

Effect of selenium fertiliser formulation and rate of application on selenium concentrations in irrigated and dryland wheat (*Triticum aestivum*)

D. CURTIN

R. HANSON

New Zealand Institute for Crop & Food
Research
Private Bag 4704
Christchurch, New Zealand
email: curtind@crop.cri.nz

T. J. VAN DER WEERDEN

Ravensdown Fertiliser Co-Operative Limited
P.O. Box 1049
Christchurch, New Zealand

Abstract Field trials were carried out on two wheat (*Triticum aestivum*) crops (one irrigated, one dryland) in Canterbury, New Zealand during the 2005–06 growing season to evaluate the effectiveness of two selenium (Se) fertilisers in raising grain Se levels. Both contained sodium selenate: “AgSel” is a fast release formulation (100% water-soluble Se) whereas “Selprill Double” (76% water-soluble Se) has been formulated to slow the release of Se. The fertilisers were broadcast in spring (Zadoks growth stage 32) at rates of 5 to 20 g Se/ha. Grain Se increased linearly with application rate, but concentrations were higher with the fully-soluble formulation. Mean Se concentration was significantly lower in irrigated (grain yield 9.1 t/ha) than dryland (yield 7.4 t/ha) wheat (0.17 versus 0.25 mg Se/kg), possibly owing to yield dilution. For the fully-soluble Se fertiliser, grain Se increased by 0.018 mg/kg in irrigated wheat for each g/ha of applied Se. An application of 4–5 g/ha would raise grain Se to 0.1 mg/kg (approximate concentration in imported Australian wheat), assuming natural levels in Canterbury wheat are c. 0.02 mg/kg. The water-insoluble component of Selprill Double made little

or no contribution to Se uptake when the fertiliser was applied in spring and therefore application rates should be c. 30% higher than those of the fully-soluble fertiliser.

Keywords wheat; Se application rate; sodium selenate; fertiliser formulation; water-soluble Se; Se recovery in grain; irrigation

INTRODUCTION

Selenium (Se) is an essential element for livestock and humans, but not for plants. It is necessary for the activity of numerous enzyme systems in mammals (Thomson 2004). These include enzymes that provide antioxidant protection (e.g., glutathione peroxidase, which catalyses the reduction of peroxidases) and enzymes required for the functioning of thyroid hormones. Chronic health problems that may be associated with oxidative damage include cardiovascular disease, some cancers, and lung diseases such as asthma and chronic pulmonary disease (Rayman 2000).

New Zealand soils, particularly those in the South Island, are very low in Se and crops grown on them provide marginal levels of Se to consumers. Wheat products can be an important dietary source of Se (e.g., bread may contribute 15–25% of dietary Se). However, bread made from South Island wheat (*Triticum aestivum*) contains only c. 0.025 mg Se/kg compared with 0.09, 0.11, and 0.26 mg Se/kg in bread made from North Island, Australian, and American wheat, respectively (Ministry of Health 2000). Enhancing wheat Se has been identified as a way of achieving a significant increase in dietary Se intake at little cost (Broadley et al. 2006). The New Zealand Flour Millers Association is encouraging South Island growers to take voluntary action to increase grain Se to 0.10 mg/kg, which is about the level in imported wheat (Paul Fahy pers. comm.). However, growers may need to receive financial incentives to apply Se as it will not increase crop yield (Stephen et al. 1989).

In contrast to pastoral systems, there has been relatively little research on Se management in wheat in New Zealand (Stephen et al. 1989). Previous studies have shown that Se fertiliser application is an effective way of raising grain Se concentrations, though proper timing of application is important to achieve maximum uptake by the crop (Curtin et al. 2006). Se applied with the base fertiliser at sowing was relatively ineffective, possibly because the applied selenate-Se was converted to less available selenite-Se before the crop's rapid growth phase in spring. Best results were obtained when Se (sodium selenate) was applied in spring (at growth stage 31) when 4–5 g/ha of fertiliser Se was sufficient to raise grain Se to the 0.1 mg/kg threshold. This recommendation was based on a small data set (trials at two Canterbury locations in a single growing season) and needs to be confirmed by further research.

In the trials referred to above, sodium selenate, a fast-release form of Se, was used. Recently, a slow-release formulation of sodium selenate, introduced by Ravensdown Fertiliser Co-Operative Limited, has been evaluated for its ability to maintain adequate pasture Se over the whole growing season (Loganathan & Hedley 2006; McLaren & Clucas 2006). The results showed that the slow release formulation was effective in maintaining herbage Se above the critical value for c. 1 year whereas the fast-release form gave high initial herbage Se, but Se declined to background concentrations within c. 150 days (McLaren & Clucas 2006).

