VG011
The reduction of cadmium contamination in Tasmanian vegetables and poppies

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VG011

This report is published by the Horticultural Research and Development Corporation to pass on information concerning horticultural research and development undertaken for the vegetable industry.

The research contained in this report was funded by the Horticultural Research and Development Corporation with the financial support of Edgell Birdseye, Tasmanian Alkaloids Pty Ltd, Glaxo, and EZ Fertilisers.

Cover Price $20.00

HRDC ISBN 1 86423 493 8

Published and Distributed by:

Horticultural Research and Development Corporation
Level 6
7 Merriwa Street
Gordon NSW 2072

Telephone: (02) 9418 2200
Fax: (02) 9418 1352

The Reduction Of Cadmium Contamination in Tasmanian Vegetables and Poppies (V0011RO)

FINAL REPORT TO THE HORTICULTURAL RESEARCH AND DEVELOPMENT CORPORATION

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December 1993

Department of Primary Industry and Fisheries, Tasmania

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1 (a) INDUSTRY SUMMARY

This project sought to determine the extent of cadmium (Cd) impurities in Tasmanian vegetables and poppies, and to experiment with ways of decreasing Cd in crops or areas found to have unacceptably high concentrations.

Surveys of Cd in vegetables showed that only potatoes and carrots had concentrations which exceeded the maximum permitted concentration (MPC) set by the National Food Authority. All green pea, green bean, lettuce and brassica samples and all but one onion sample had concentrations lower than the MPC. Common soil tests did not show sufficient relation to Cd uptake for them to be used to predict where Cd may be a problem in potatoes and carrots.

Lime was tested at three field sites because studies elsewhere have shown that lime application (higher soil pH) decreases Cd availability. We found that broadcast lime had no effect on Cd uptake of potatoes grown within 2-3 months of lime application, or on the Cd uptake by poppy seed grown in the following year. However, at one site broadcast lime did decrease Cd uptake by potatoes grown a second time, two years after liming. The Cd decrease due to lime may have been delayed because the lime treatments needed time and further cultivation to influence most of the root zone. Lime also increased common scab (*Streptomyces scabies*) in the second potato crop, and this disease may have been the cause of restricted cadmium uptake. We are confirming this in further work.

Phosphate fertilisers with different concentrations of Cd were compared to see if lower concentrations would give lower Cd in the current crop. However, the low Cd fertiliser (15 ppm) gave the same Cd concentration in potatoes as the high Cd fertiliser (90 ppm). This was probably because even the low Cd fertiliser added many times more Cd than was removed in the tubers. Phosphate fertilisers may need to be almost free of Cd before benefits for the current crop are seen.

Pot and field trials with potatoes and poppies showed that substituting potassium sulphate for potassium chloride in NPK fertiliser gave lower Cd uptake. The decrease was of the order of 20-30% in field grown potatoes, and is thought to be due to the decreased availability of Cd in the presence of sulphate compared with chloride. Further field verification of this effect is needed, but it may provide growers with a simple means of decreasing Cd uptake which, if combined with a predictive soil test, could be used where it was most needed. Potassium sulphate costs about double that of potassium chloride so an industry wide change is not recommended. Also, research in South Australia has shown that the benefits of changing to potassium sulphate are negated where irrigation water high in chloride is used.

In summary, changing potassium source is a possible short term measure to decrease Cd uptake, but liming or decreasing fertiliser cadmium concentrations are longer term measures. Further work is being done to verify these views and to refine management recommendations.

1(b) TECHNICAL SUMMARY

Surveys showed that in Tasmania only potatoes, poppy seed and carrots consistently threaten or violate the MPC for cadmium (Cd). Other vegetables were well below the MPC. The studies reported here have concentrated on potatoes and poppies.

Broadcast lime had no immediate effect on Cd uptake by potatoes despite increasing soil pH by about one unit at each of three field sites. At two of these sites, it also had no effect on Cd uptake by poppy seeds in the following year, despite the extra time for lime reaction and despite the extra soil mixing afforded by the potato harvest and subsequent cultivation. However, a return to potatoes at one site in the third year showed a significant decrease in tuber Cd with lime, which by this time had raised soil pH over a depth of 250 mm. Lime also increased common scab (Streptomyces scabies) in the return potato crop, and may have influenced cadmium uptake. We conclude that deep distribution of lime through leaching and cultivation may help to make it an effective medium to long term ameliorant, at least for potatoes, but the influence of common scab needs clarifying. Banding lime with potato fertiliser had no effect on tuber Cd at one site.

