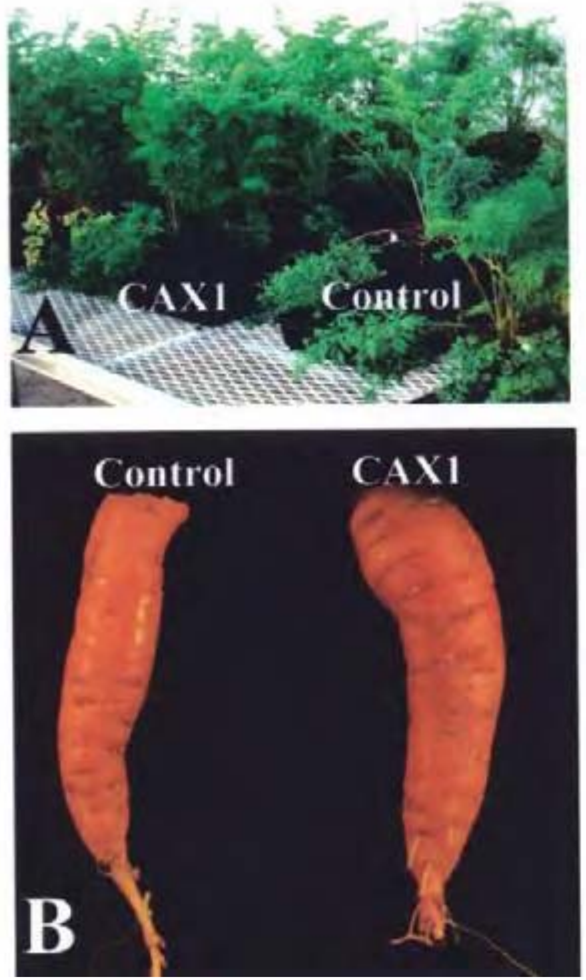
A genetically modified carrot delivers 41% more calcium to the body, Texas scientists have shown. Kendal Hirschi and colleagues had previously engineered the carrots to have a two-fold higher calcium content, but it was unclear whether consumption of this marvel of science actually increased the amount of calcium in the body of the eater.

Now, in a paper that should shortly appear in PNAS, they report that people who ate 100g of their 'super carrots' absorbed 41% more calcium than those who ate boring old normal carrots. This could help to treat osteoporosis, notes the briefest press release ever.

Whether these carrots will overcome consumer scepticism about GM foods remains to be seen. "Much more research needs to be conducted before this would be available to consumers," admits Hirschi (BBC).

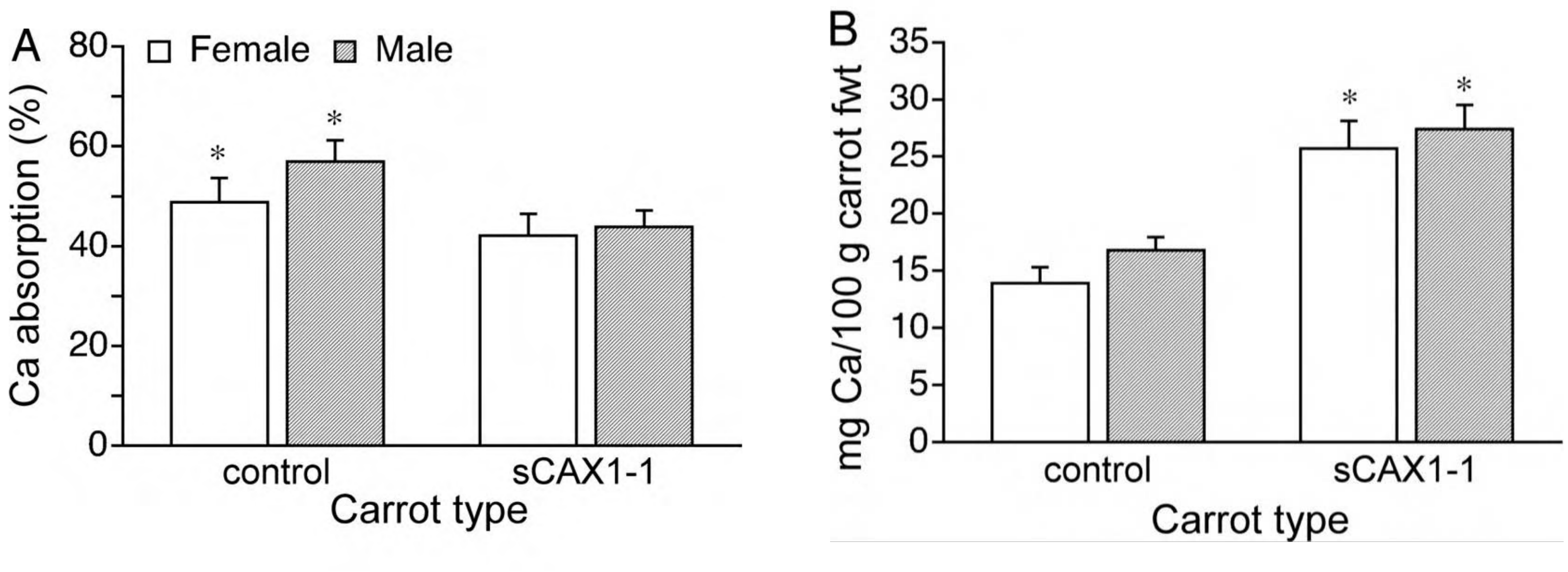
Candidate genes





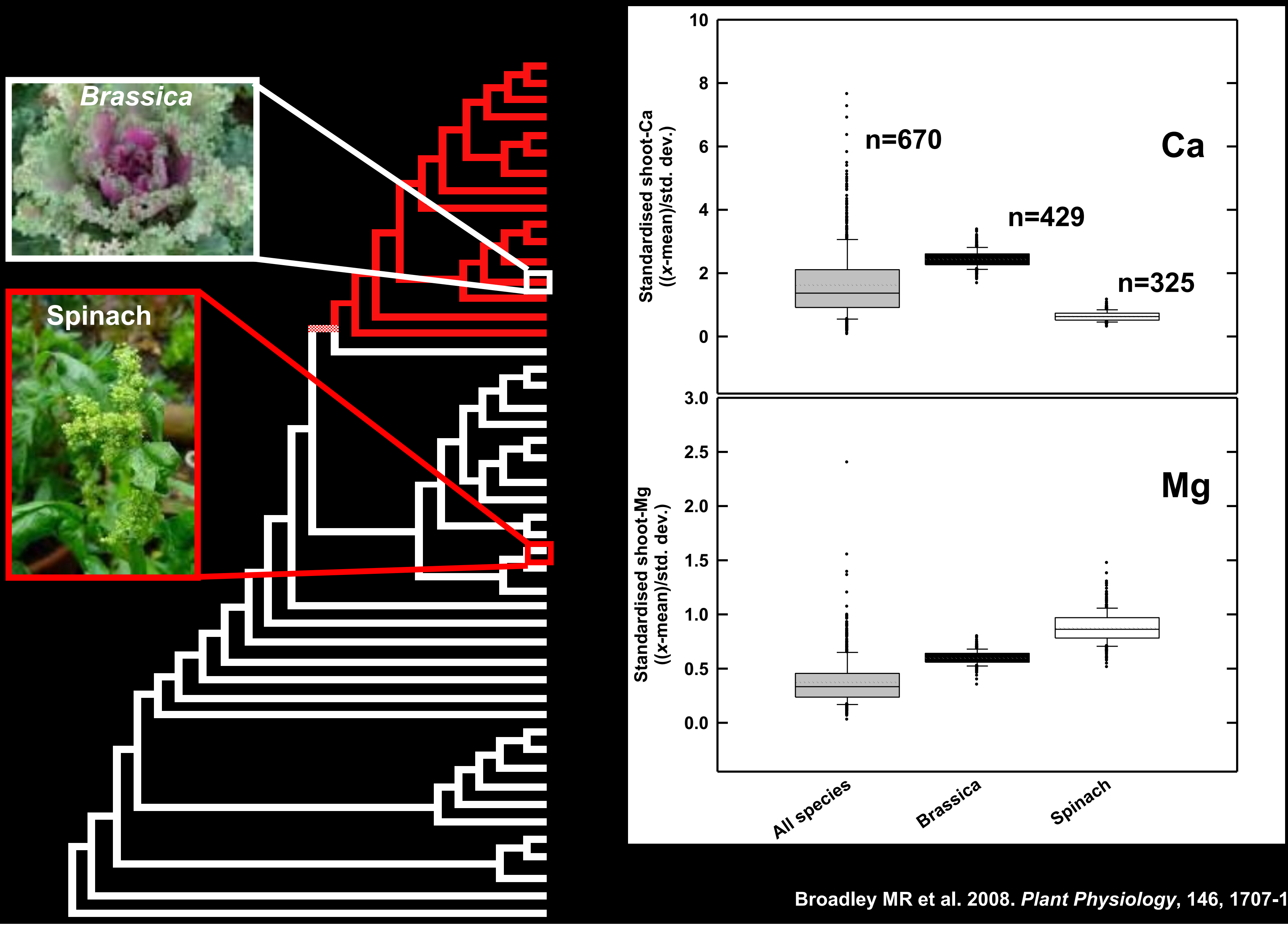
Park et al. (2004). *Molecular Breeding,* 14: 275-282.

Candidate genes



Morris J et al. (2008) *PNAS*, 105, 1431-1435

Brassica is a good breeding target for Ca and Mg



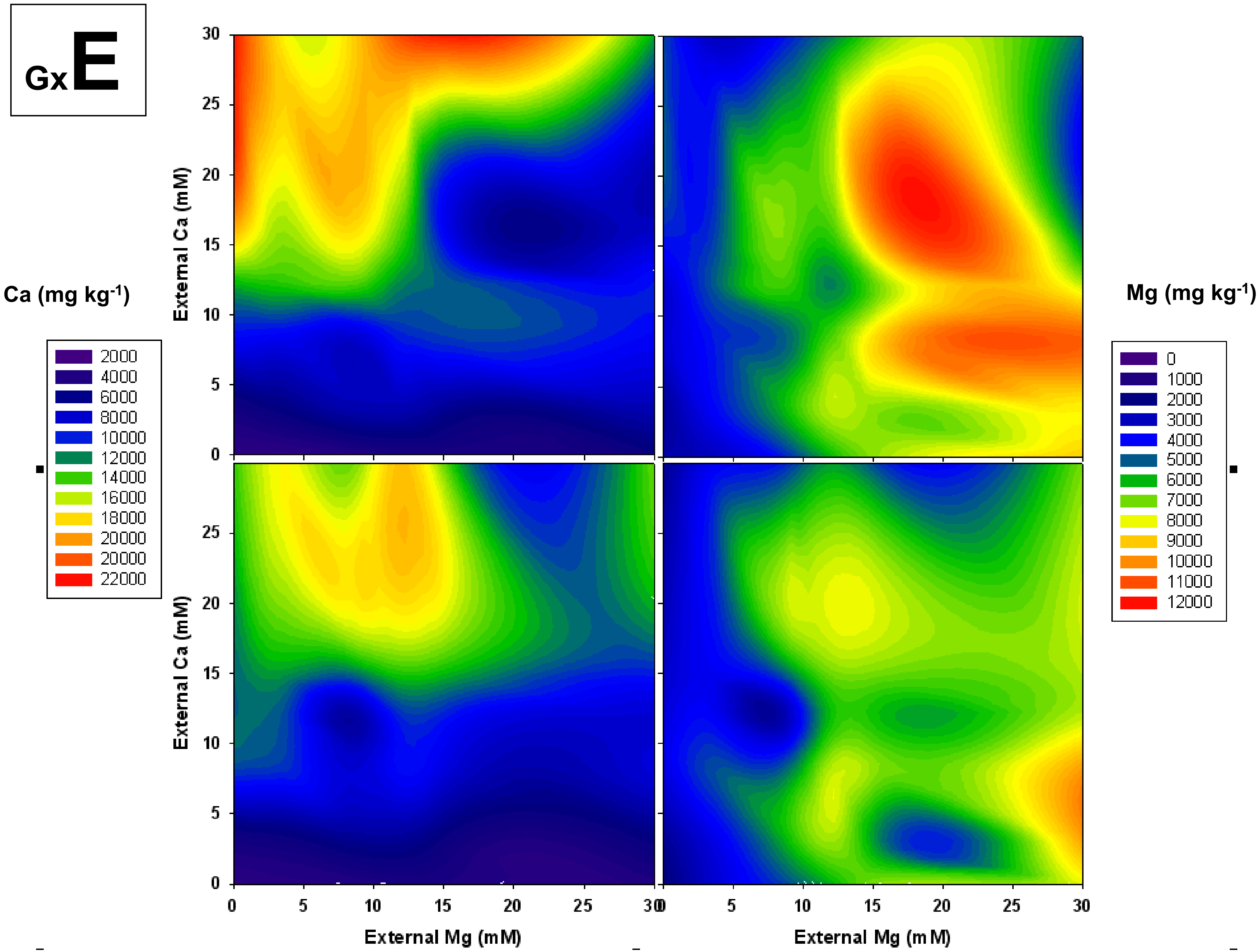
Broadley MR et al. 2008. *Plant Physiology*, 146, 1707-1720

Brassica is a good breeding target for Ca and Mg

Brassica rapa **rapid-cycling, selfs easily, sequenced, current major focus for G x E work and novel gene identification:**

7 11 16 19 23 27 31 36 39 43 47 51 55

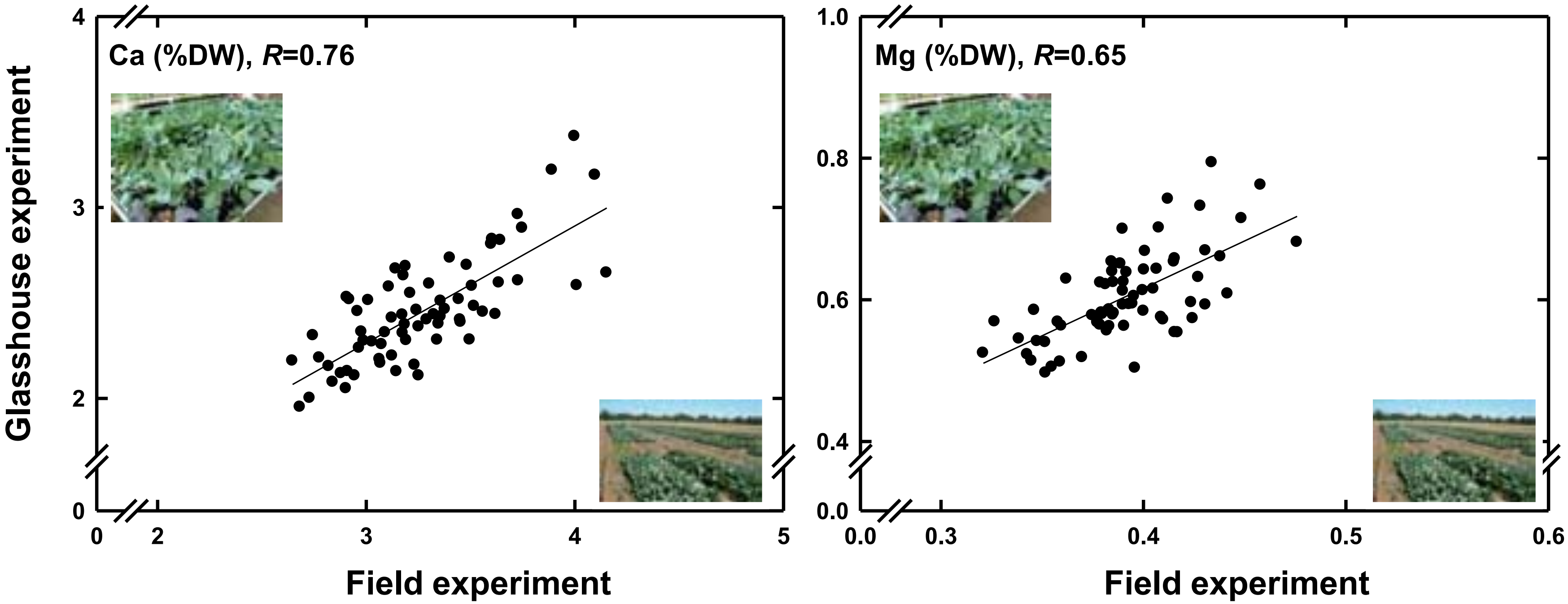
Days after sowing (composite image)