Wheat producers need guidance on whether Se application rates should be varied depending on the sodium selenate formulation used. In this paper, we report on field trials comparing fast- and slow-release formulations of sodium selenate for their ability to increase Se in wheat grain produced in dryland and irrigated systems.

MATERIALS AND METHODS

Selenium fertilisers

The fertilisers used were: (1) Selenium Chip™ (brand name "AgSel"), supplied by Wrightson Limited. This fertiliser contains 1% Se (as sodium selenate) in a prill that is coated with polymer to encapsulate Se until moistened. The Se is regarded as fully water soluble. This product was used as Se source in the trials of Curtin et al. (2006). (2) Se prill containing 2% Se as sodium selenate, of which 76% is water soluble (McLaren & Clucas 2006). This product is

marketed by Ravensdown Fertiliser Co-Operative Limited with the brand name "Selprill Double". This fertiliser was referred to as "Ravensdown B" by McLaren & Clucas (2006).

Field trials

The trials were conducted on commercial farms in Canterbury during the 2005–06 growing season. The irrigated trial was on a Wakanui silt loam (Immature Pallic Soil, Hewitt 1993) (pH 5.9; Olsen P 25 mg/kg; quick test K 5) at Wakanui and the dryland trial was on a Lyndhurst silt loam (Pallic Firm Brown Soil, Hewitt 1993) (pH 6.0; Olsen P 20 mg/kg; quick test K 3) at Methven. At each site, the two fertilisers (AgSel and Selprill Double) were applied at rates intended to provide 5, 10, 15, and 20 g Se/ha and there was a control that received no Se. There were four replicates of each treatment, arranged in a randomised block design. Plot size was 8 m × 2.5 m. The cultivars grown were 'Aquila' at Methven and 'Torlesse' at Wakanui. The crops were sown (in May 2005) in seedbeds prepared using conventional cultivation methods and managed by the host farmers using their best practices to minimise weeds, pests, diseases, and nutrient stress. The treatments were applied at growth stage 32 on the Zadok scale (16 October 2005 at Wakanui and 6 October 2005 at Methven) which is the recommended growth stage for the first spring nitrogen (N) application for first-year autumn-sown wheat. The Se fertilisers were broadcast onto the plots by hand. Because of the small quantity of Se to be applied, it was necessary to add a bulking material to achieve uniform distribution. As bulking material, we used 1–2 mm soil aggregates (similar in size to the fertiliser granules) separated by dry sieving from a local Templeton soil (Se fertiliser was mixed with 150 g of soil aggregates applied to each plot).

A small plot harvester was used to harvest the crops at grain maturity (15 February 2006 at Wakanui and 30 January 2006 at Methven). Grain yield was determined for each plot and a sample of c. 1 kg/plot (>2 mm diam.) was retained for Se determination.

Selenium analysis was carried out at Analytical Research Laboratories Limited, Napier. Grain was finely ground and subsamples (1 g) were digested in nitric-perchloric acid (10 parts concentrated HNO₃ and 4 parts HClO₄) at 200°C for c. 1–1.5 h (i.e., until white fumes appeared), after which the temperature was increased to 250°C for 15 min. The digests were then allowed to cool partially before addition of 1 ml of concentrated HCl to convert the selenate-Se formed during digestion to selenite-Se. Selenium in the digests was determined by conversion to its

hydride by sodium borohydride reagent (Clinton 1977) and aspiration into an inductively coupled plasma-atomic emission spectrometer (Varian Vista AX), via a vapour generation apparatus (Varian VGA-77).

Statistical analysis

Results were analysed using ANOVA (GenStat v.9) to estimate variances and to test for differences between treatments. The relationship between grain Se concentration and Se application rate was evaluated by standard linear regression analysis.

RESULTS AND DISCUSSION

Grain yield

Weather conditions in 2005–06 were relatively good for wheat production at the dryland site, with well-distributed rainfall between September 2005 and January 2006 (monthly rainfall amounts were 23, 96, 89, 55, and 66 mm during this period). Mean grain

yield of the dryland crop was 7.4 t/ha, though this was significantly ($P < 0.001$) less than that achieved at the irrigated Wakanui site (mean yield 9.1 t/ha) (Table 1). The Se fertilisers had no effect on yield. Previous work (Stephen et al. 1989) suggested that wheat growth might be marginally depressed by sodium selenate application, but our results show no adverse effect even at a high application rate (20 g Se/ha).