A comparison of two double-superphosphates containing 15 and 90 ppm Cd respectively showed no difference in Cd uptake by potato tubers. Tuber Cd was more responsive to rate of phosphorus (P), which may be because P encourages root proliferation and Cd uptake either inside the fertiliser band or in the bulk soil. Basic studies on Cd uptake and redistribution are needed to determine whether management of the bulk soil or of the fertiliser band has the greatest effect on Cd uptake. Because of the high P requirement of potatoes on Tasmania's krasnozems, Cd in P fertiliser may have to be actively removed during fertilizer production to enable less Cd to be added in fertiliser than is removed in tubers.

Substitution of sulphate for chloride in fertilisers decreased Cd uptake by poppies and potatoes in both pots and in the field, except in heavily leached pots where the reverse was the case. This is the first time that manipulation of anions has been shown to affect plant Cd uptake, and presents the possibility that where leaching is unlikely, substitution of sulphate for chloride might reduce Cd uptake. Where leaching is likely, addition of K as KCl may promote removal of Cd from the rootzone.

In other States, chloride in irrigation water has overriden the effects of anion substitution in fertilisers. Irrigation water in Tasmania mostly comes from surface storage or from perennial streams, and so is generally of good quality. However, in the northern Midlands, surface water storage in saline depressions is becoming more common and may lead to higher Cd availability in these areas.

A soil test which predicts Cd availability under Tasmanian conditions is necessary so that ameliorants such as lime or alternate K sources can be recommended only where they are most needed. Petiole Cd has been shown to be a relatively poor predictor of tuber Cd and in any case petiole tests come too late to save farmers the cost of crop establishment. Dilute calcium chloride is an extract which has been somewhat successful elsewhere and deserves testing in Tasmania.

2. RECOMMENDATIONS

2(a) Extension/Adoption by Industry

At this stage, further work is needed in most areas before firm recommendations can be made to industry. This has already been recognised through industry and HRDC support for continuation of this work for a further three years from July 1993. Detail of this further research is given below.

Cadmium in food is a sensitive issue. There is potential for unnecessary concern to be aroused both within the industry and the public. Thus, even when clear recommendations are available, any extension and public relations about Cd, particularly for potatoes, needs to be coordinated nationally, as recognised by the HRDC-sponsored Cd workshop held in August 1993. While the results presented for Tasmania in this report are more favourable than some elsewhere, it would not be prudent to draw attention to Tasmania's situation at the expense of others. Tasmania is willing to contribute to a national extension program, possibly coordinated and funded in part by HRDC, as suggested at the workshop.

Another conclusion from this workshop was that the industry and HRDC should pursue an application to the National Food Authority to have the MPC for Cd in potato products raised. Depending on the outcome of such an application, the target audience for some of the information generated could be smaller than it is now.

2 (b) Directions for future research

Because cadmium in food is an issue of importance in many parts of Australia, studies have been conducted in a number of States. There are good reasons why separate studies are warranted. Environmental conditions (soil, climate, water quality), production systems (e.g. potato for crisps, potatoes for french fries, poppies) and the cost and availability of potential ameliorants like lime vary greatly from State to State. Solutions may well be region specific. For these reasons, Tasmania, with the support of local industry and HRDC, has continued research on Cd. We believe that we are in a good position to follow up on the longer term benefits of lime, using some of the sites established in the first project. The issue of manipulating K fertilisers to either restrict Cd uptake or to enhance Cd leaching is one which Tasmania is also well placed to tackle because of its previous work in this area. Field trials on the effect of potassium rate, source and method of application will help to address this issue. Areas will be treated with a range of K fertilisers or other sources of chloride (NaCl, HCl) over winter and compared with untreated areas to see if leaching rains are able to remove chloride from the rootzone. All of the above strategies would need local testing before they could be recommended in other areas.

One area of research which warrants resources on a national scale is the development of a model, perhaps incorporating a soil test, which predicts Cd availability to subsequent crops. Such a model would be useful in identifying where ameliorants are best used. It is likely that models would vary from region to region but that many model components would be similar. Tasmania would therefore be keen to cooperate in any national study of this nature.