GxE
Ca (mg kg-1)
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
20000
22000
Mg (mg kg-1)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
External Ca (mM)
External Mg (mM)
0
5
10
15
20
25
30

G$_{xE}$

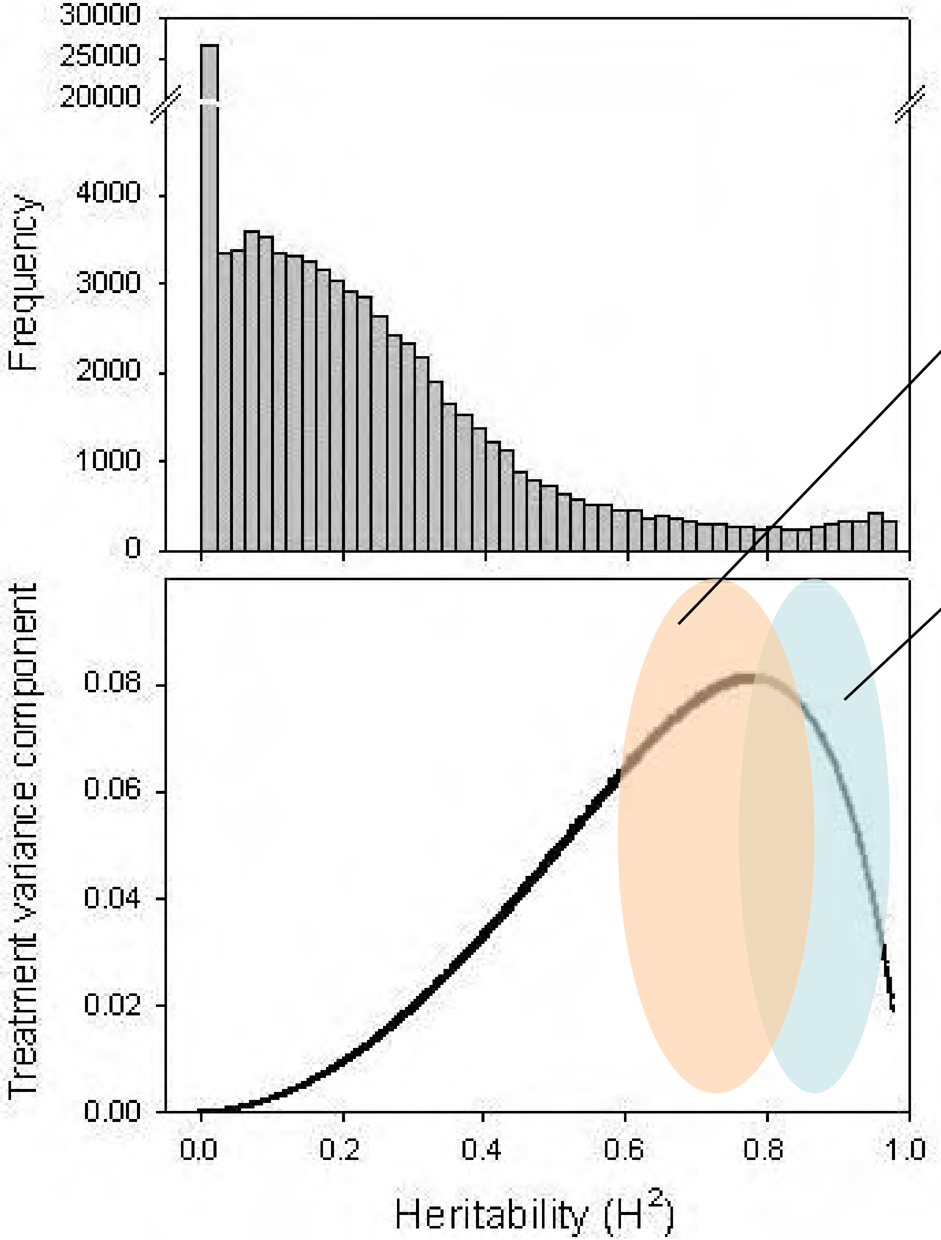
F_1 hybrids in field *vs* glasshouse experiments (2002-2007)…



…indicates strong genetic component to leaf/shoot Ca and Mg

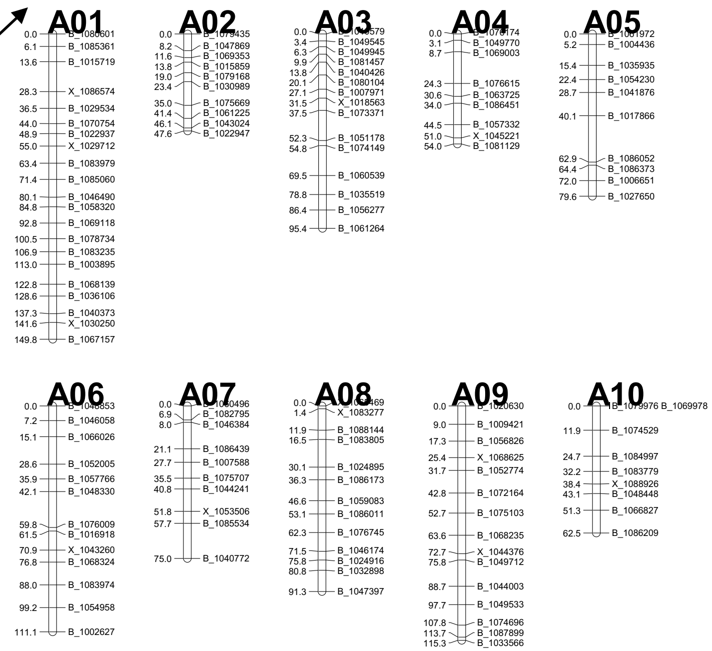
Broadley MR et al. 2008. *Plant Physiology*, 146, 1707-1720.

GxE

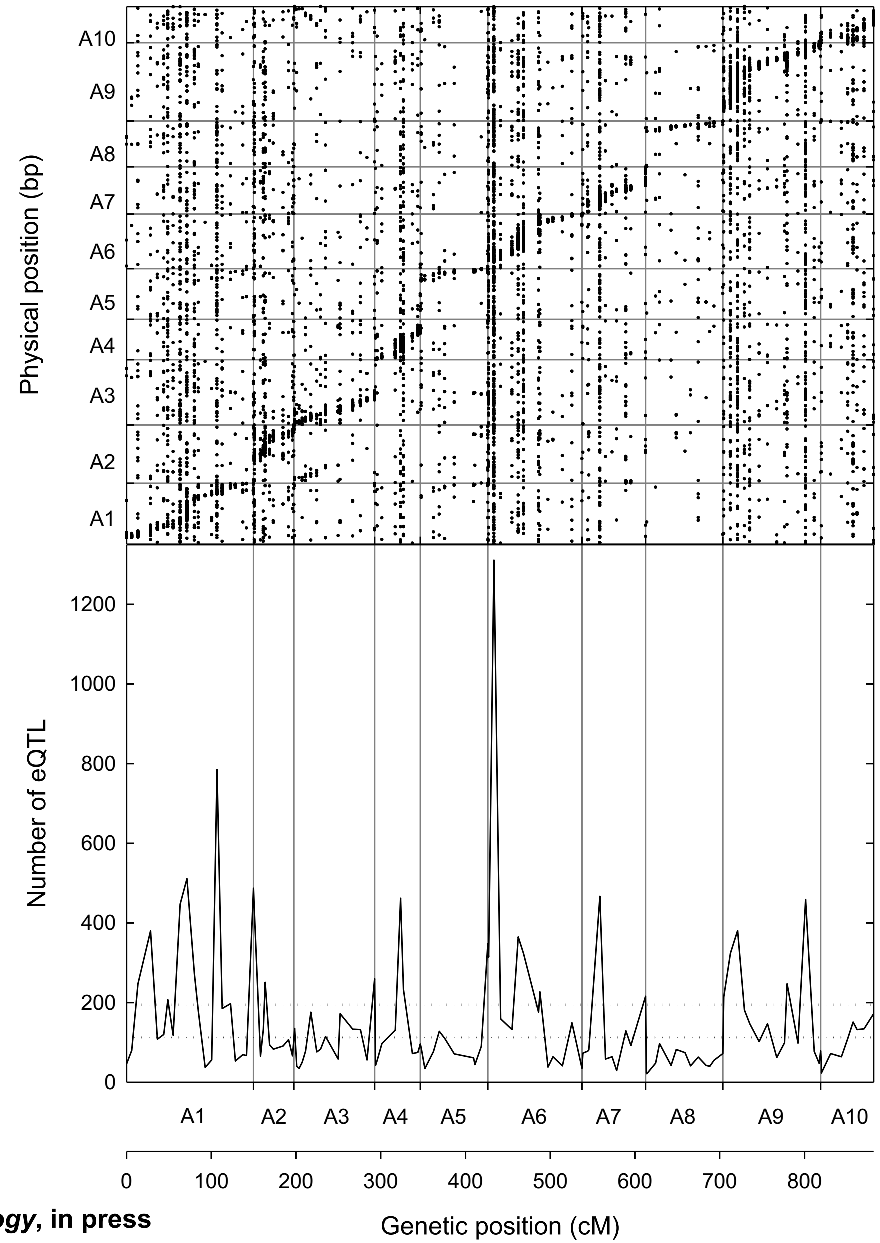


Nutrient-responsive genes

GEMs



Targets regulating leaf Ca and Mg concentration (eQTL)



Hammond et a. (2011). *Plant Physiology*, in press

Selenium

Essential for animals, not plants

25 mammalian selenoproteins

Many identified roles in health

Fairweather-Tait *et al.* (2011). *Antiox. Redox Signal.* 14, 1337-83

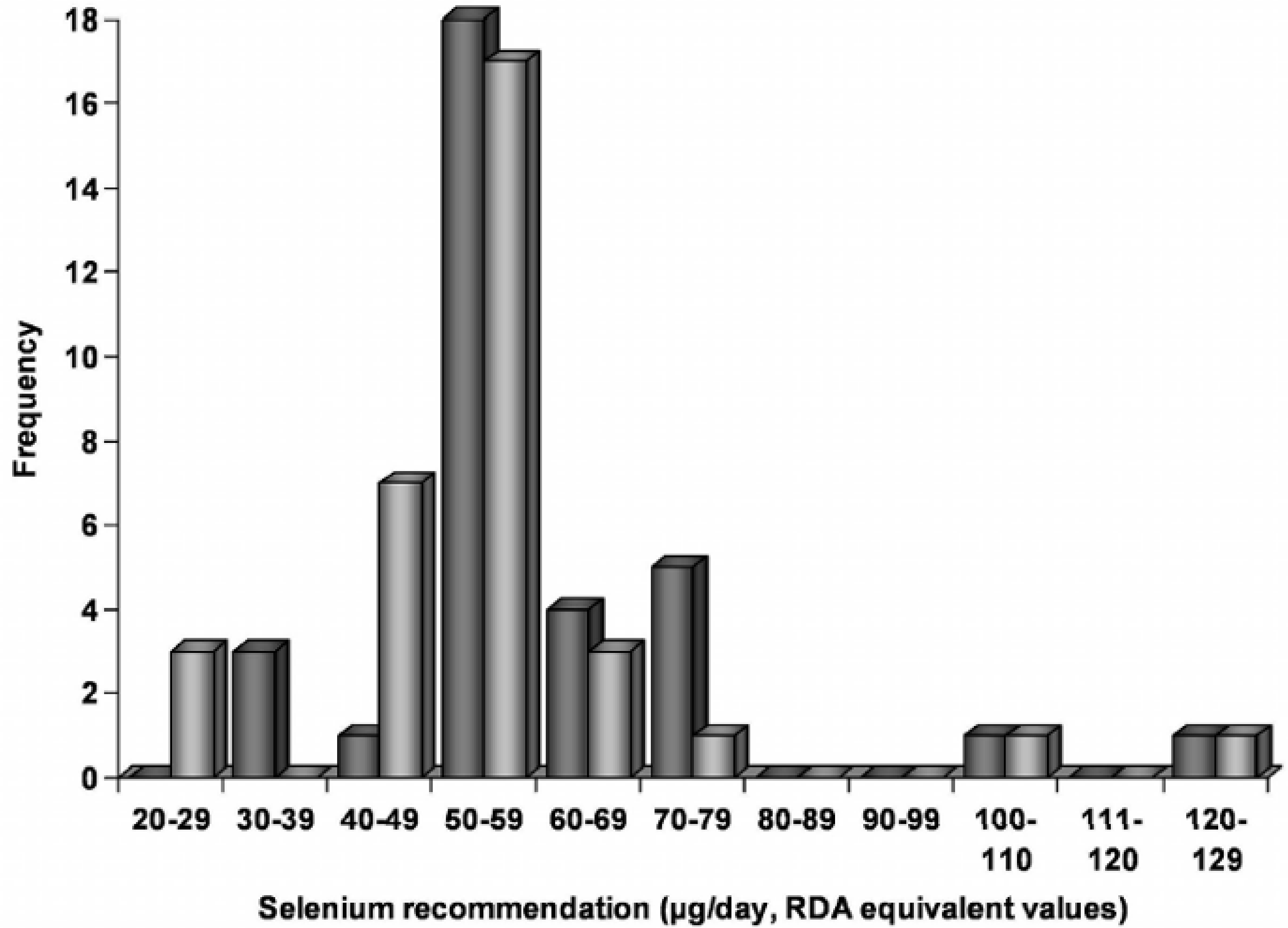
Serum/ plasma selenium (ng/ml)		References
>3200-7500	>3200-7500 ng/ml toxicity - death/mortality	Yang et al 1983, Lech et al 2002
>490-<640	Selenium related side-effects; no serious toxicity	Reid et al 2004
>250	Selenium related side-effects; hair loss, dermatitis	Lippman et al 2009
180		
160	Protection against some cancers; [increased risk of diabetes, high blood pressure and hypertension]	Yu et al 1999, [Bleys et al 2007, Laclaustra et al 2009]
140	Protection against some cancers; reduction in total mortality	Nomura et al 2000, Combs et al 2001, Bleys et al 2008, Yu et al 1999, [Vogt et al 2003]
120	Optimisation of selenoprotein P, protection against some cancers, reduction in total mortality	Combs et al 2001, Burk 2006, Hurst 2010, Thompson 2004, Bleys et al 2008
100		
80	Optimisation of glutathione peroxidase	Thompson 2004
60	Optimisation of iodothyronine deiodinases	Thompson 2004
40		
20	< 20-40 ng/ml Se deficiency diseases, Keshan, Kashin-Beck, cretinism (with iodine deficiency)	Thompson 2004; Shi et al 2010

> Requirements, up to toxic effects

Adequacy/'optimal'

