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Agronomic biofortification of maize with selenium (Se) in Malawi

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ABSTRACT

Suboptimal dietary Se intake is widespread in Malawi due to low levels of plant-available Se in most soils and narrow food choices. The aim of this study was to determine the potential for biofortifying maize using Se-enriched fertilisers in Malawi. The response of maize to three forms of selenate-Se fertiliser was determined. Crops were treated with a liquid drench of $Na_2SeO_{4(aq)}$ (0–100 g Se ha^{-1}), a compound NPK + Se fertiliser (0–6 g Se ha^{-1}), or Se-enriched calcium ammonium nitrate (CAN + Se; 0–20 g Se ha^{-1}). Experiments with $Na_2SeO_{4(aq)}$ and NPK + Se were conducted at six field sites, and at a subset of three sites with CAN + Se, in 2008/09 and 2009/10 (i.e. 30 experimental units). The increase in grain Se concentration was approximately linear for all Se forms and application rates ($R^2 > 0.90$ for 27 of the 30 experimental units). On average, whole-grain Se increased by 20, 21 and 15 μg Se kg^{-1} for each gram of Se applied as $Na_2SeO_{4(aq)}$, NPK + Se and CAN + Se, respectively. Grain and stover yields were unaffected by Se applications. An application of 5 g Se ha^{-1} to maize crops in Malawi would increase dietary Se intake by 26–37 μg Se $person^{-1}$ d^{-1} based on national maize consumption patterns. Agronomic biofortification with Se in Malawi is feasible in theory through the existing national Farm Input Subsidy Programme (FISP) if deemed to be economically and politically acceptable.

1. Introduction

Selenium (Se) is an essential element for humans and is derived primarily from dietary sources (Fairweather-Tait et al., 2011). Habitual suboptimal dietary Se intake leads to reduced Se status, which is associated with a range of adverse health outcomes including cardiovascular disorders, impaired immune function, and some forms of cancer. In Malawi, where subsistence agriculture is widespread and food choices are relatively narrow, there is evidence of widespread suboptimal dietary Se intakes (Donovan et al., 1992; Eick et al., 2009; Chilimba et al., 2011) and status (van Lettow et al., 2004). In Malawi, over 50% of dietary calorie intake (2,172 kcal $person^{-1}$ d^{-1}; 2007 data; FAO, 2011) is derived from maize grain, equating to 0.354 kg person d^{-1} based on trade and production statistics (FAO, 2011). Consumption of animal products with higher Se concentrations (fish, meat, offal, fats, milk and eggs) accounts for just 64 kcal $person^{-1}$ d^{-1} (FAO, 2011). From nationwide surveys of farmers' fields, the median maize grain Se concentration of 0.019 mg Se kg^{-1} (range 0.005–0.533 mg Se kg^{-1}) represents an intake of only 6.7 μg Se $person^{-1}$ d^{-1} from maize based on national consumption patterns (Chilimba et al., 2011). Low Se concentrations in edible crop material produced in Malawi are due to the widespread occurrence of highly weathered acid soils with low total and plant-available Se concentrations. In these soils, most Se is likely to be present in organic and mineral-occluded forms which are not directly available to plants, with most of the remainder present as strongly adsorbed $Se^{(IV)}$ species, which are poorly available compared to $Se^{(VI)}$ (Chilimba et al., 2011).

Suboptimal Se intake can be addressed through dietary diversification, food imports, supplements, food fortification and biofortification (Rayman, 2004, 2008; Broadley et al., 2006, 2010; Fairweather-Tait et al., 2011). Dietary diversification is an attractive option in terms of general protein, mineral and vitamin intake. In Burundi, greater consumption of fish, meat and offal among more affluent groups has been linked to higher Se intakes (Benemariya et al., 1993). However, access to diverse diets is not possible in many socio-economic contexts. Similarly, despite clear links between the Se composition and the geographic origin of staple foods such as wheat and rice (Thomson, 2004; Williams et al., 2009; Johnson et al., 2010; Fairweather-Tait et al., 2011), altering trade patterns is undesirable in many contexts. Supplementation of diets or foodstuffs with inorganic or organic forms of Se is again feasible (Rayman, 2004), although the production and equitable distribution of Se supplements is logistically challenging and expensive, and robust

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Table 1
Site location, soil characteristics and type of Se fertiliser applied.