Cadmium concentrations in plant leaves are generally higher by an order of magnitude than they are in seeds, fruits or storage organs. Removal of plant tops may therefore offer a way of removing Cd from soil. Some effort to construct Cd budgets for intensive horticultural systems may identify opportunities to detoxify soils.

An important gap in our knowledge is that of the physiology of Cd uptake by plants, particularly potatoes. We need to know what influences the relative uptake of Cd from fertiliser vs soil, if and how this varies with plant age, and how Cd is distributed and redistributed within plants. This knowledge is necessary for efficient application of ameliorants, and would best be carried out at an institution with specialist facilities and expertise in plant physiology.

2 (c) Financial/Commercial Benefits

Subject to further confirmation, the results presented here suggest that in some circumstances, decreases of 20-30% in tuber Cd are possible, and may mean the difference between violation and non-violation. The significance of such decreases to industry depends on the market discrimination against food which violates the MPC. At present there is no such discrimination, but the situation could deteriorate. In such circumstances, if we have the capacity to identify specific problem areas and to ameliorate them, it could mean the difference between the survival or failure of our poppy seed and particularly our potato industries, currently worth about $1m and $60m at the farm gate respectively. A more realistic scenario for potatoes is that areas elsewhere which have more severe violation rates than those in Tasmania will be exluded from markets first, leaving a production deficit which Tasmania is well placed to make up. However this will only be possible if further work to reliably identify Tasmania's violative areas or paddocks is conducted.

3. Technical Report

3(a) Survey Work

3(a) i Introduction

Prior to this study, it was well known that poppy seed consistently violated the MPC, but there was little information about Cd concentrations in Tasmanian vegetables. Several surveys were conducted during this study to provide such information.

3(a) ii Materials and Methods

A number of commercial vegetable crops were sampled and analysed for Cd in order to determine which were most in need of amelioration. Each crop sample consisted of either fifteen (cauliflower), twenty (carrot) or thirty subsamples from a paddock. The samples were reduced in size where necessary by dicing and subsampling before washing in tap water, rinsing in distilled water, and drying at 60°C. Gravimetric moisture content was determined for each sample. Samples were ground and analysed for Cd by atomic absorption spectroscopy as detailed previously.

Potato tuber samples were also taken in conjunction with CSIRO Division of Soils. In this study, three tubers were taken from a single location in each of 58 paddocks. Corresponding soil samples were also taken in an effort to relate tuber Cd to soil characteristics. Results will be reported by CSIRO in their final report due in December 1994.

3(a) iii Results and Discussion

Table 1. Cadmium (mg/kg fresh wt) in Tasmanian crops surveyed by DPIF and CSIRO

Crop	No of Samples	Cd_{min}	Cd_{max}	Cd_{mean}	% > MPC
Potato-Kennebec 1990	11	0.021	0.108	0.053	36
Potato-Russet Burbank 1990	31	0.016	0.083	0.036	16.1
Russet Burbank 1991	19	<0.01	0.053	0.028	10.5
Kennebec 1992	3	0.020	0.036	0.027	nil
Russet Burbank 1992	18	<0.01	0.044	0.025	nil
Kennebec CSIRO 1992	21	0.018	0.058	0.037	19.0
Russet Burbank CSIRO 1992	37	0.01	0.083	0.037	10.8
Carrot 1990	17	<0.01	0.072	0.027	20
Carrot 1992	13	<0.01	0.034	0.017	nil
Onion 1990	29	<0.01	0.053	0.016	3
Lettuce 1990	12	<0.01	0.035	0.013	nil
Cauliflower 1990	14	<0.01	0.014	<0.01	nil
Brussels Sprouts 1990	11	<0.01	0.014	<0.01	nil
Green Pea 1990	19	<0.01	0.011	<0.01	nil
Green Bean 1990	20	<0.01	<0.01	<0.01	nil

Table 1 shows that only potatoes and carrots showed any significant rate of violation of the MPC. Of the other crops, only one onion crop was violative. There was a marked difference between the carrots from 1990 and 1992 which may reflect seasonal conditions. There was also variation in the rate of violation of Russet Burbank potatoes. The nil violation rate in the DPIF survey of 1992 may reflect the small geographical area (around Gawler in NW Tasmania) from which these samples came; the CSIRO survey in the same year covered all production areas and showed a violation rate similar to those measured in 1990 and 1991.