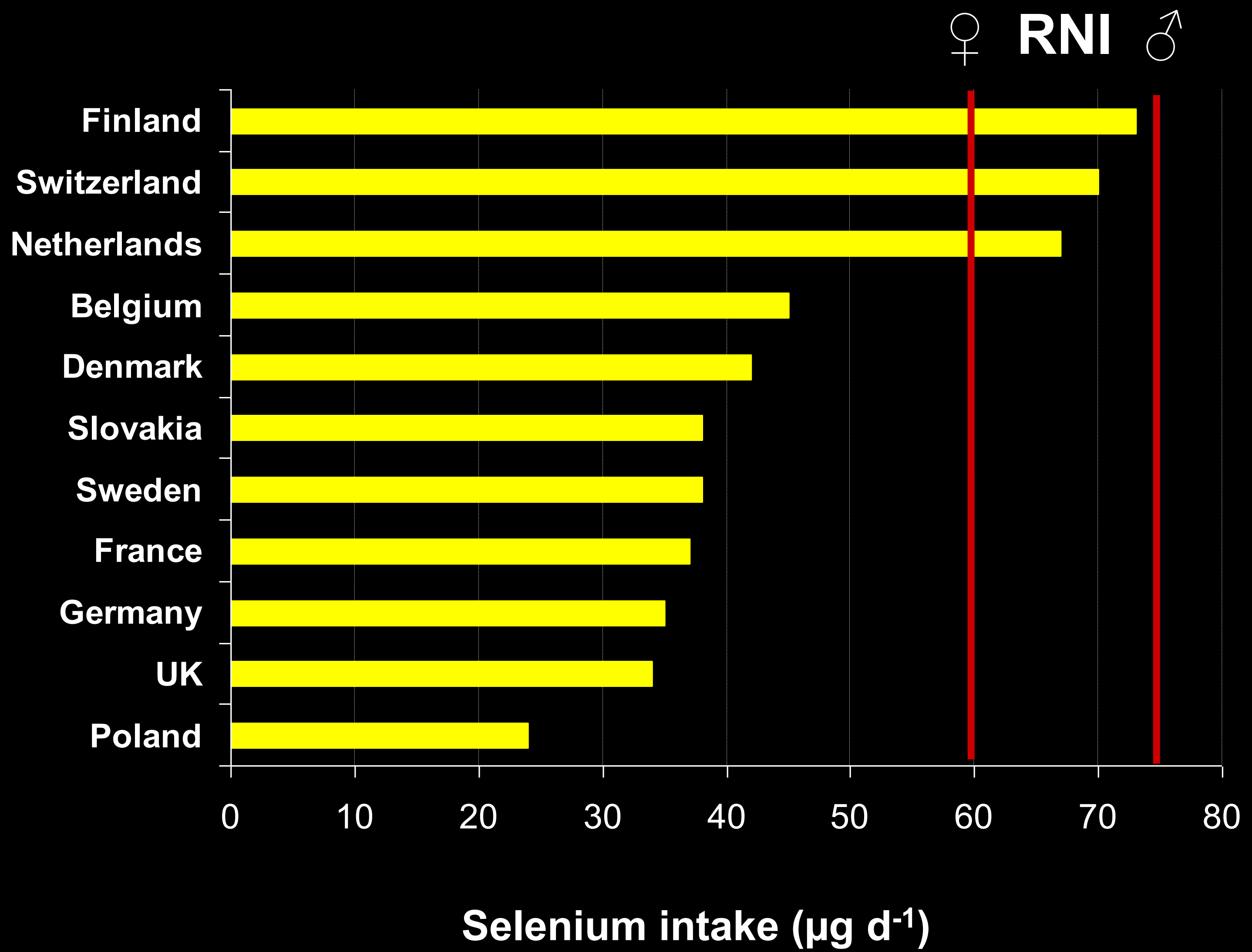
Deficiency

Selenium recommended intakes



SJ Fairweather-Tait et al. (2011). Current diversity in Se recommendations. Compiled using the EURRECA Nutri-RecQuest database. Where recommendations are given as ranges the midpoint has been used. Males (M) and females (F) are shaded as dark grey or light grey bars respectively.

Selenium actual intakes



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

Wheat-grain Se (UK)

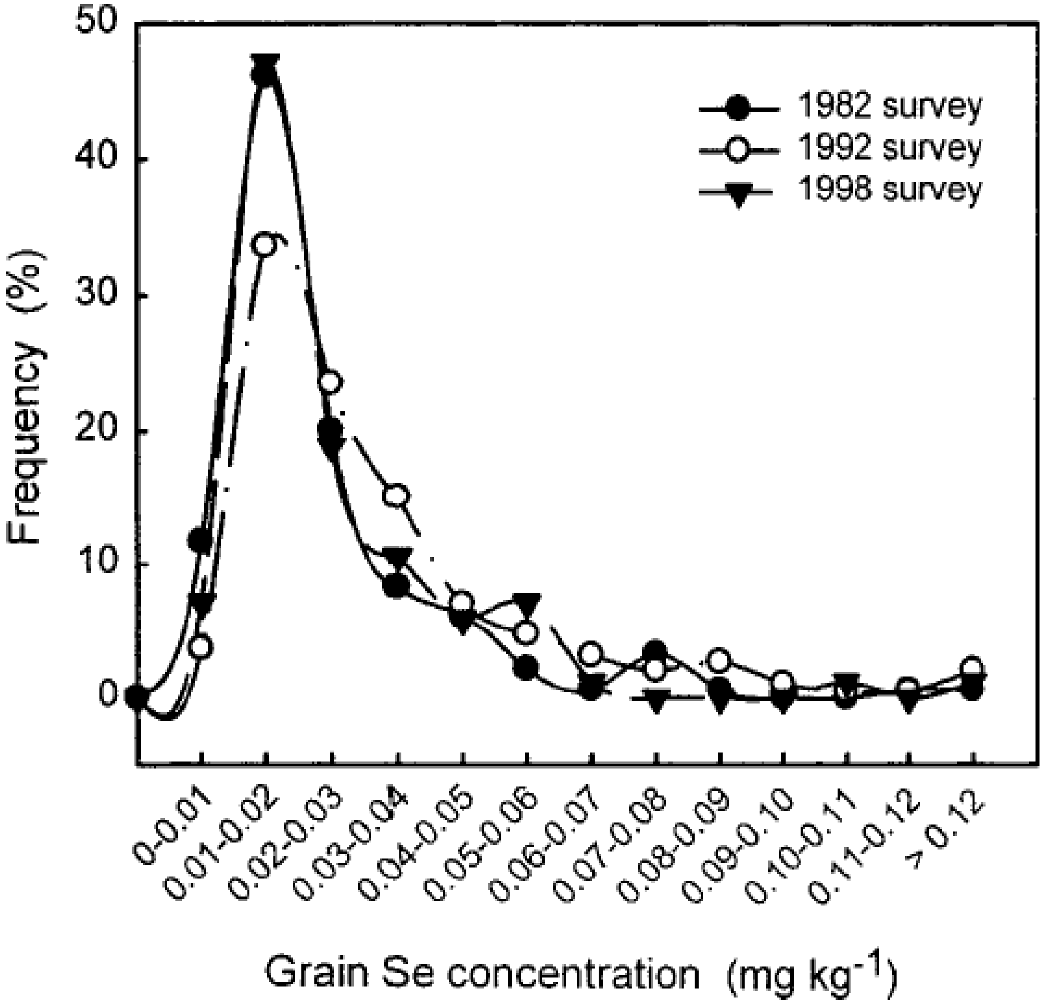
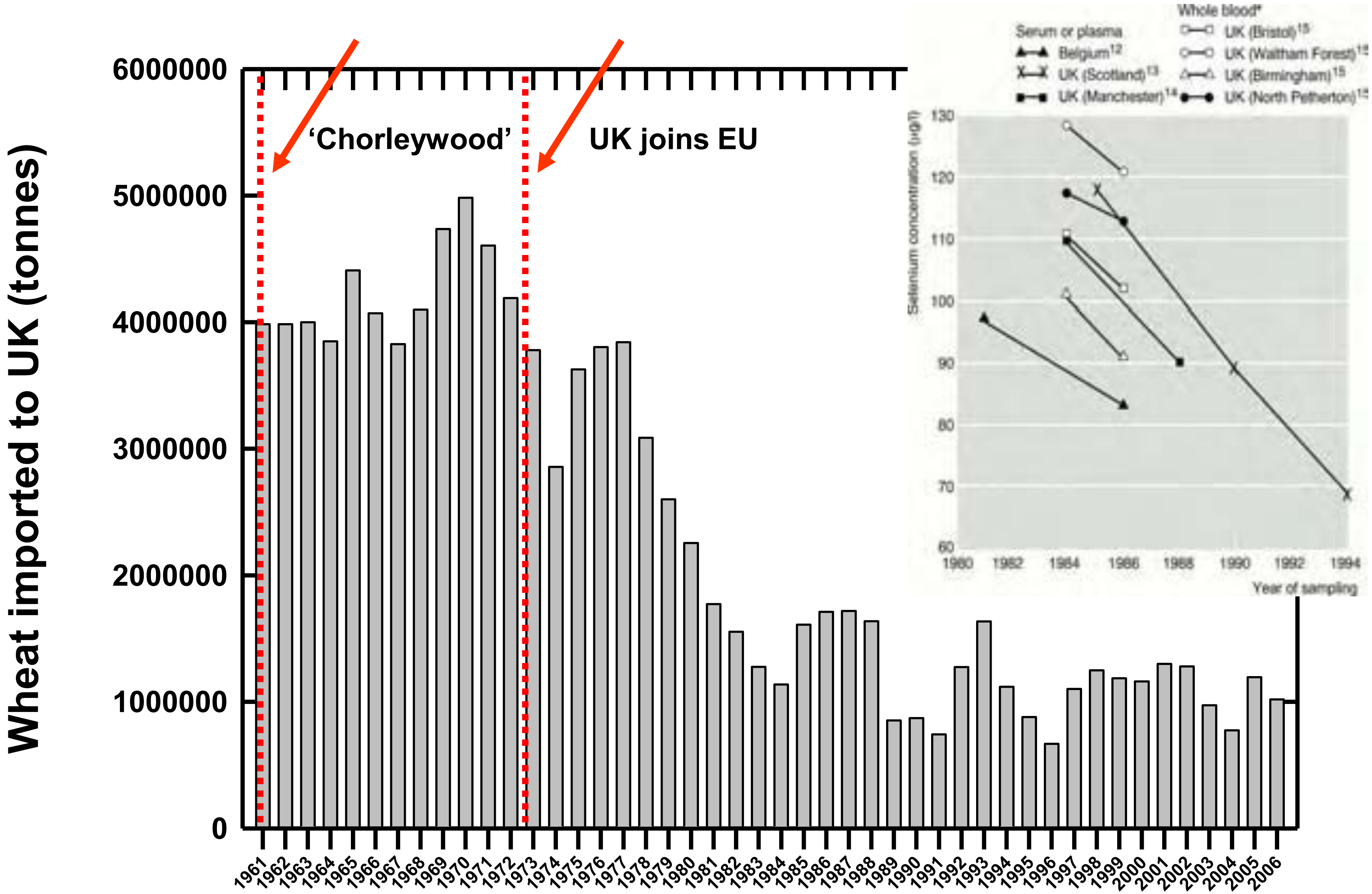


Figure 1. Distribution of selenium in bread-making wheat grain varieties collected from representative sites throughout the UK during 1982 (n=180), 1992 (n=187) and 1998 (n=85).

Canada = 0.760 mg kg^{-1}

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

Low dietary Se intakes in UK

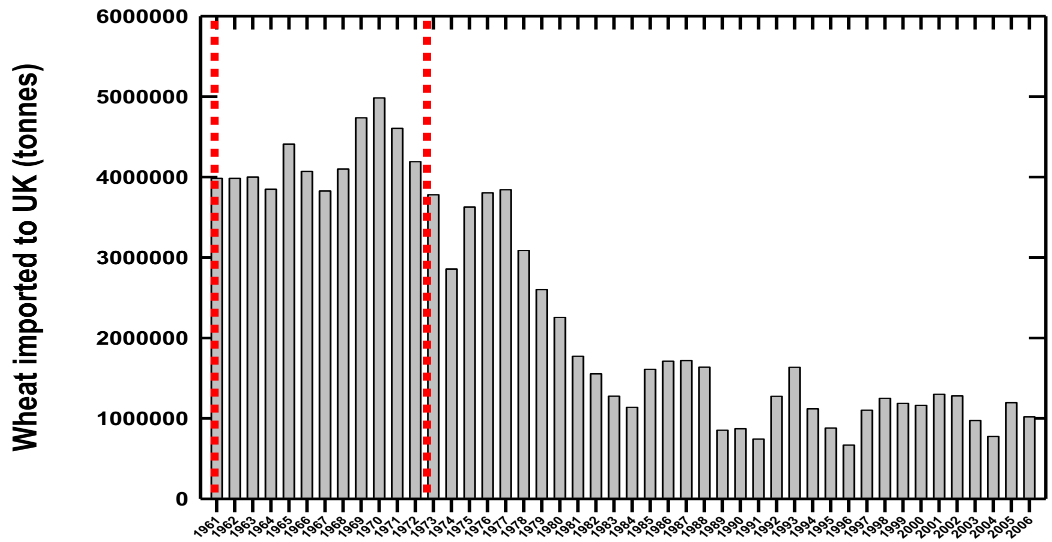


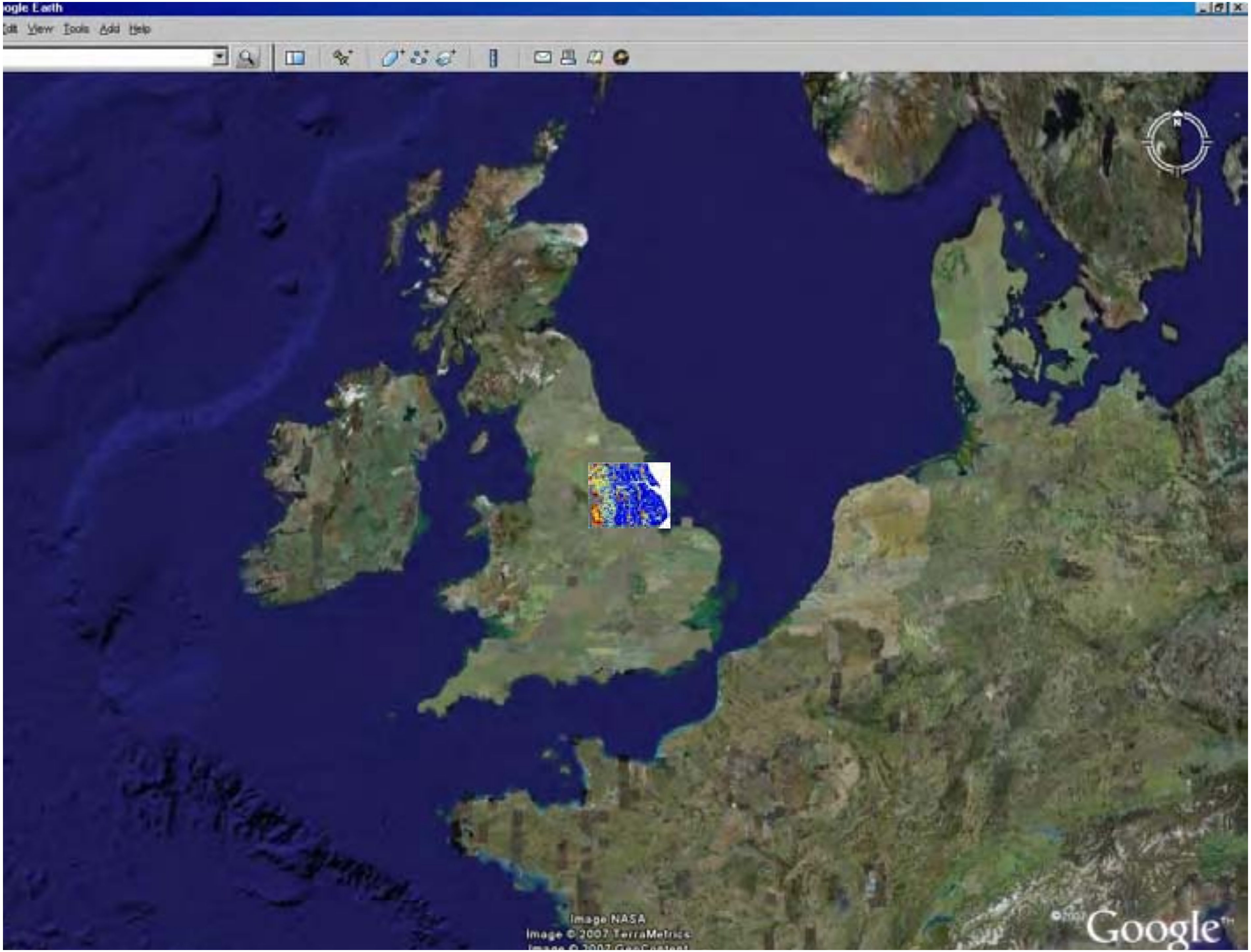
SJ Fairweather-Tait *et al.* (2011). *Antiox. Redox Signal.* 14, 1337-83. Figure 5a. UK wheat imports 1961-2006.