Grain Se concentration

Grain Se concentrations in the controls at both sites were very low, but especially in the irrigated trial where grain had only 0.01 mg Se/kg (Table 2). Grain Se was strongly influenced by Se application rate and by fertiliser formulation. Se concentrations were higher where the fully-soluble formulation (AgSel) was used. There was also evidence of an interaction between formulation and application rate, i.e., the rate of increase of grain Se in response to Se application rate was greater for the product with most water-soluble Se.

Table 1 Grain yield (t/ha at 14% moisture) in irrigated (Wakanui) and dryland (Methven) trials in New Zealand, as influenced by application of selenium (Se) fertilisers.

Se application rate (g/ha)*	Wakanui		Methven	
	AgSel	Selprill Double	AgSel	Selprill Double
0	9.0		7.5	
5	9.2	9.0	7.4	7.3
10	8.9	8.9	7.5	7.3
15	8.9	9.2	7.5	7.4
20	9.2	9.2	7.3	7.1
LSD ($P = 0.05$; 24 d.f.)	0.47		0.33	

*Based on nominal Se contents of 1% and 2% for AgSel and Selprill Double, respectively.

Table 2 Grain selenium (Se) concentration (mg/kg) in the irrigated (Wakanui) and dryland (Methven) trials in New Zealand, as influenced by application of Se fertilisers.

Se application rate (g/ha)*	Wakanui		Methven	
	AgSel	Selprill Double	AgSel	Selprill Double
0	0.01		0.03	
5	0.11	0.07	0.15	0.09
10	0.20	0.11	0.27	0.19
15	0.24	0.19	0.37	0.27
20	0.40	0.24	0.49	0.37
LSD ($P = 0.05$; 24 d.f.)	0.060		0.075	

*Based on nominal Se contents of 1% and 2% for AgSel and Selprill Double, respectively.

Analysis of the fertilisers used in the trials indicated that the actual Se content of the Selprill Double was 1.7%, rather than the nominal value of 2%. Variation in Se concentration is likely to occur when small samples of fertiliser are taken. Se concentrations in Selprill Double typically range from 1.7% to 2.2%. The measured Se content of AgSel (0.96%) was very close to the nominal value (1%). Some of the difference in grain Se between fertiliser formulations was because of differences in amounts of Se applied. However, when adjustments were made for under-application of Selprill Double, grain Se was still less than for AgSel (Fig. 1).

Wheat accumulates a large amount of biomass in spring, when daily dry matter accumulation rates can reach 150 kg/ha (P. D. Jamieson pers. comm.). When Se is applied at growth stage 32, the rapidly growing crop will have a large acquisition potential for Se over a relatively short period (several weeks). This contrasts with pasture where maximum rates of dry matter production in Canterbury are usually <60–70 kg/ha per day (McKenzie et al. 1999), and demand for Se is spread over a much longer growing period. Our results indicate that a fully-soluble formulation providing rapid release maximises Se uptake by wheat.

The grain Se levels achieved where AgSel was applied were similar to those obtained in the previous study of Curtin et al. (2006). In that study, where AgSel was applied at growth stage 31, an application of 20 g Se/ha resulted in grain Se levels of 0.4–0.5 mg/kg, similar to the values shown in Table 2. This suggests that Se application at either growth stage 31 or 32 would be equally effective in raising grain Se concentrations. Mean Se concentration was slightly higher in dryland than in irrigated wheat (0.246 versus 0.173 mg/kg). This was probably because of “yield dilution”, i.e., concentration decreases as yield increases, as observed for nutrients such as N in wheat (Zentner et al. 1996). Irrigation has been shown to decrease wheat Se concentration in trials in the United Kingdom because of yield dilution and suppression of Se uptake owing to competition from sulfate in the irrigation water (Zhao et al. 2007). Irrigation water in Canterbury is low in sulfate compared to the tap water used in the study of Zhao et al. (2007) (water sulfur (S) concentration of 49 mg/litre; total amount of applied sulfate-S ranged from 20 to 200 kg/ha) and irrigation effects on wheat Se in Canterbury are likely to be because of yield dilution rather than inhibition of Se uptake by sulfate in the water. Different cultivars were used in our irrigated and dryland trials, but Australian studies