In keeping with their relative production in Tasmania, there were fewer samples of the cv Kennebec than cv Russet Burbank. Any comparison of the two cultivars should be treated cautiously, but the indications are that Kennebec violates the MPC more often than Russet Burbank. This is in accord with the relative Cd concentrations of the two cultivars in the experiment in section 3c, and also with their ranking in cultivar trials (M J McLaughlin pers comm).

3 (b) Field studies of cadmium in potatoes (*Solanum tuberosum* L.) I. Effects of lime and phosphorus on cv. Russet Burbank.

3(b)i Summary

Field experiments were conducted at 3 sites on basaltic krasnozems to examine cadmium (Cd) responses of Russet Burbank potatoes to different rates of broadcast lime and banded phosphorus (P). Double superphosphate (DSP, containing 15 and 90 mg Cd kg^{-1}) and triple superphosphate (TSP, 12 mg Cd kg^{-1}) were the sources of P. In a fourth experiment, lime was banded with the basal fertiliser. Despite producing a range of topsoil pH (1:5 H_2O) of 5.2 to 7.1, broadcast lime had no effect on tuber Cd concentrations. Neither did lime when banded with the basal fertiliser, although the practice did not adversely affect yields. With broadcast lime, Cd availability from the fertiliser band may have been unaffected. However, there were also no lime by P interactions at any site, suggesting that lime had no effect on the availability of Cd in the soil either. It is possible that Tasmanian krasnozems, with their high organic matter and iron oxide content, restrict the availability of Cd in the soil such that pH change exerts little net influence on Cd availability. Increasing amounts of Cd applied in P fertiliser increased tuber Cd concentrations significantly, but the increases were less per unit of P than those found previously when TSP with 151 mg Cd kg^{-1} was used.

3(b) ii Introduction

There is increasing concern about Cd as a contaminant in the environment and in food. Phosphorus (P) fertilisers are considered a likely source of extra cadmium in agricultural soils, and studies have linked their prolonged and/or heavy use with increased plant cadmium concentrations (Williams and David 1976), although this has not been so in every case (Williams and David, 1976; Mulla *et al.* 1980; Mortvedt 1987). Liming is generally considered a means of decreasing the availability of cadmium in soils, but here too there is evidence to the contrary (Andersson and Siman 1991; Eriksson 1989). Plant response to cadmium additions in P fertiliser will depend on the genotype concerned, the cadmium concentration of the fertiliser, the rate and method of fertiliser application, the soil type and seasonal conditions.

Potatoes are thought to be a major source of cadmium in the Australian diet because they are consumed in quantity and because they have relatively high concentrations of cadmium (National Health and Medical Research Council 1990). The current maxium permitted concentration (MPC) for potatoes in Australia is 0.05 mg Cd kg fresh wt^{-1} (National Health and Medical Research Council 1988). Cadmium in potato tubers has been shown to increase with increasing rates of banded triple superphosphate (TSP) high in cadmium (Sparrow *et al.* 1992), but there are no published studies of the effects of liming on tuber cadmium. Russet Burbank is a major cultivar in southern Australia, and we wanted to evaluate the potential of lime as a cadmium control measure for this cultivar.

This paper reports on 3 field experiments where the effects of broadcast lime on tuber cadmium were examined at a range of rates of banded phosphorus, and also on a further field experiment where different rates of lime were banded with a single rate of basal NPK fertiliser.

3(b) iii Materials and Methods

Trial sites

All sites were in north-western Tasmania, on krasnozems (red, dystrophic Ferrosols; Isbell 1992) developed on basalt (Loveday and Farquhar 1958). The broadcast lime experiments were located on the Forthside Vegetable Research Station (FVRS, 41° 12'S, 146° 15'E) near Devonport, on Elliott Research Station (ERS, 41° 6'S, 145° 46'E) near Burnie, and on a private farm near FVRS. These sites will be referred to as CD2, CD3, and CD6 respectively, and are part of a series of experiments on Cd. The banded lime experiment was immediately adjacent to the CD6 experiment and will be referred to as CD7. Site CD6/7 had been continuously cropped to vegetables for at least 10 years, site CD2 had been cropped 1 year in 5 for 20 years, and site CD3 had been in pasture for at least 20 years. These histories were reflected in the characteristics of the surface soils at the sites (Table 2), with site CD6/7 typical of limed and heavily fertilised cropping soils in this region. The EDTA Cd concentrations are in the upper range of values reported for agricultural soils by Merry and Tiller (1991). The relative proportions of sand, silt and clay were 29:31:40 for CD2, 27:29:44 for CD3, and 21:25:54 for CD6/7.