Low dietary Se intakes in UK

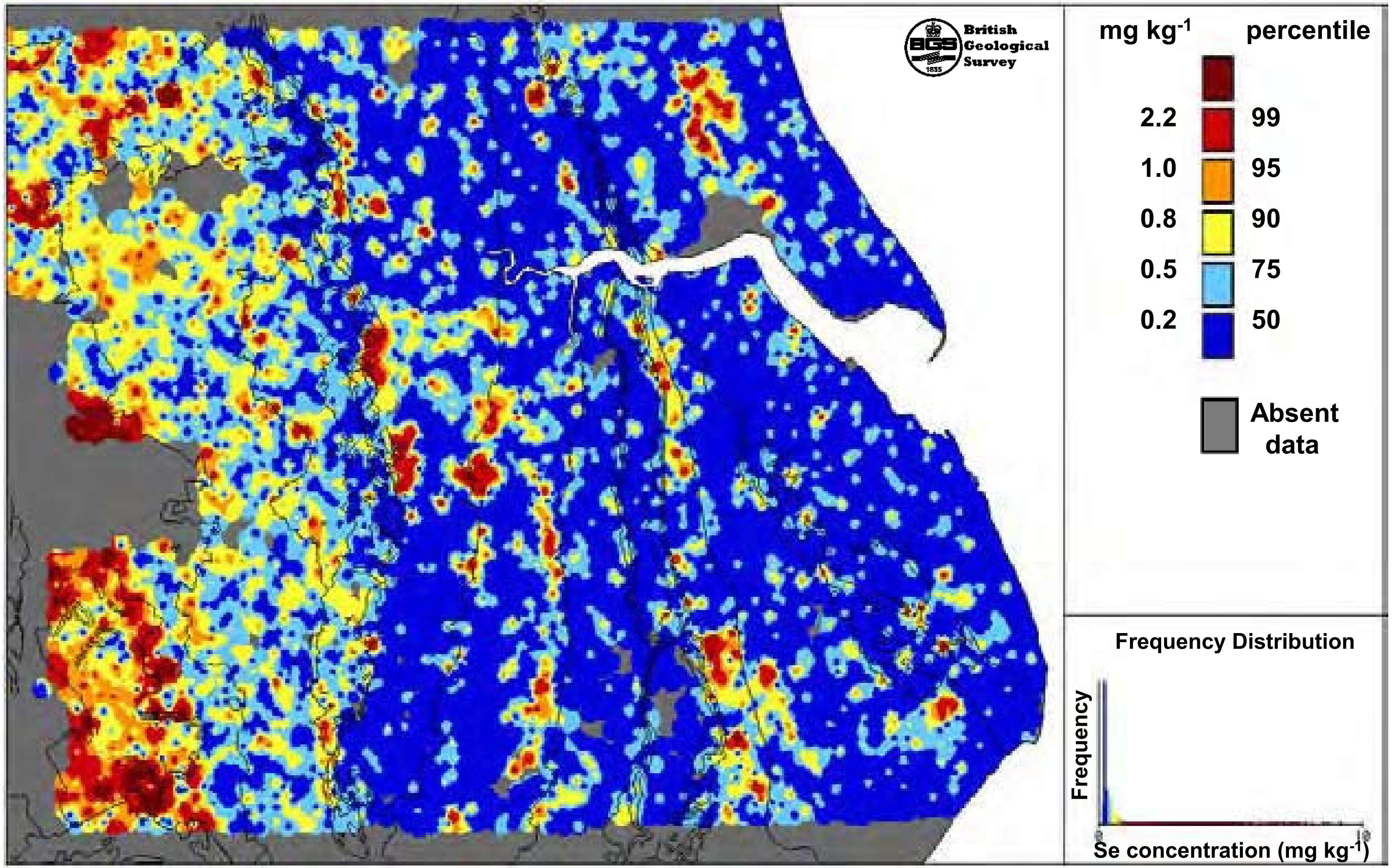
~87 µg Se person d^{-1}

~17 µg Se person d^{-1}




View Tools Add Help
Image NASA
Image © 2007 TerraMetrics
Google

Low baseline selenium in UK soils



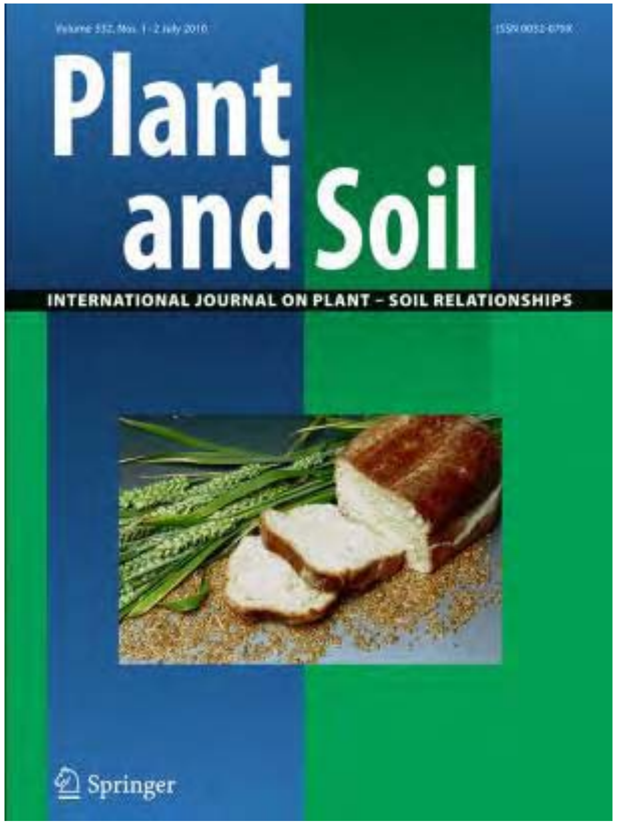
British Geological Survey

Broadley MR et al., 2006. *Proceedings of the Nutrition Society*, 65, 169-181.

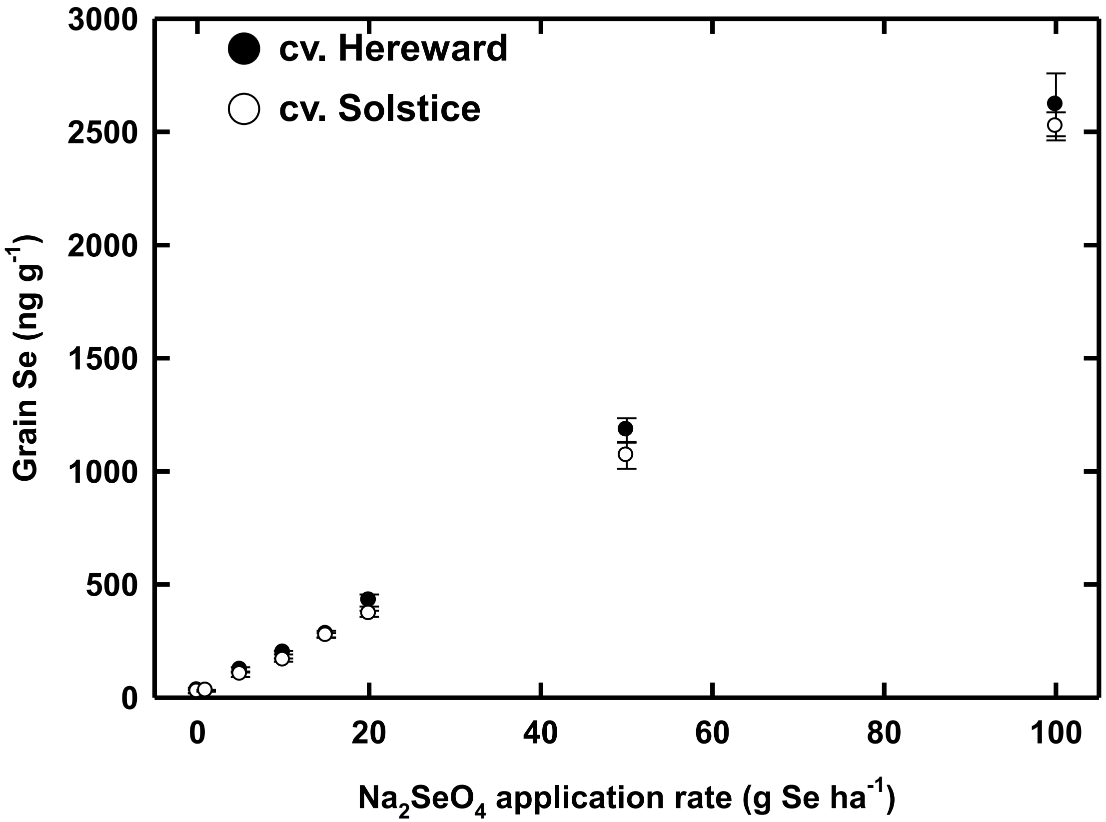
Biofortification experiments, UK (2005-2009)


Biofortification experiments, UK (2005-2009)
University of Nottingham, Sutton Bonington Farm, 2006

Biofortification experiments, UK (2005-2009)



16-24 ng Se g^{-1} grain . g^{-1} Se ha^{-1}



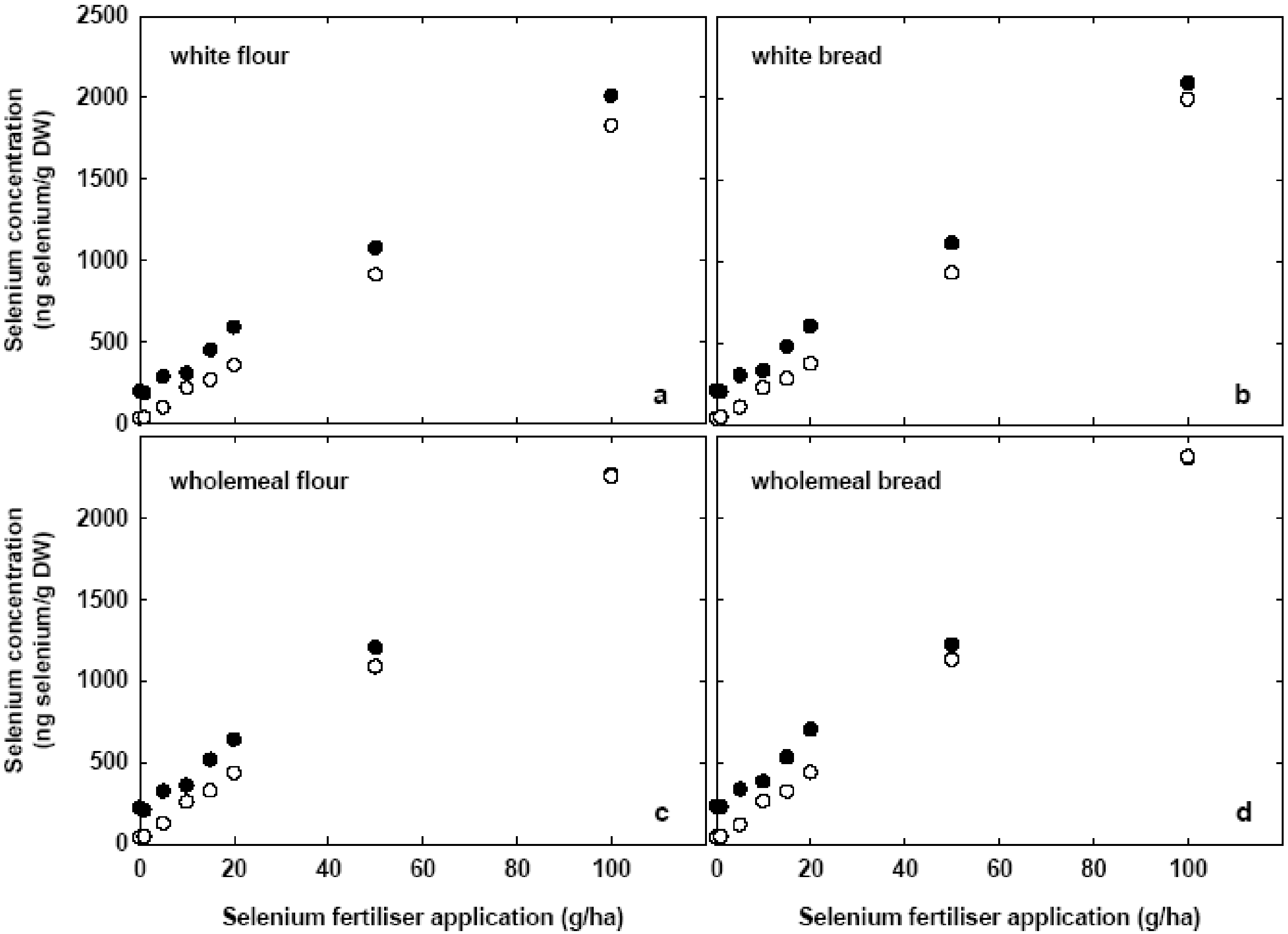
Broadley MR, Alcock J, Alford J, Cartwright P, Fairweather-Tait SJ, Foot I, Hart DJ, Hurst R, Knott P, McGrath SP, Meacham MC, Norman K, Mowat H, Scott P, Stroud JL, Tovey M, Tucker M, White PJ, Young SD, Zhao F-J (2010). Selenium biofortification of high-yielding winter wheat (*Triticum aestivum* L.) by liquid or granular Se fertilisation. *Plant & Soil*, 332, 5-18.

Stroud JL et al. (2010). *Plant & Soil*, 332, 19-30.

Stroud JL et al. (2010). *Plant & Soil*, 332, 31-40.

Hart DJ et al. (2011). *Food Chemistry*, 126, 1771-1778.

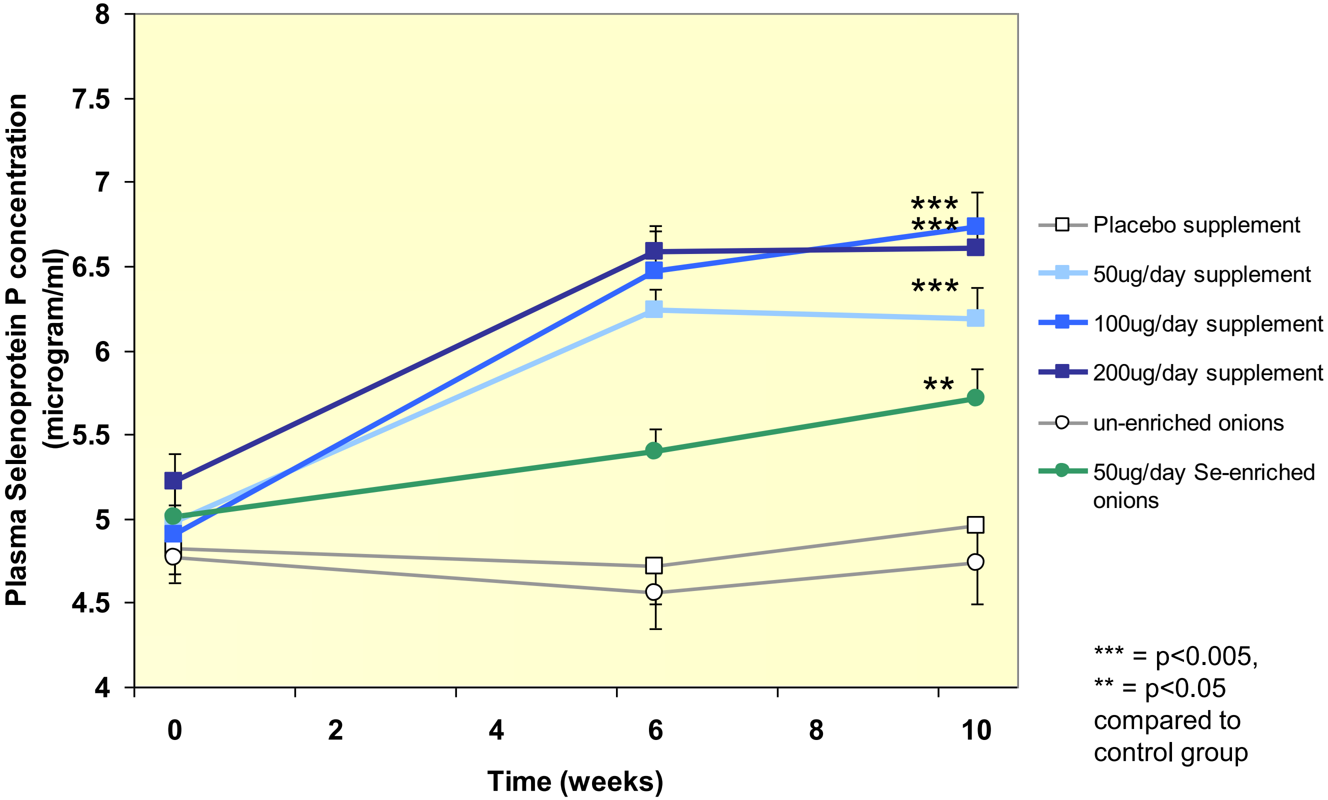
Biofortification experiments, UK (2005-2009)



5 g Se ha^{-1} = ~3.5 µg Se slice bread

Hart DJ et al. (2011). *Food Chemistry*, 126, 1771-1778.