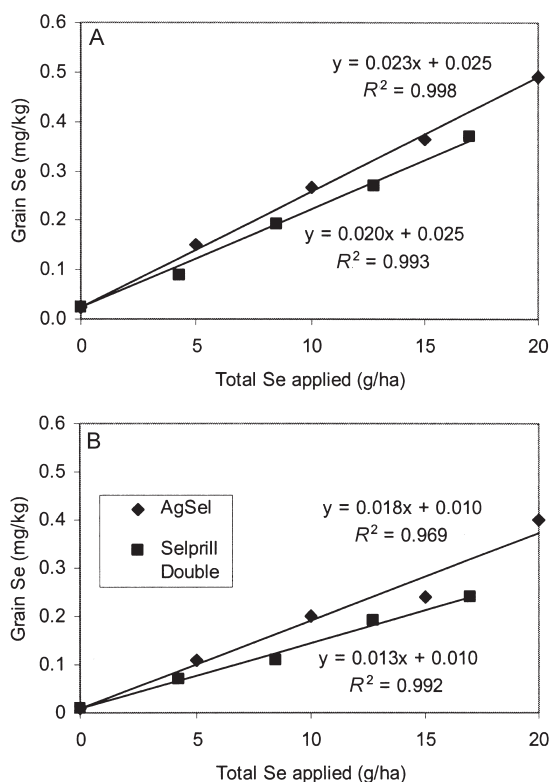


Fig. 1 Relationship between grain selenium (Se) and total fertiliser Se applied to: **A**, dryland (Methven) and **B**, irrigated (Wakanui) wheat (*Triticum aestivum*) crops (regressions for “Selprill Double” are based on measured (1.7%), rather than the nominal (2%) Se content).

suggest that genotypic variation in grain Se is likely to be small in modern wheat cultivars (Lyons et al. 2005). Results from previous Canterbury trials confirm that cultivar effects on grain Se are small and generally not significant (Curtin et al. 2006).

Selenium recovery

The proportion of fertiliser Se recovered in grain did not change with application rate but fertiliser formulation had an effect on Se recovery (Table 3). On average, 17.0% of AgSel-Se was recovered in grain compared with 12.7% of Selprill Double-Se (note: the recovery values for Selprill Double discussed in this section were estimated using the actual Se content of the fertiliser).

Fertiliser Se recovery was similar for the irrigated and dryland sites. Recovery of AgSel-Se averaged

17.6% in the irrigated versus 16.4% in the dryland trial. The corresponding values for Selprill Double were 13.4% and 12.1%, respectively. Thus, total Se uptake was little affected by the presence or absence of irrigation, but yield dilution did result in lower Se concentrations in irrigated wheat. To increase the probability of achieving the required grain Se concentration, it would therefore be prudent to base Se application rates on data for irrigated wheat.

Recovery of Selprill Double-Se averaged 74% and 76% of that achieved using AgSel, for the irrigated and dryland trials, respectively. When recovery was calculated as a proportion of water-soluble Se in the fertilisers, values were very similar for the two fertilisers; mean recovery of water-soluble Se was 16.8% for Selprill Double versus 17.0% for AgSel. These results indicate that the water-insoluble component of Selprill Double was not released quickly enough to contribute much Se to the rapidly growing wheat crops. In pasture, Selprill Double was less effective in supplying Se in the initial period of c. 2 months, but it was superior to the fully-soluble formulation (AgSel) during the following 10 months (McLaren & Clucas 2006). For a rapidly growing wheat crop, the slow release component of Selprill Double is not an advantage, as it is in the case of pasture where long-term Se supply is important.

Recovery rates for fertiliser Se in our trials compare favourably with those achieved in other studies. Stephen et al. (1989) reported that 6.9% and 4.9% of autumn-applied Se was recovered by wheat at two locations in Canterbury. In pasture (dry matter production c. 12 t/ha), 15–17% of applied Se was recovered over a 1-year period (McLaren & Clucas 2006). It should be noted that our estimates

of recovery do not include straw Se (Se content of straw may be about half that of grain (Stephen et al. 1989)), so total Se recovery will be significantly greater than indicated by the grain data in Table 3.

Rate of application to raise grain Se

Grain Se was regressed on the applied Se rate, with a separate regression line for each trial and fertiliser formulation (Fig. 1). In all instances, grain Se showed a linear increase as the rate of Se application increased ($R^2 \geq 0.967$). These regressions gave rates of grain Se increase of 0.018 and 0.023 mg/kg per g/ha of applied AgSel-Se for the irrigated and dryland trials, respectively. These values are very close to those recorded for 9–10 t/ha wheat crops, i.e., increases of 0.016–0.021 mg Se/kg for each g/ha of AgSel-Se (Curtin et al. 2006). Assuming a natural grain Se content of 0.02 mg/kg for Canterbury wheat, an increase to 0.10 mg/kg (likely grain Se target concentration) would require the application of 4.4 g Se/ha of AgSel-Se for irrigated wheat and 3.5 g/ha for dryland wheat. Corresponding values for the slow-release formulation are 6.2 and 4.0 g/ha for irrigated and dryland wheat, respectively. Spring application of Se (either fertiliser formulation) was substantially more efficient in raising wheat Se than the autumn application of (Stephen et al. 1989), who found that c. 10 g/ha of Se was needed to raise grain Se to 0.1 mg/kg in low-yielding (c. 5 t/ha) crops.