Site	Soil Se concentration ($mg\,kg^{-1}$)[a]	Selenium form	Location (°) (Lat., Long.)	Soil type[b]	Texture class[c]	pH[d]	OM (%)[e]	Fertiliser applied ($kg\,ha^{-1}$)[f]		
								N	P_2O_5	K_2O
Bvumbwe (Dwale)[g]	0.288	Na_2SeO_4	−15.92, 35.07	Chromic Luvisols	sl	5.2	1.08	92	20	10
		NPK + Se						100	20	20
		CAN + Se						130	45	23
Chitala (Chinguluwe)	0.362	Na_2SeO_4	−13.68, 34.28	Chromic Luvisols	scl	5.6	2.38	92	20	10
		NPK + Se						100	20	20
Chitedze (Chitsime)	0.300	Na_2SeO_4	−13.98, 33.63	Chromic Luvisols	scl	5.9	2.03	92	20	10
		NPK + Se						100	20	20
		CAN + Se						130	45	23
Makoka (Thondwe)	0.272	Na_2SeO_4	−15.52, 35.22	Chromic Luvisols	scl	5.4	1.87	92	20	10
		NPK + Se						100	20	20
Mbawa (Mbawa)	0.124	Na_2SeO_4	−12.12, 33.42	Haplic Luvisols	ls	5.7	1.86	92	20	10
		NPK + Se						100	20	20
Ngabu (Mikalango)[h]	0.217	Na_2SeO_4	−16.60, 34.35	Eutric Vertisols	c	7.9	2.64	92	20	10
		NPK + Se						100	20	20
		CAN + Se						130	45	23
Kasinthula (Mitole)[i]	0.197	Na_2SeO_4	−16.05, 34.81	Eutric Vertisols	sl	7.4	2.95	92	20	10
		NPK + Se						100	20	20
		CAN + Se						130	45	23

[a] Total soil Se.
[b] FAO classification (Green and Nanthambwe, 1992).
[c] sl = sandy loam, scl = sandy clay loam, ls = loamy sand, c = clay.
[d] Water.
[e] Organic matter.
[f] Na_2SeO_4, uniform NPK (base, 23:10:5 + 3S) and N (top, urea); NPK + Se (25:5:5 + 0.0012), varying Se splits; CAN + Se, uniform NPK (base 23:10:5 + 3S) and N (top, CAN/CAN + Se).
[g] Extension planning area (EPA) in parentheses.
[h] 2008/09 only.
[i] 2009/10 only (irrigated site).

controls are required to minimise risks of toxicity. The potential for genetic biofortification of crops through breeding is not yet clear. Lyons et al. (2005) screened cereal grain Se composition among modern wheat (*Triticum aestivum* L.), durum wheat (*Triticum dicoccum* (Schrank) Schubl.), wheat landraces, ancestral diploid relatives (*Aegilops tauschii* (Coss.) Schmal.), barley (*Hordeum vulgare* L.), triticale (x *Triticosecale* Wittmack ex A. Camus.) and rye (*Secale cereale* L.), all grown on soils with low bioavailable Se concentrations. A lack of breeding potential was noted, with cereal grain Se composition being associated primarily with non-genetic factors, as also seen in UK bread wheat ($n = 150$; Zhao et al., 2009). However, variation in grain Se composition among non-cultivated varieties and at higher bioavailable soil Se concentrations indicates that future breeding efforts may yet be possible (Lyons et al., 2005; Garvin et al., 2006; White and Broadley, 2009). In terms of agronomic biofortification, the Se concentrations of all fractions of cereal grains can be increased easily when Se is applied in its selenate form (Broadley et al., 2010; Hart et al., 2011). In a public health setting, Se fertilisation has already been adopted at a national scale in Finland, in 1984, following primary legislation. This led to immediate increases in the Se concentrations of Finnish foods and dietary Se intakes (Eurola et al., 1991; Broadley et al., 2006).

The aim of this study was to determine the potential for increasing grain Se concentration in maize in Malawi using fertiliser-based approaches. Malawi was chosen because there is evidence of widespread low Se intakes and status among the population due to the low plant-available Se concentrations of the soils and a lack of diversity within the typical diet (Chilimba et al., 2011). Furthermore, to secure maize yields, Malawi has operated a Farm Input Subsidy Programme (FISP) since 2005/06 (Dorward and Chirwa, 2011), under which fertiliser is distributed to small-scale farmers *via* a voucher system. The FISP involves major commitments of financial and human resources through the national extension service system and represents a potential public health intervention route, as adopted previously in Finland.

2. Materials and methods

2.1. Overview

Three sets of field experiments were conducted in Malawi, in each of the 2008/09 and 2009/10 cropping seasons, to determine the response of maize to three forms of selenate-Se containing fertiliser. These were: (1) a liquid drench of $Na_2SeO_{4(aq)}$ (41.8% Se, Sigma–Aldrich Company Ltd, Dorset, UK), (2) compound fertiliser granules containing NPK + Se, representing a 25:5:5 + Na product marketed under the trade name Top Stock® (Yara UK, Immingham, UK) which contains 0.0012% Se (w/w) as Na_2SeO_4 and (3) calcium ammonium nitrate (CAN + Se; Yara) containing 0.005% Se (w/w), also as Na_2SeO_4.

2.2. Site and crop selection, cultivation and experimental design

In both years, fields were selected at research stations of the Malawi Ministry of Agriculture and Food Security (MoAFS), at Bvumbwe, Chitala, Chitedze, Makoka, Mbawa and Ngabu (Table 1). All sites were rain-fed. As lack of rain and crop failure occurred at Ngabu in 2009/10, a late-sown crop was grown under irrigation at a replacement site at nearby Kasinthula, within the same Shire Valley Agricultural Development Division (ADD). Soils at all sites were Luvisols except for the Shire Valley ADD sites (Eutric Vertisol). Experiments with $Na_2SeO_{4(aq)}$ and NPK + Se were conducted at six sites in 2008/09 and 2009/10 using *Zea mays* L. var. SC627 (a local hybrid). Experiments with CAN + Se were conducted at a subset of