Health outcomes...? (feeding studies UK, 2005-2009)



*** = p<0.005,
** = p<0.05
compared to
control group

Hurst et al. (2010). *American Journal of Clinical Nutrition*, 91, 923-931.

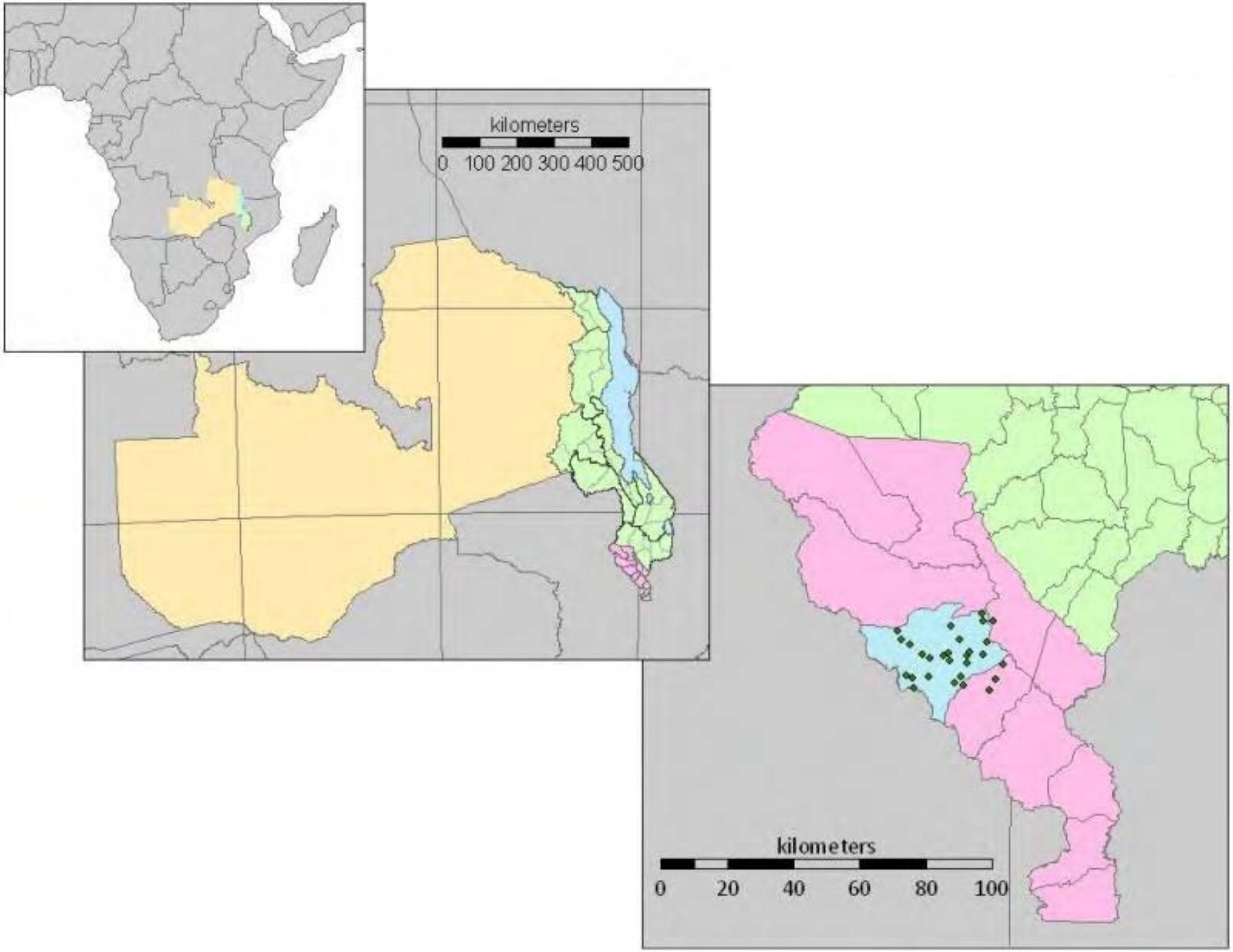
Biofortification-related work, Malawi, Zambia (2008-…)

Phase I, 2008-11

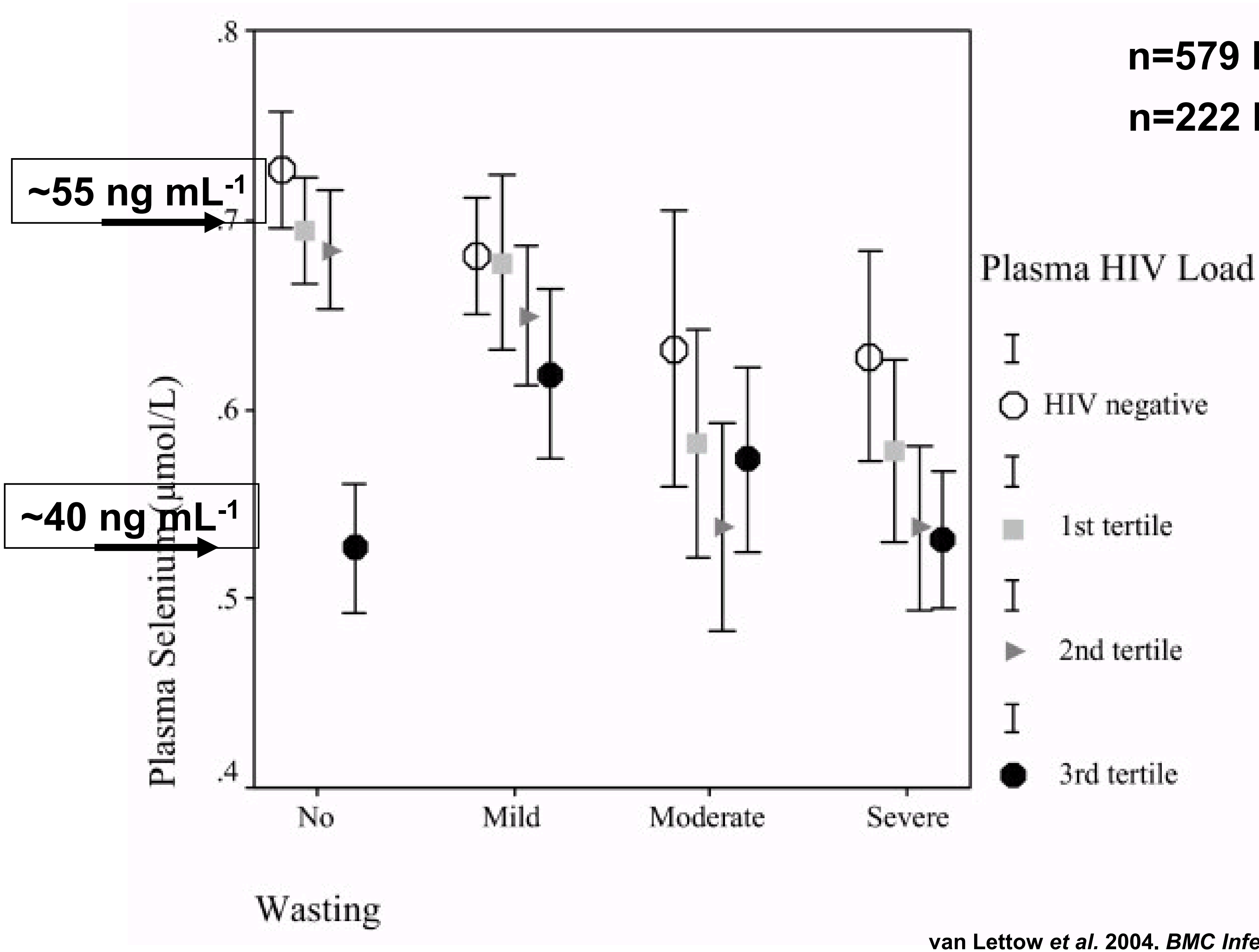
Phase II, 2010-11

Phase III….

Biofortification-related work, Malawi, Zambia (2008-…)