The relationship between grain Se and application rate of water-soluble Se was similar for both fertiliser formulations (Fig. 2). In the dryland trial, there was some evidence that Selprill Double gave slightly higher grain Se concentrations per unit of applied water-soluble Se than did AgSel. This may indicate that the water-insoluble Se in Selprill Double made

Table 3 Percentage of selenium (Se) recovered in grain following application of “AgSel” and “Selprill Double” at rates of 5–20 g Se/ha to irrigated (Wakanui) and dryland (Methven) wheat (*Triticum aestivum*). Values not in parentheses were calculated using the nominal (2%) Se content of Selprill Double and the values in parentheses are based on the measured Se content (1.7%).

Se application rate (g/ha)*	Wakanui		Methven	
	AgSel	Selprill Double	AgSel	Selprill Double
5	17.5	10.8 (12.7)	18.3	9.3 (10.9)
10	16.5	9.2 (10.8)	18.1	12.1 (14.2)
15	13.7	10.6 (12.5)	16.9	12.0 (14.2)
20	17.8	10.4 (12.3)	16.9	12.3 (14.5)
LSD ($P = 0.05$; 21 d.f.)	4.73		3.52	

*Based on nominal Se contents of 1% and 2% for AgSel and Selprill Double, respectively.

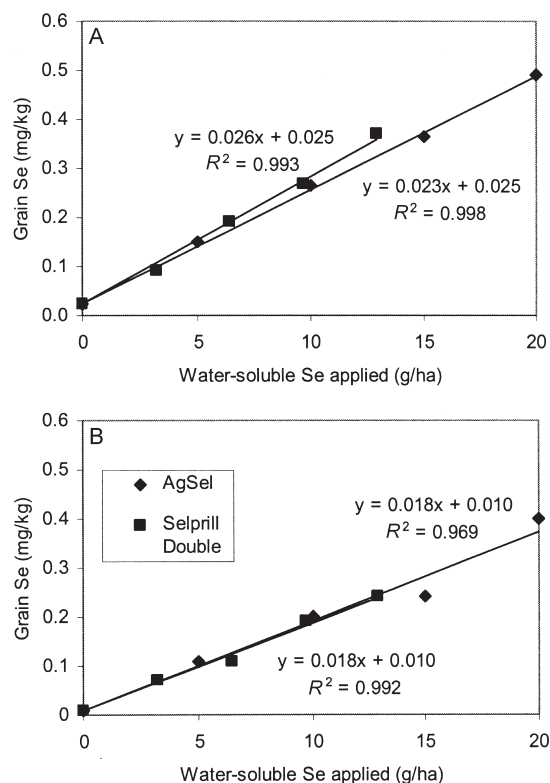


Fig. 2 Relationship between grain selenium (Se) and water-soluble Se in fertilisers applied to: **A**, dryland (Methven) and **B**, irrigated (Wakanui) wheat (*Triticum aestivum*) crops (regressions for “Selprill Double” are based on measured (1.7%), rather than the nominal (2%) Se content).

a small contribution to plant Se uptake in that trial. However, as there was not a consistent benefit from the water-insoluble Se, application rates for wheat should be based on the amount of water-soluble Se in the fertiliser.

CONCLUSIONS

Our results show that application of Se fertiliser at growth stage 32 (i.e., the recommended stage for first spring N application to autumn-sown wheat) was effective in increasing wheat Se concentrations. When applied in spring, the water-insoluble component of Se fertiliser appeared to make little or no contribution to wheat Se uptake. Therefore, application rates should be based on water-soluble Se, rather than on total fertiliser Se. Our trials also provide evidence that irrigated crops with high yield

potential may require more fertiliser Se to reach the target Se concentration than dryland crops. To improve the likelihood of achieving the required grain Se concentration, it would be wise to base application rate on data for irrigated wheat. For the fully soluble Se source (AgSel), an application rate of 4–5 g Se/ha should raise grain Se to 0.1 mg/kg. For fertiliser with 76% water-soluble Se (Selprill Double), the Se application rate should be increased by c. 30% compared to AgSel.

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