Selenium biofortification of food crops


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Selenium biofortification

- Background (UK studies)

- Malawi (part I)
  Soil and grain surveys
  Fertiliser studies

- Malawi (part II)
  Data integration
  Pilot human studies
Selenium

Essential for animals, not plants

~25 mammalian selenoproteins

Many roles in health
Serum/plasma selenium (ng/ml)

- 20-40 ng/ml: Se deficiency diseases, Keshan, Kashin-Beck, cretinism (with iodine deficiency)
- 60-80 ng/ml: Optimisation of iodothyronine deiodinases
- 100-120 ng/ml: Optimisation of glutathione peroxidase
- 140-160 ng/ml: Protection against some cancers; reduction in total mortality
- 180-250 ng/ml: Selenium related side-effects; hair loss, dermatitis
- 250-<640 ng/ml: Selenium related side-effects; no serious toxicity
- >3200-7500 ng/ml: >3200-7500 ng/ml toxicity - death/mortality

References:

- Reid et al 2004
- Lippman et al 2009
- Thompson 2004
- Thompson 2004
- Thompson 2004; Shi et al 2010

Current diversity in Se recommendations. Compiled using 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

- Finland
- Switzerland
- Netherlands
- Belgium
- Denmark
- Slovakia
- Sweden
- France
- Germany
- UK
- Poland

Selenium intake (µg d⁻¹)

Se status (UK)

Low dietary Se intakes and status in UK

Wheat imported to UK (tonnes)

UK soils and wheat grain are low in Se

Canada = 0.76 mg kg\(^{-1}\)

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 (\(n=85\)).

Soil Se concentration in Humber/Trent region

Frequency Distribution

- Frequency
- Se concentration (mg kg\(^{-1}\))
  - Absent data
  - 50th percentile: 0.2 mg kg\(^{-1}\)
  - 75th percentile: 0.8 mg kg\(^{-1}\)
  - 90th percentile: 1.0 mg kg\(^{-1}\)
  - 95th percentile: 2.2 mg kg\(^{-1}\)

Biofortification experiments (wheat), UK (2005-2009)
Biofortification experiments, UK (2005-2009)
Biofortification experiments, UK (2005-2009)

16-26 ng Se g⁻¹ grain . g⁻¹ Se ha⁻¹


Biofortification experiments, UK (2005-2009)


5 g Se ha\(^{-1}\) = \(~3.5\) µg Se slice bread
Feeding experiments UK (2005-09)

n=119

Control (placebo)

Se-yeast 50μg/d

Se-yeast 100μg/d

Se-yeast 200μg/d

5 onions/week
~50 μg Se/d

Se-enriched onions 50μg/d

5 onions/week
<1μg Se/d

Unenriched onions
Feeding experiments UK, 2005-2009

Uncooked onions:
- gamma-glutamyl selenium-methylselenocysteine (66%)
- selenomethionine (8.6%)
- selenite/selenate (6%)
- selenocysteine (1.2%)

Selenium-enriched potatoes from Peter Keoghe

19 Feb 2009

Peter Keoghe & Sons, the potato-growing and packing company owned by the north County Dublin Keoghe family, has launched a selenium-enriched Rooster potato called Selena, which is currently available exclusively in Superquinn stores in Ireland.

Pretty fab sprout

Whether as the traditional green bullet or in its new purple flowerlike form, a sprout is not just for Christmas. Carolyn Hart meets a grower who is pushing the boundaries of...
Selenium biofortification

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  Pilot human studies
Malawi (2008-…)

Part I, 2008-11
Selenium supply (Food Balance Sheets)

EdwardJoy et al., unpublished
Low Se intakes reported in Malawi

Donovan et al. (1991, 1992), Se intake 15-21 µg d\(^{-1}\) (rural Zomba)

Eick et al. (2009), Se intake 44-46 µg person d\(^{-1}\) (fish consumption)

[Benemariya et al. (1993), 17 µg d\(^{-1}\) (rural Burundi), but 38 / 82 µg d\(^{-1}\) in middle-class mothers / men respectively, due to fish consumption]
Low plasma Se status in Malawi

~55 ng mL\(^{-1}\)
~40 ng mL\(^{-1}\)

van Lettow et al. 2004. *BMC Infectious Diseases* 4: 61
Low plasma Se status in Malawi

**Serum/plasma selenium (ng/ml)**

- **>3200-7500 ng/ml toxicity - death/mortality**

- **>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**
  - Protection against some cancers; [increased risk of diabetes, high blood pressure and hypertension]

- **160**
  - Protection against some cancers; reduction in total mortality

- **140**
  - Optimisation of selenoprotein P, protection against some cancers, reduction in total mortality

- **120**
  - Optimisation of glutathione peroxidase
  - Thompson 2004

- **100**
  - Optimisation of iodothyronine deiodinases
  - Thompson 2004

- **< 20-40 ng/ml Se deficiency diseases, Keshan, Kashin-Beck, cretinism (with iodine deficiency)**
  - Thompson 2004; Shi et al 2010