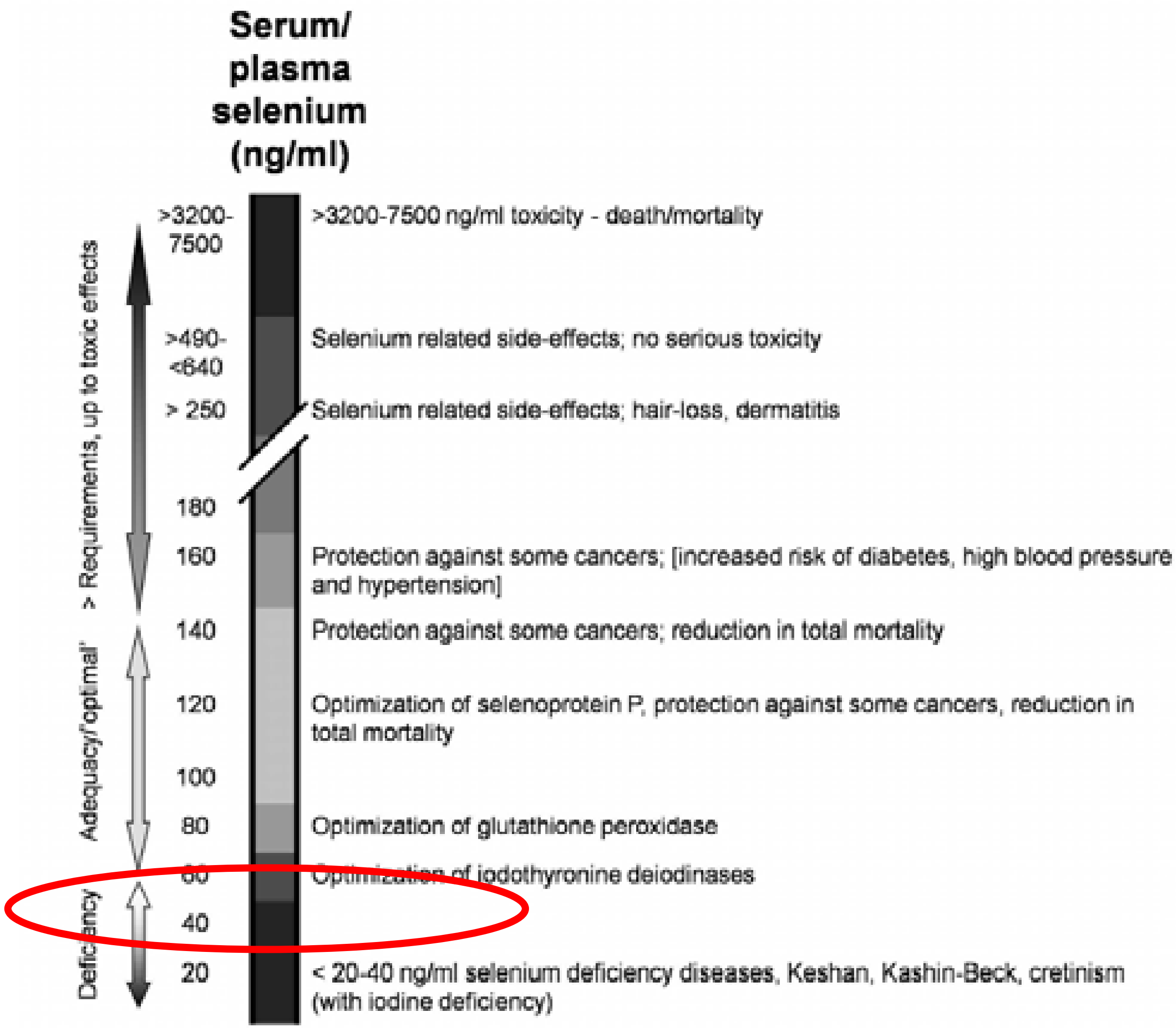
Low plasma Se status in Malawi



n=579 HIV$^+$

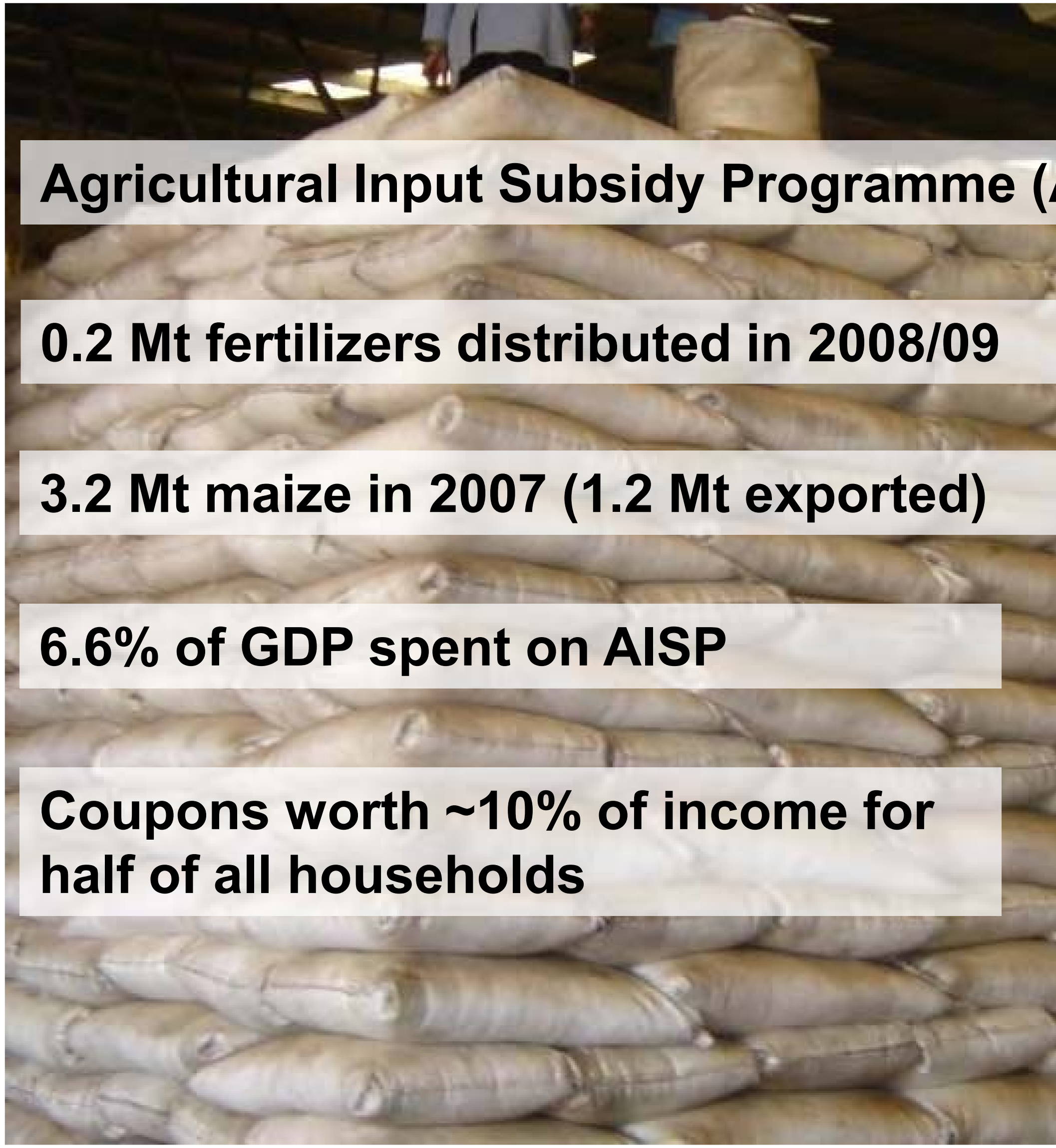
n=222 HIV$^-$

van Lettow *et al.* 2004. *BMC Infectious Diseases* 4: 61



Fairweather-Tait *et al.* (2011). *Antiox. Redox Signal.* 14, 1337-83

Yield security in Malawi



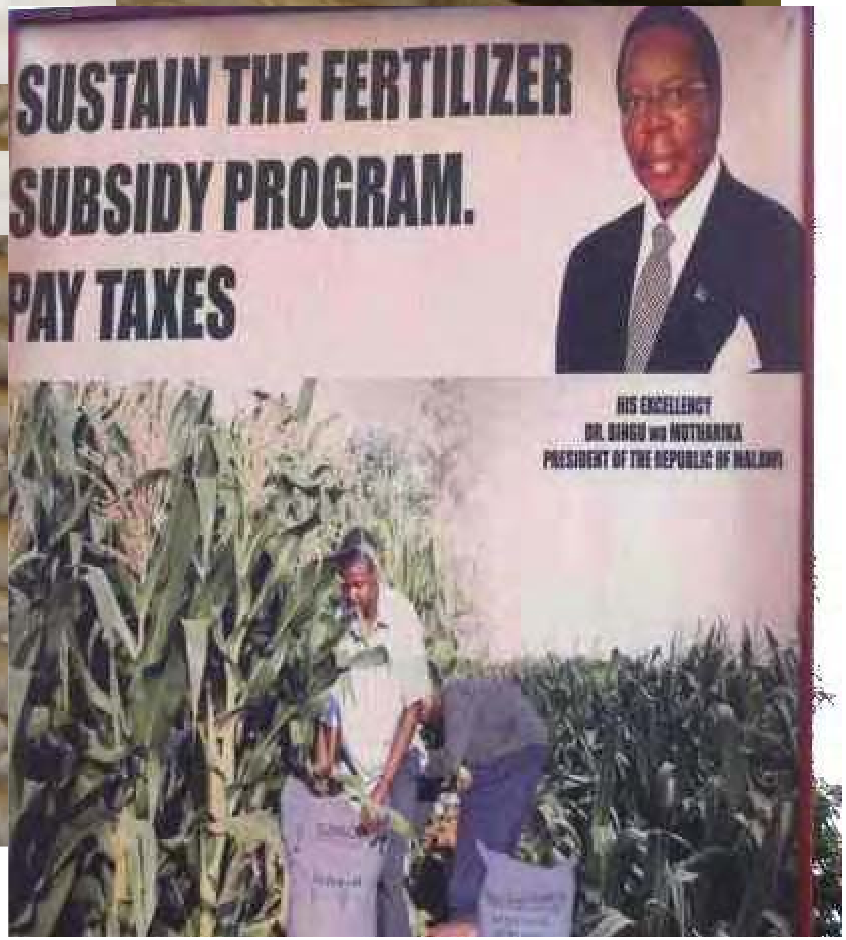
Agricultural Input Subsidy Programme (AISP) since 2005/06

0.2 Mt fertilizers distributed in 2008/09

3.2 Mt maize in 2007 (1.2 Mt exported)

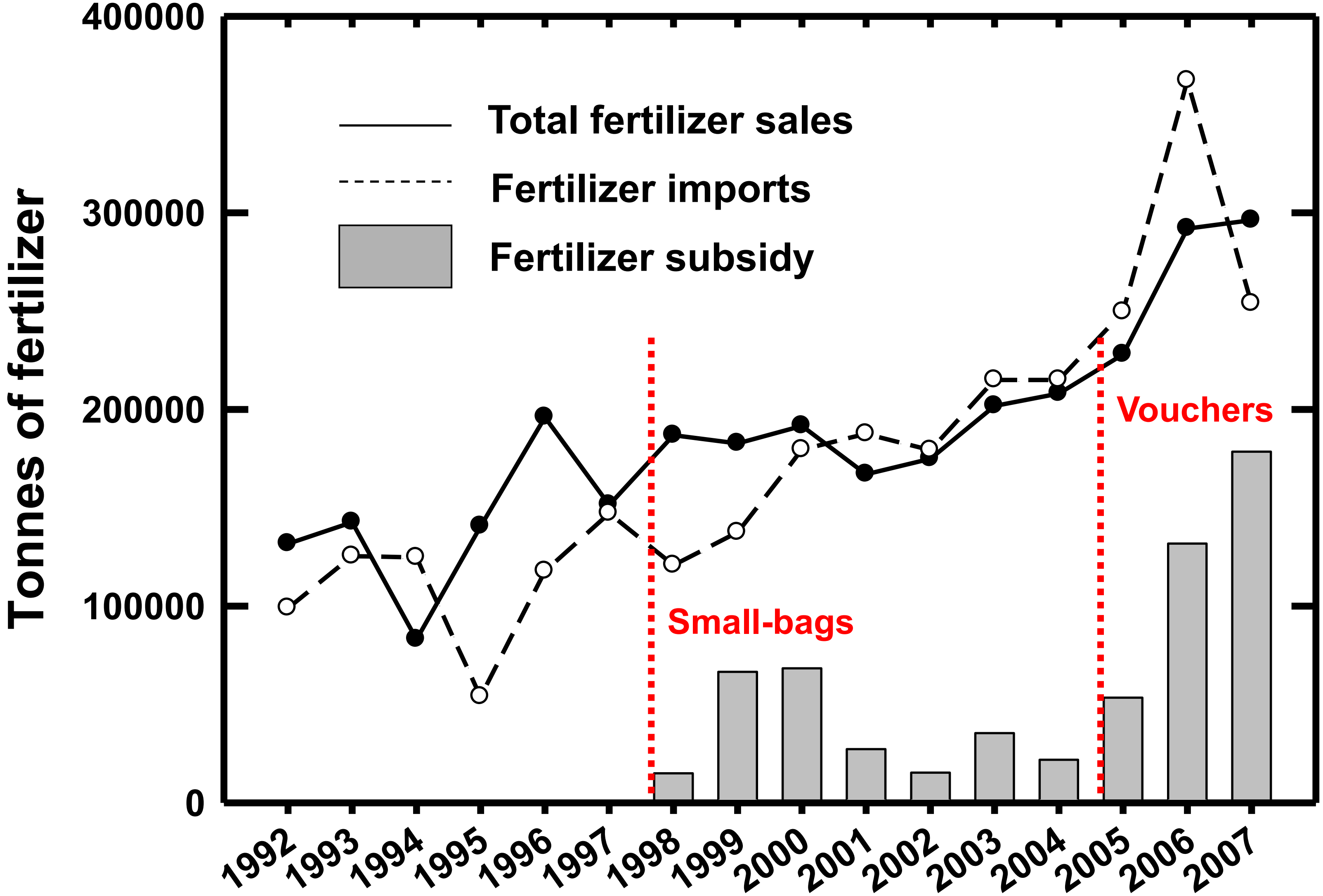
6.6% of GDP spent on AISP

Coupons worth ~10% of income for half of all households



http://go.worldbank.org/KIGRBOO0B0

Yield security in Malawi



http://www.aec.msu.edu/fs2/inputs/documents/AISPFinalReportmarch.pdf

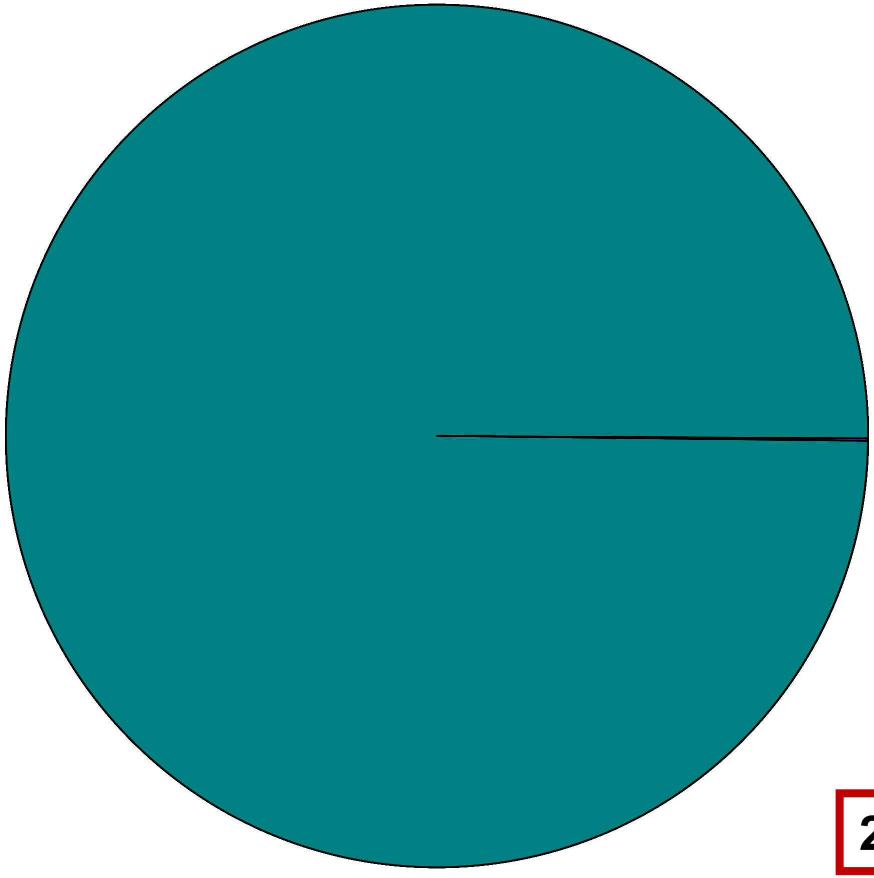
Yield security in Malawi

>50% of Malawian calorie intake from maize (0.35 kg $person^{-1}$ d^{-1})

http://go.worldbank.org/KIGRBOO0B0
http://faostat.fao.org

Dietary energy *availability* in Malawi

FAO, 2011 (2007)



2,172 kcal person^{-1} d^{-1}

maize

potato

other pulses

plantain

beans

cassava

groundnut oil

wheat

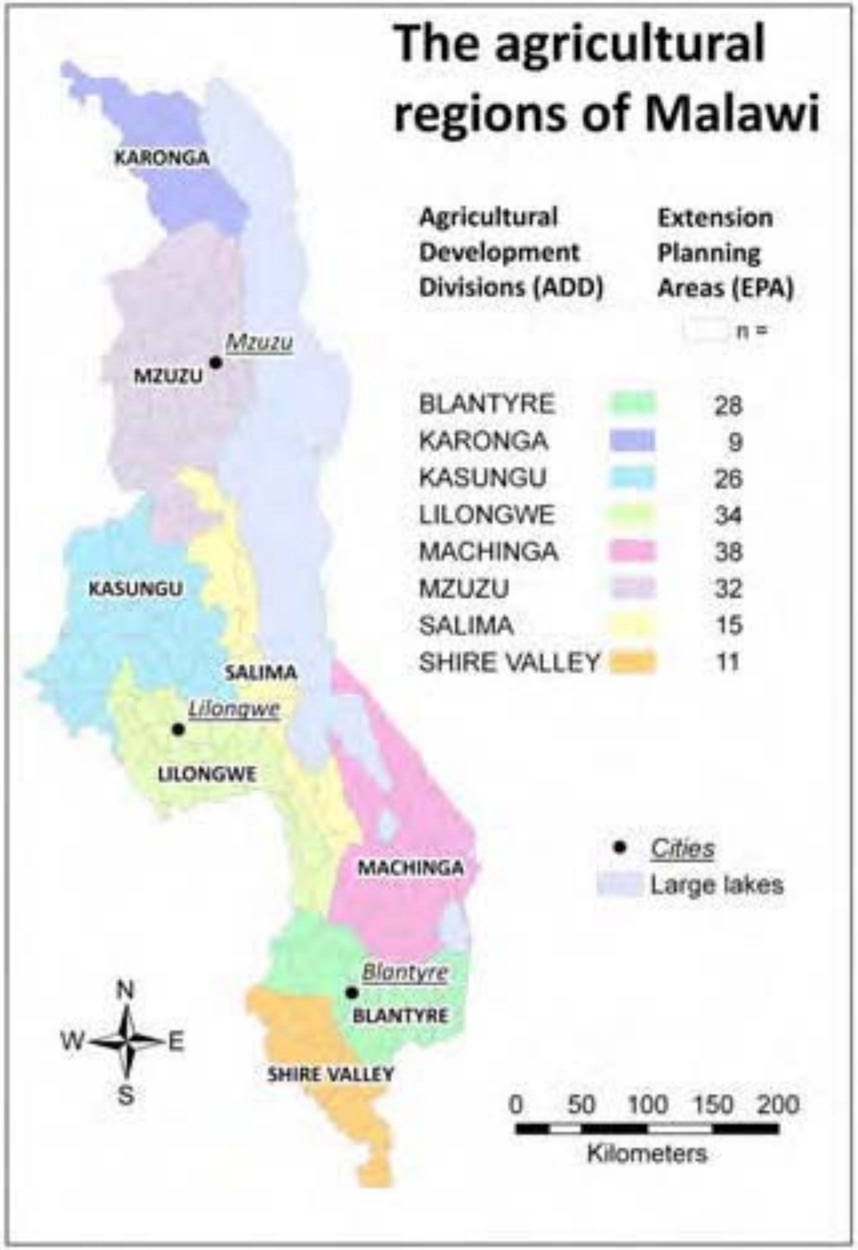
banana

raw sugar

veg. oil

rice

other fruit

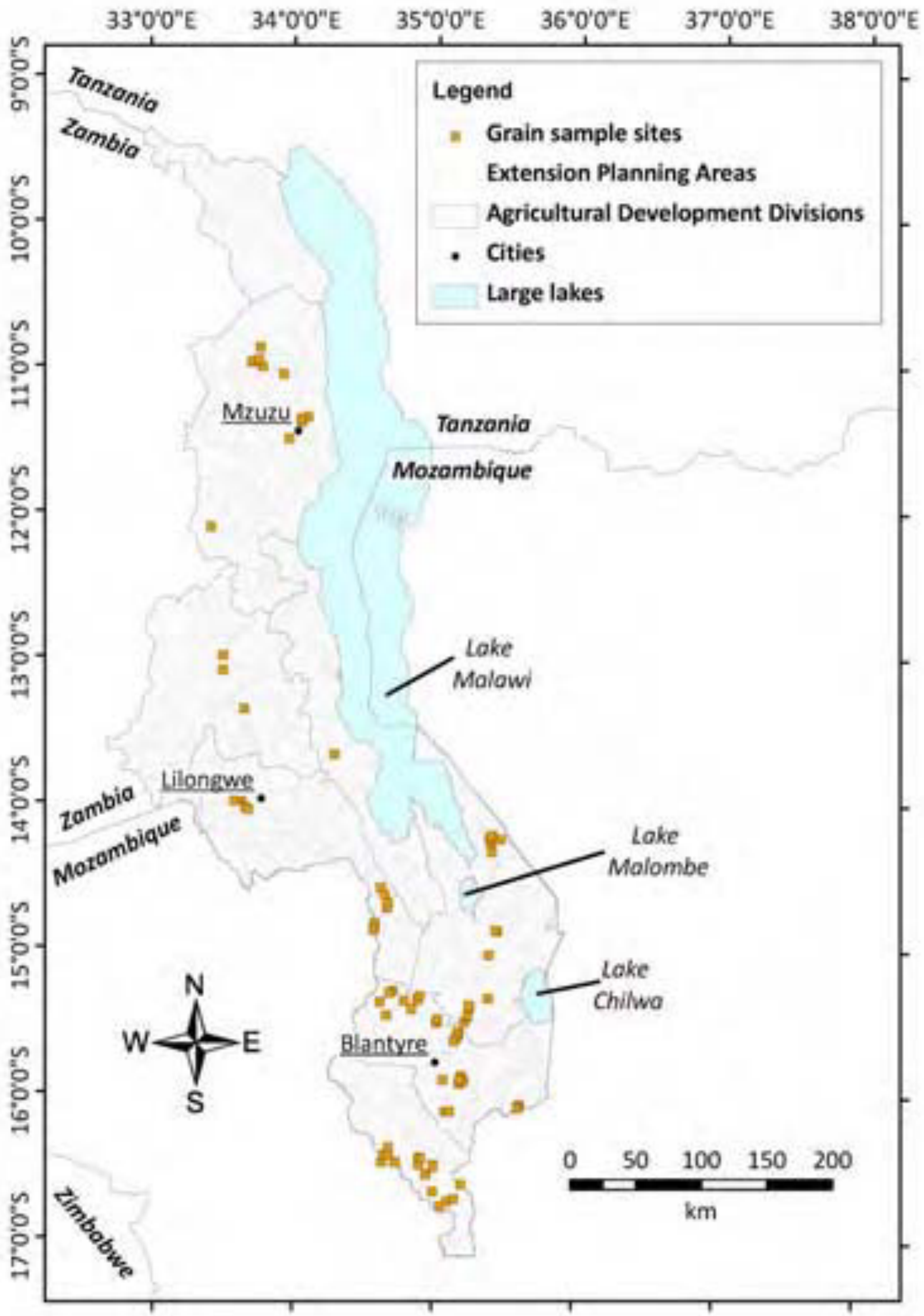


Phase I

- Soil / grain survey

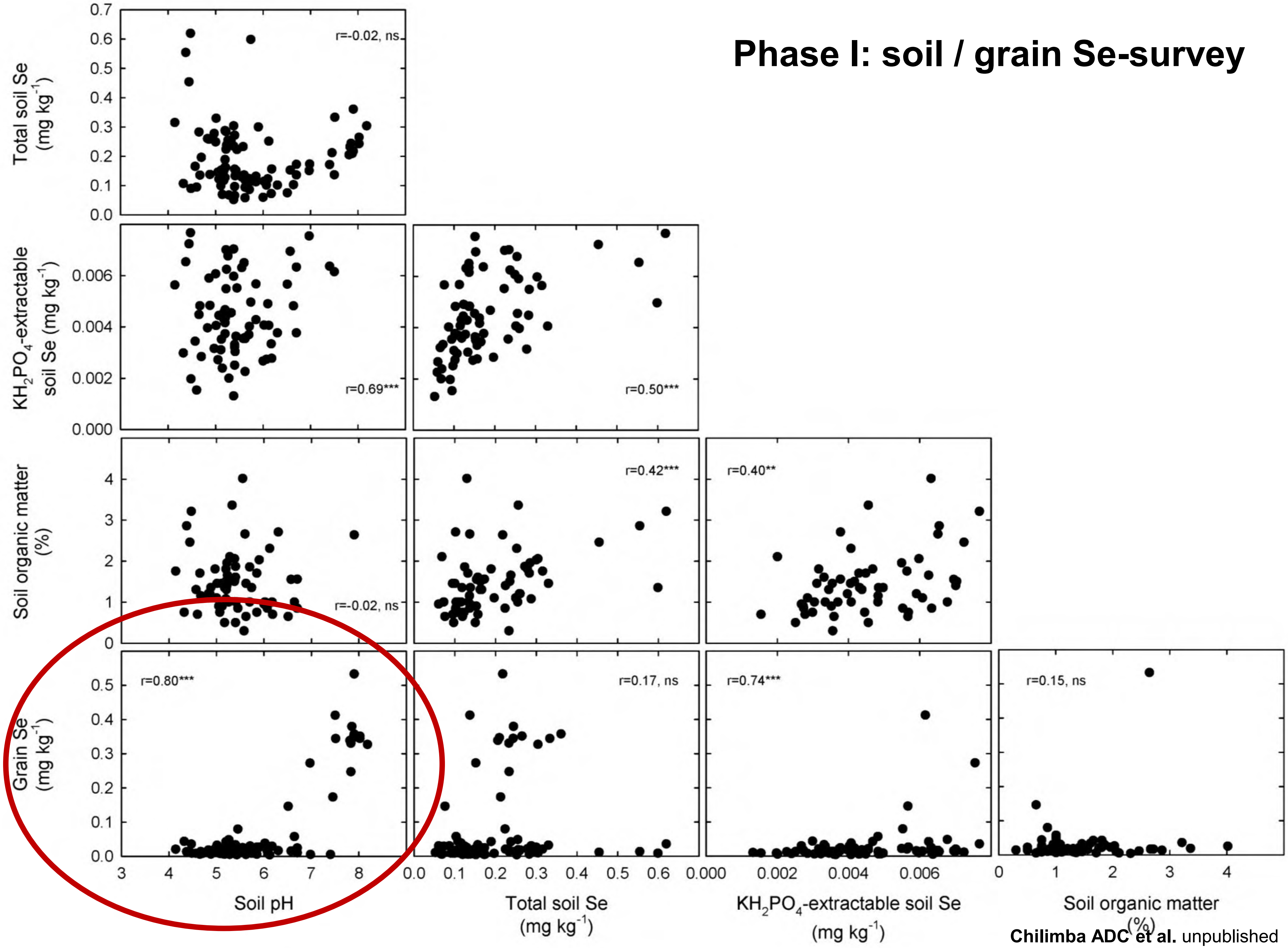
- Fertilizer experiments

Phase I: soil / grain Se-survey

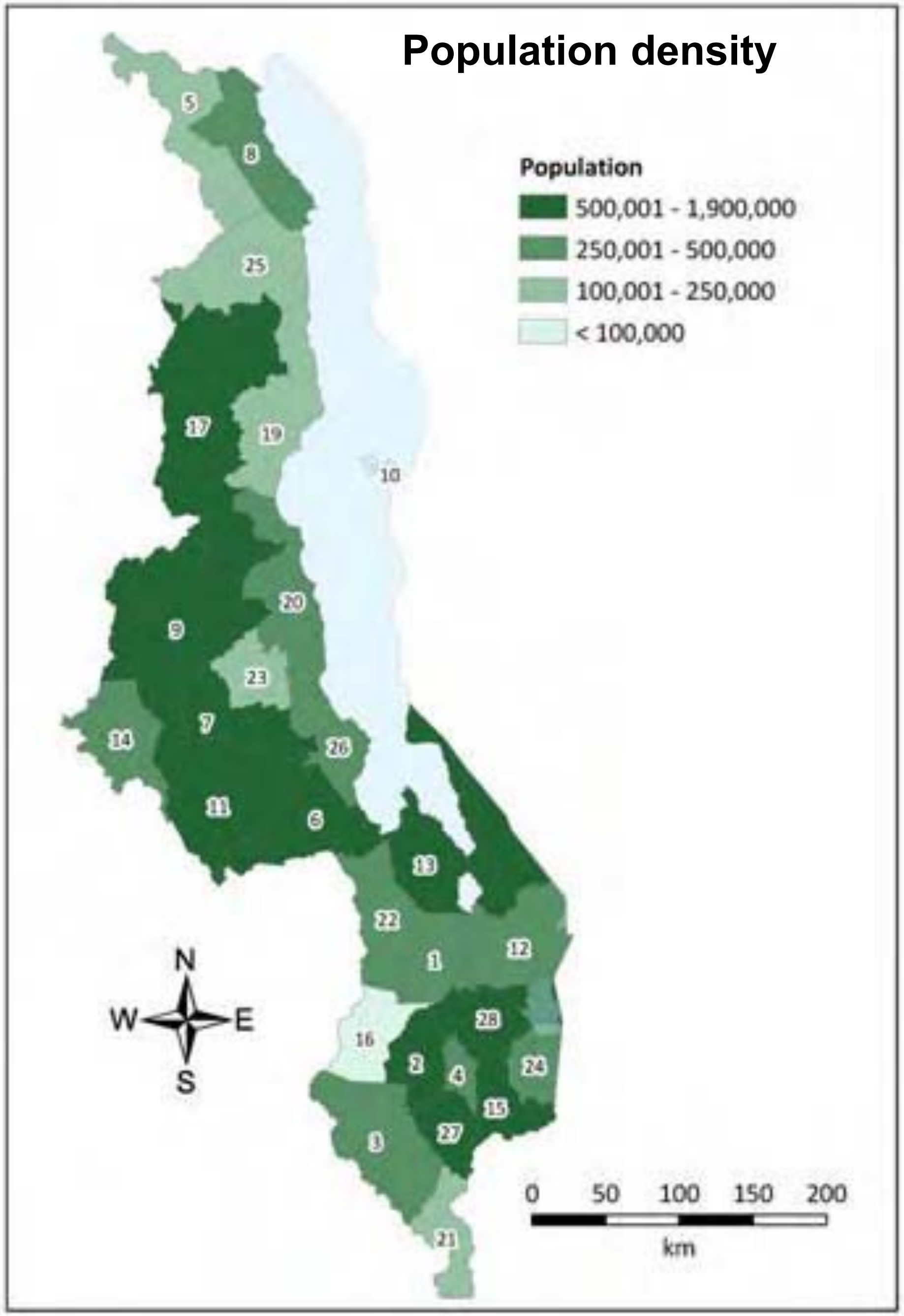


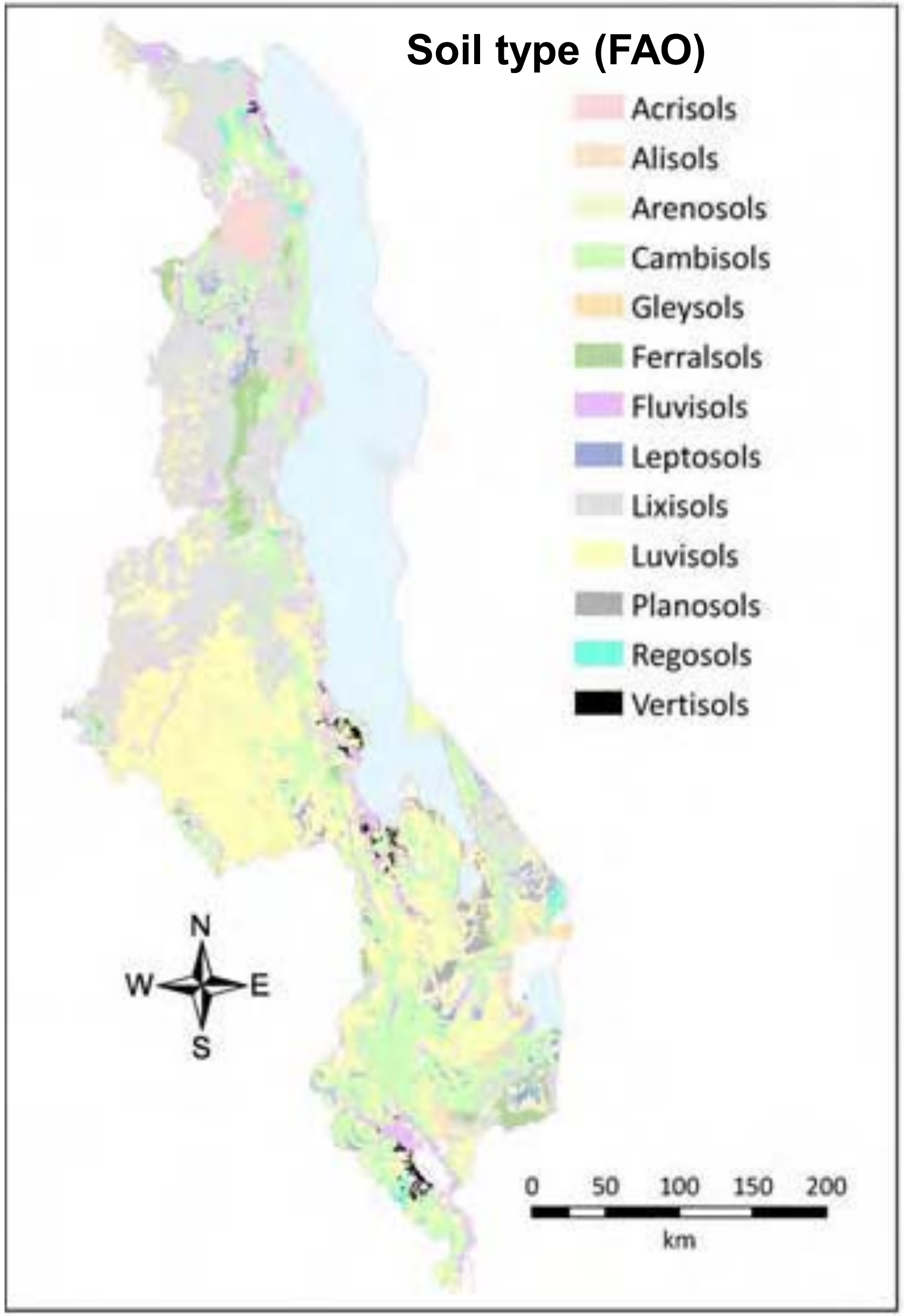
Chilimba ADC et al. unpublished

Phase I: soil / grain Se-survey

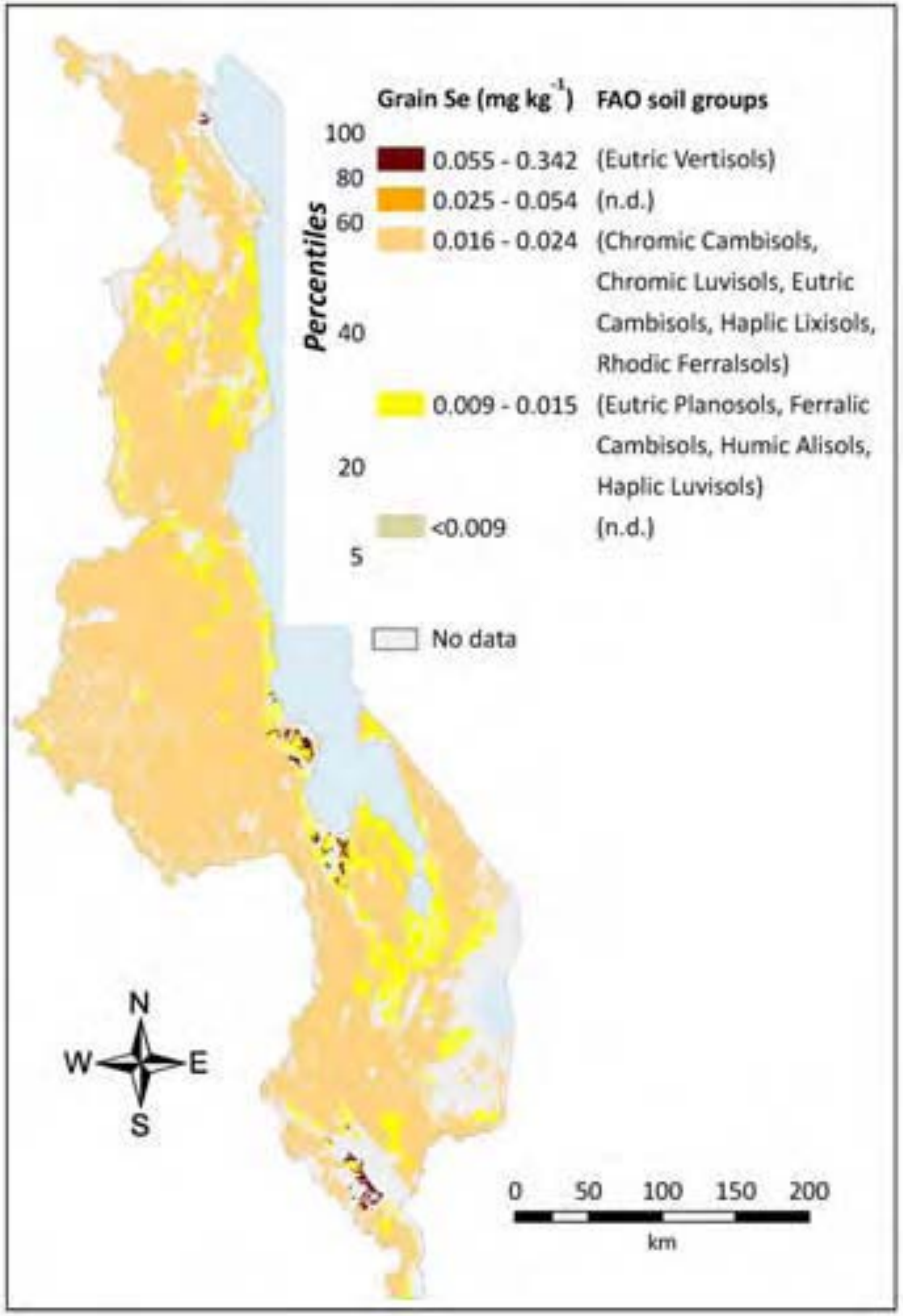


Chilimba ADC et al. unpublished





Chilimba ADC et al. unpublished



Phase II: data integration

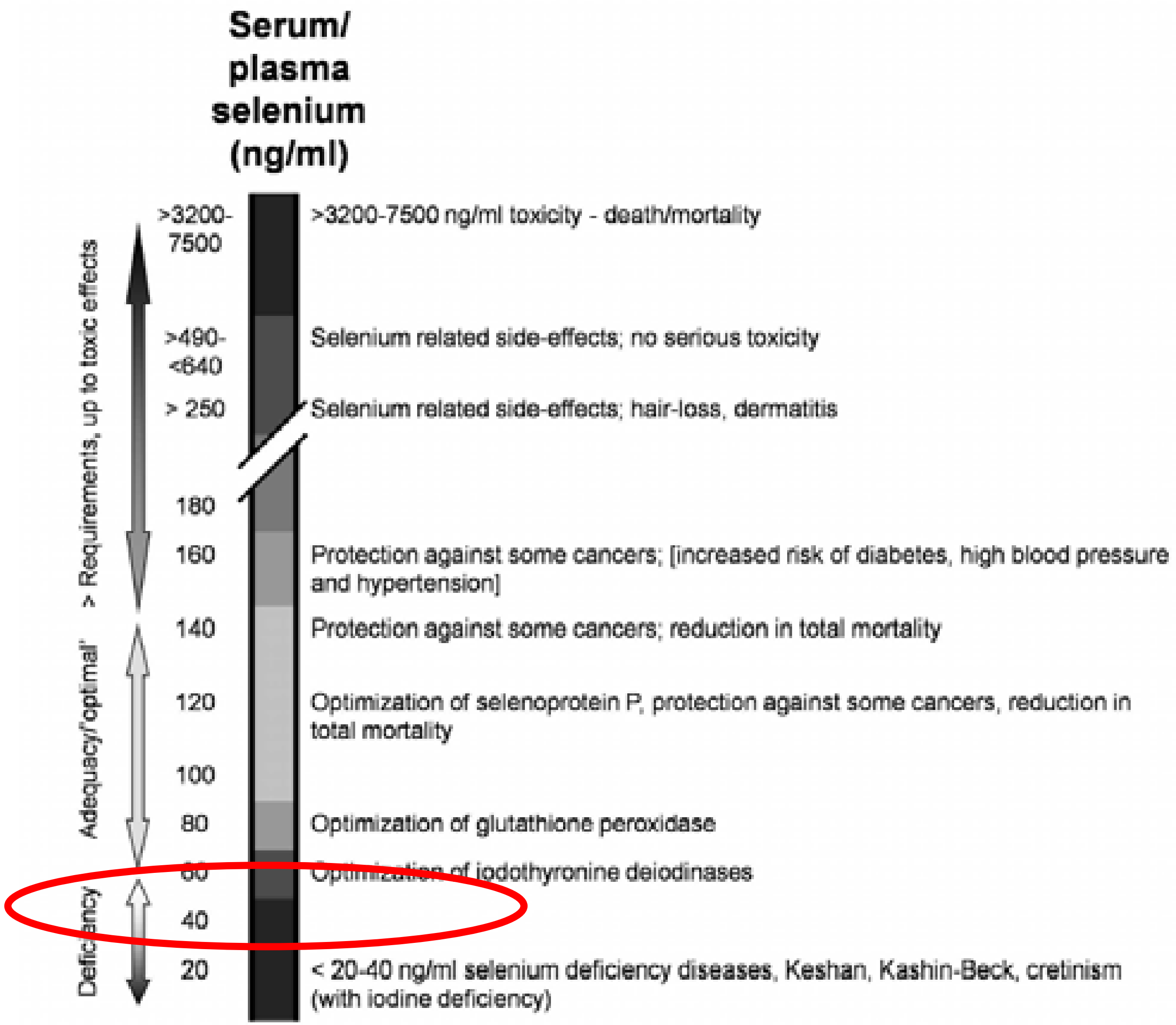
Se intake from maize sources:

50% of population	**<6.0 µg d^{-1}**
75%	**<7.0 µg d^{-1}**
90%	**<7.5 µg d^{-1}**

Se intake from non-maize sources:
15-22 µg d^{-1}

Se deficiency is the norm, based on intake…

Chilimba ADC et al. unpublished



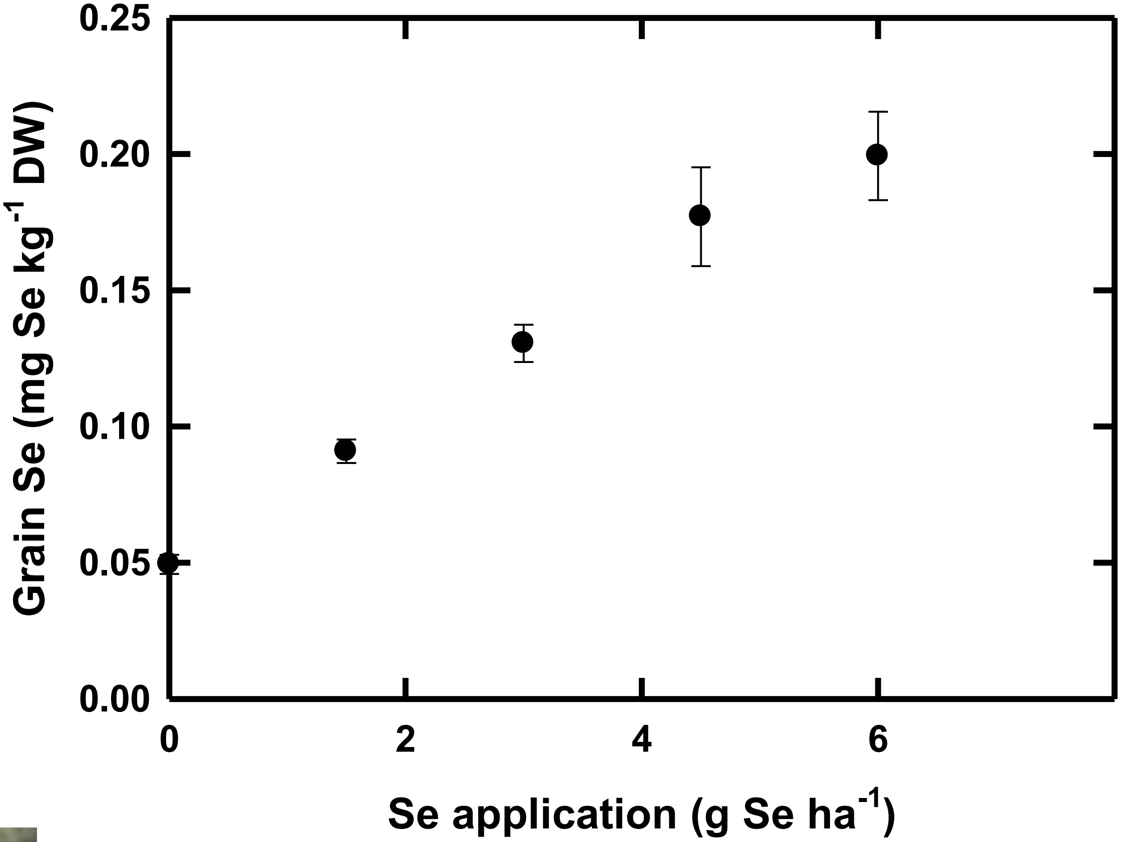
Fairweather-Tait *et al.* (2011). *Antiox. Redox Signal.* 14, 1337-83

Phase I: fertilizer experiments

Phase I: fertilizer experiments

Maize-grain Se (2009)

Makoka



Chilimba ADC et al. unpublished

Phase I: preliminary conclusions