**References**

- Fairweather-Tait et al. (2011). *Antiox. Redox Signal.* 14, 1337-83
Dietary energy supply in Malawi (FAO, 2007)

- 2,172 kcal person\(^{-1}\) d\(^{-1}\)
- 354 g maize person\(^{-1}\) d\(^{-1}\)
Experimental studies

Part I:
1. Soil/grain Se-surveys
2. Fertiliser experiments

Part II:
1. Data integration
2. Pilot human studies
Soil selenium, total (mg kg$^{-1}$)

Median = 0.162 mg kg$^{-1}$
Range = 0.052-0.620 mg kg$^{-1}$
Maize flour selenium (mg kg\(^{-1}\))

Median = 0.019 mg kg\(^{-1}\)

Range = 0.005-0.533 mg kg\(^{-1}\)
Part I: soil/grain Se-survey
Maize-grain Se is affected by soil pH

Stability of Se species in soil

Oxidising

Reducing

Eh (volts)

25°C

pH

H₂Se

HSe⁻

HSeO₃⁻

SeO₃⁻⁻

SeO₄⁻⁻

Ngabu
Fig. 2. Sorbed amount of selenite vs pH ([Se] = 4 \times 10^{-4} \text{ M}) for two ionic strengths: NaNO₃ 0.01 M (hollow symbols) and 0.1 M (filled symbols).

A role for agricultural-grade lime?
Selenium biofortification

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  Pilot human studies
Malawi (2008-…)

Part I, 2008-11

YARA

The University of Nottingham

Part II, 2010-

Natural Environment Research Council

DFID Department for International Development

British Geological Survey

University of East Anglia

University of Malawi
Part II: data integration

Se intake from maize:

50% population < 6.0 µg d\(^{-1}\)
90% “ < 7.5 µg d\(^{-1}\)

Se intake from non-maize:

15-22 µg d\(^{-1}\)
Maize grain and soil surveys reveal suboptimal dietary selenium intake is widespread in Malawi

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Selenium is an essential element in human diets but the risk of suboptimal intake increases where food
Selenium biofortification

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  Pilot human studies
Part II: pilot human studies
Part II: pilot human studies
Part II: pilot human studies

(a) Dietary Se intake (mg d⁻¹)

(b) Blood plasma Se (µg L⁻¹)
Part II: pilot human studies

Blood plasma Se (µg L⁻¹)

Urinary Se (µg L⁻¹)

Mozyenti
Moses
Chimkango
Chifundo
Chamwaka
Billy
Yolamu
Yesaya Jere
Ngayiwona
Msekeni
Kenani
Bandawe Tembo

Dietary Se intake (mg d⁻¹)

Blood GPx3 activity (nmol min⁻¹ mL⁻¹)

0 20 40 60 80 100

0 50 100 150 200
Part II: pilot human studies

![Graph showing the relationship between dietary Se intake and blood plasma Se, as well as urinary Se levels. The graph indicates a positive correlation between dietary Se intake and blood plasma Se, while urinary Se levels increase with dietary intake.]
Geochemical control of urine mineral composition

Urine concentration (creatinine corr.; µg L⁻¹)

Mg

Se

Ca

Cs

Urine concentration (creatinine corr.; mg L⁻¹)

Zombwe Mikalango

*creatinine-corrected
Mineral intakes from maize (mg/day, ~50% of energy)

Chilimba et al., unpublished
Blood plasma mineral concentrations

Hurst, Siyame et al., unpublished
Selenium biofortification in Malawi

- Background (UK studies)

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- Malawi (part II)
  Data integration
  Pilot human studies
Farm Input Subsidy Programme (FISP) operating since 2005/06

~7% of GDP (~$250m USD per annum)

>200,000 t fertilisers distributed 2008/09

3.2 Mt maize in 2007 (1.2 Mt exported),
[3.6 Mt projected yield in 2012]

Dorward and Chirwa (2011)
Farm input subsidy in Malawi

Part I: fertiliser experiments
Part I: fertiliser experiments
Maize-grain Se (2009 & 2010, plots=979, n=4)

\[
\begin{align*}
\text{Liquid drench} & : y = 0.019x + 0.061 \\
\text{CAN+Se (granular)} & : y = 0.015x + 0.085 \\
\text{NPK+Se (granular)} & : y = 0.022x + 0.056
\end{align*}
\]

15-22 µg Se kg\(^{-1}\) grain . g\(^{-1}\) Se ha\(^{-1}\)
[~9 g ha\(^{-1}\) for 55 µg d\(^{-1}\)]

Chilimba ADC et al. Field Crops Research 125, 118-128
Part I: fertiliser experiments

Agronomic biofortification of maize with selenium (Se) in Malawi

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³Yara International, Research Centre, Hanningen, 48249 Duellmen, Germany

Se-biofortification precedent in Finland in place since 1984
Assessing residual availability of selenium applied to maize crops in Malawi

Allan D.C. Chilimba\textsuperscript{a,b}, Scott D. Young\textsuperscript{a,*}, Colin R. Black\textsuperscript{a}, Mark C. Meacham\textsuperscript{a}, Joachim Lammel\textsuperscript{c}, Martin R. Broadley\textsuperscript{a}

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e.g. \textsuperscript{74}Se experiments
Is Se biofortification feasible in terms of cost?