0.015 mg Se kg^{-1} grain *.* g^{-1} Se ha^{-1} **[*~9 g ha^{-1} for 55 µg d^{-1}*]**

200 kg ha^{-1} fertilizer basal dressing typical **[*e.g. 23:10:5:5 NPKS*]**

Existing products would deliver 10 / 2.2 g Se ha^{-1} at typical N rates

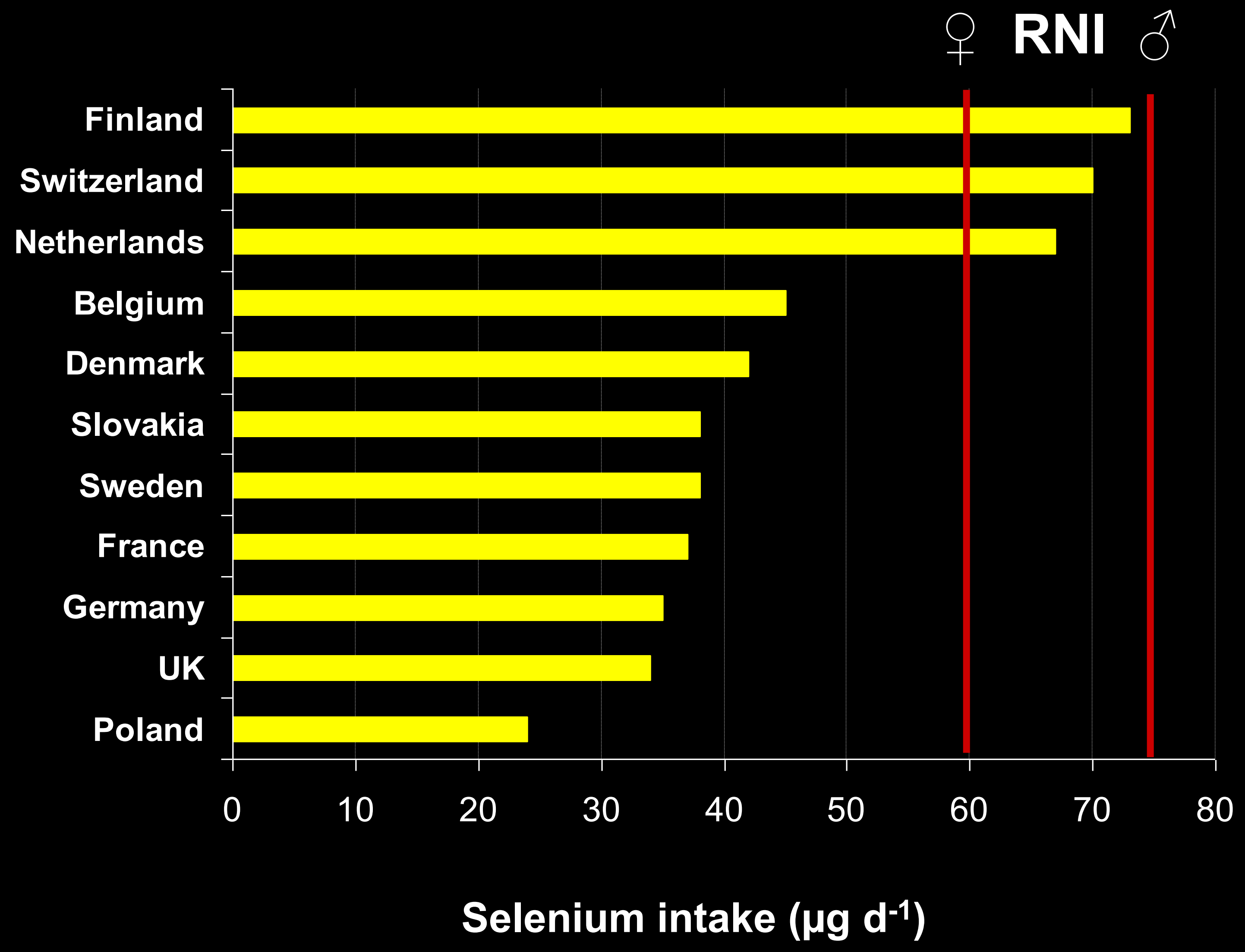
[*23:10:5:5:<u>0.005Se</u>*]

[*25:5:5:<u>0.0012Se</u>*]

200,000 t fertiliser Se-enriched at USD \$30 t^{-1} (*??*) = \$6m annum^{-1}

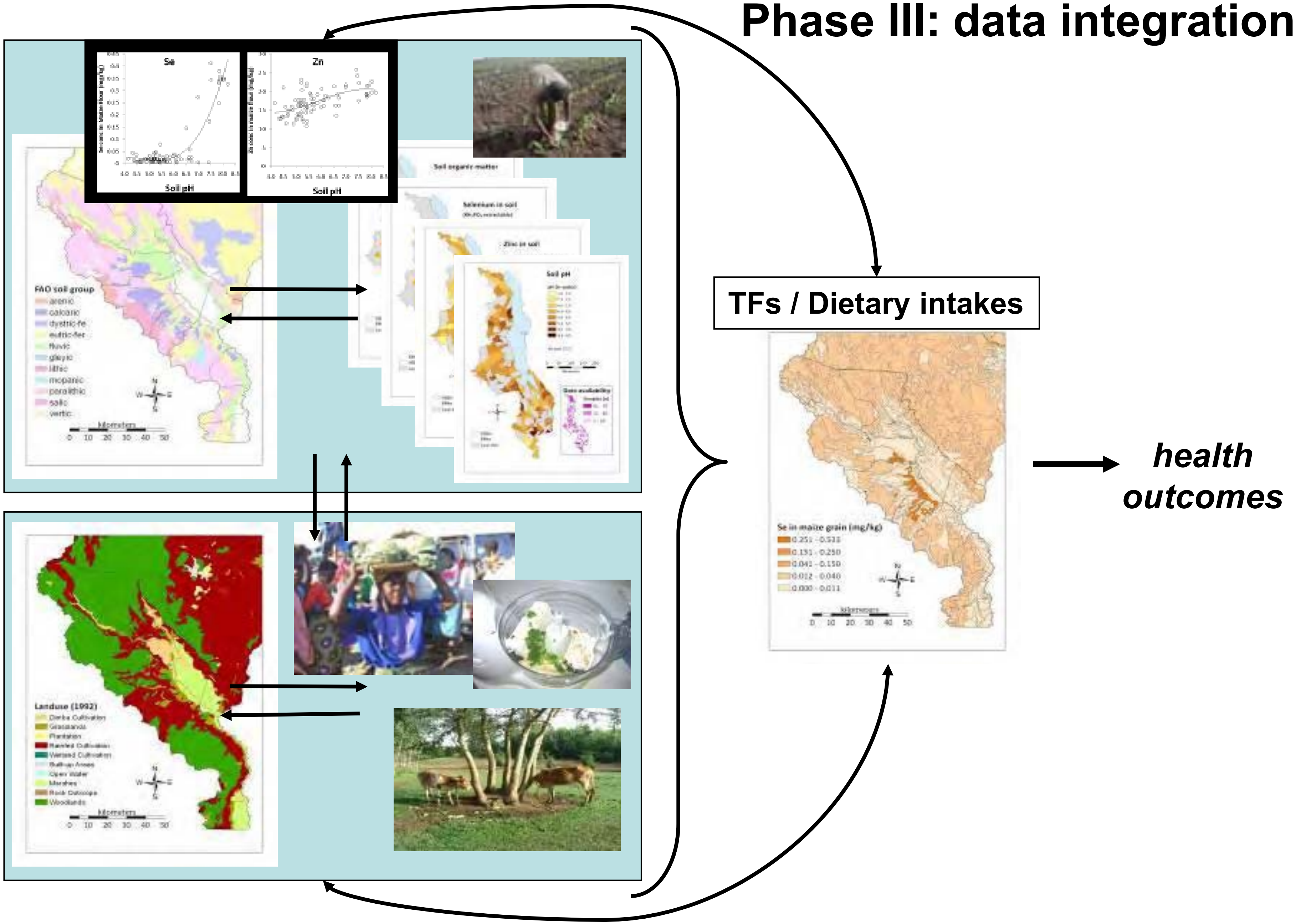
[*<50¢ capita^{-1}*]

Selenium actual intakes



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

Phase III: data integration



Summary

Billions are malnourished due to mineral supply limitations

Biogeochemical cycles, agriculture, dietary choice underpin supply

Much more data collection / integration required
- ***soils-crops-people-health outcomes***

Nutritionally-informed agriculture: mineral intervention when required
- ***engagement // fertilizer and breeding sectors***
- ***awareness of likely market failure***

Acknowledgements (current/recent activities)

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Fangjie Zhao	Rothamsted Research, UK

BBSRC
Malawi: Ministry of Agriculture and Food Security, Ministry of Health
ESPA (NERC/DFID/ESRC)
Yara