200,000 tonnes fertiliser imported per annum

Assume 25% N-product applied at 50 kg N ha\(^{-1}\)

Conservative target of 5 g Se ha\(^{-1}\) (supplies 30 µg person\(^{-1}\) d\(^{-1}\))

1 tonne fertiliser treats 5 ha and therefore contains 25 g Se

Se usage = 25 g * 200,000 = 5000 kg Se per annum

Commercial-grade Se = ~$50-$100 USD kg\(^{-1}\) (2005-09; USGS, 2011)

$250k-$500k per annum, = \textbf{~1.6-3.5 US cents per person}
Is Se biofortification needed?

>90% of Malawian population is likely to consume <30 µg Se d⁻¹

[caveat: food composition data limited, geospatially unreferenced]

Pilot studies show evidence of link between local maize grain Se concentration and biomarkers of Se status

[caveat: no RCTs etc., no health economic analyses]

Logistically feasible, NPK(+Zn+S) fertilisers used relatively widely
Spatial extrapolations for other minerals

**Mg**

- 987 - 1060 (Eutric Vertisols)
- 900 - 986 (Chromic Cambisols, Eutric Cambisols, Ferralic Cambisols, Haplic Lixisols)
- 817 - 899 (Chromic Luvisols, Eutric Planosols, Haplic Luvisols, Humic Alisols, Rhodic Ferralsols)

**Ca**

- 47.5 - 98.8 (Eutric Vertisols)
- 37.2 - 47.4 (Chromic Luvisols, Eutric Planosols, Haplic Lixisols)
- 31.1 - 37.1 (Ferralic Cambisols, Haplic Luvisols, Rhodic Ferralsols)
- 25.8 - 31.0 (Chromic Cambisols, Humic Alisols)
Mg supply = 299 mg \textit{capita}^{-1} \text{ d}^{-1} \text{ (range 196-491)}

Ca supply = 12 mg \textit{capita}^{-1} \text{ d}^{-1} \text{ (range 5-35)}
Dietary Mg supply in Malawi

Edward Joy et al., unpublished data (other sources)
Dietary Ca supply in Malawi

Edward Joy et al., unpublished data
Farmer engagement in food systems approaches

Mrs Miriam Nkhoma (Zombwe EPA), with Section demographic data
Soil Mg (E. England)

Magnesium (mg/kg)

- <80,000
- <24,000
- <13,000
- <11,000
- <7,200
- <5,400
- <3,600
- <2,400
- <1,800
- <910

EL Ander, British Geological Survey, Keyworth, Notts
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Scott Young  University of Nottingham, UK  
Fangjie Zhao  Agricultural University of Nanjing, China / Rothamsted Research, UK  

BBSRC  
Malawi: Ministry of Agriculture and Food Security, Ministry of Health  
ESPA (NERC/DFID/ESRC)  
Yara
Phase II: data integration (other minerals)

Table 2. Soil and maize grain concentration data for Ca and Mg. Samples were collected at 88 sites [7].

<table>
<thead>
<tr>
<th></th>
<th>Soil concentration (g kg(^{-1}))</th>
<th>Grain concentration (mg kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ca</td>
<td>Mg</td>
</tr>
<tr>
<td>mean</td>
<td>10.15</td>
<td>5.08</td>
</tr>
<tr>
<td>median</td>
<td>5.09</td>
<td>2.88</td>
</tr>
<tr>
<td>n</td>
<td>82</td>
<td>82</td>
</tr>
<tr>
<td>minimum</td>
<td>(^a)</td>
<td>0.35</td>
</tr>
<tr>
<td>maximum</td>
<td>43.23</td>
<td>26.10</td>
</tr>
<tr>
<td>Intake (mg person(^{-1}) d(^{-1}))</td>
<td>12</td>
<td>299</td>
</tr>
</tbody>
</table>

\(^a\)Below limit of detection

Mg supply = 299 mg \textit{capita}^{-1} d^{-1} (range 196-491)

Ca supply = 12 mg \textit{capita}^{-1} d^{-1} (range 5-35)
Aims of project:
1. Investigate quantity and form of Se for optimal Se status
2. Identify new markers of Se status
3. Determine interactions between Se and immune function
Feeding experiments UK, 2005-2009

Uncooked onions:
- gamma-glutamyl selenium-methylselenocysteine (66%)
- selenomethionine (8.6%)
- selenite/selenate (6%)
- selenocysteine (1.2%)

Biofortification experiments, UK (2005-2009)

Hart DJ et al. 2011 Food Chemistry