Table 2. Pre-plant soil (0-150mm) characteristics

Results are for composite samples of 30 cores

Site	pH (1:5 H_2O)	CEC (cmol(+)kg^{-1})	Colwell P (mg kg^{-1})	Colwell K (mg kg^{-1})	Organic carbon (%)	EDTA-Cd (mg kg^{-1})
CD2	5.8	19	58	340	5.5	0.36
CD3	5.1	17	47	250	6.6	0.31
CD6/7	6.1	18	187	470	3.0	0.43

Experimental design

Experiments CD3 and CD6 were split-plot designs, with 3 and 4 replicates respectively. Main plots were rates of banded double-superphosphate (DSP, 17.1%P, 15 mg Cd kg^{-1}) at nil, 60, 120 and 240 kg P ha^{-1}. Typical rates for potatoes on krasnozems in Tasmania are 150-250 kg P ha^{-1}. At CD3 there were two extra main treatments of 120 and 240 kg P ha^{-1} of DSP containing 90 mg Cd kg^{-1}. Main plots were split into 4 lime rates: 0, 10, 20 and 30 tonne ha^{-1} at CD3 and 0, 10, 20 and 40 tonne ha^{-1} at CD6. The agricultural lime had 84% neutralising value, a particle size <2 mm (75% <0.5 mm), and a Cd content of 0.3 mg Cd kg^{-1}. It is not normal for single applications of lime to Tasmanian krasnozems to exceed 5 t ha^{-1}, but different long term liming strategies by farmers have given rise to a pH range of 5-7 for potato production (Sparrow unpublished data). We wanted to cover this range with our lime treatments. Plot size at CD3 was 7.5 m by 4 rows, and 7 m by 4 rows at CD6.

Experiment CD2 was a variant of a split-plot design with sub-unit treatments in strips (Cochran and Cox 1957) with 3 replicates and with P treatments (0, 60, 120 and 240 kg P ha^{-1}) as triple superphosphate (TSP, 21.1% P, 12 mg Cd kg^{-1}), parallel with the rows, and lime treatments (0, 10, 20 and 30 tonne ha^{-1}) across the rows. Individual lime by P plots were 6 m by 6 rows.

A randomised block design with 4 replicates was used for CD7, with treatments consisting of 4 rates of lime (0, 0.75, 1.45 and 2.90 t ha^{-1}) banded with 200 kg P ha^{-1} as DSP containing 90 mg Cd kg^{-1}.

Trial establishment

Broadcast lime treatments were applied by hand as soon as it was convenient to do so (4, 6 and 12 weeks before planting for CD2, 3 and 6 respectively). Within a day of application the lime was incorporated into the surface 150-200 mm by a rotary hoe. Inspection revealed little movement of lime in the direction of travel. Subsequent rainfall and irrigation was sufficient at all sites to keep the soil moist and aid reaction of the lime.

Fifty-gram, hand-cut seed pieces were planted at a spacing of 280-320 mm by a mechanical planter on 25 October 1990 (CD2), 13 November 1990 (CD3) and 10 October 1991 (CD6 and 7). The Cd concentration of the seed was not measured, but assuming a concentration of 0.05 mg Cd kg $seed^{-1}$, 2 t seed ha^{-1} would add only 100 mg Cd ha^{-1}. The seed was placed approximately 75 mm below the pre-plant soil surface, and approximately 200 mm below the top of the ridge formed by moulders on the planter. The latter distance decreased by about 25 mm as the ridges settled. Between-row spacing was 800 mm. In all cases, nitrogen (N, at 200 kg ha^{-1}) and potassium (K, 310 kg ha^{-1}), as a mixture of fertiliser grade ammonium sulphate and potassium chloride, were placed with the P (and the lime at CD7) in two 50 mm wide bands placed 25 mm below and 50 mm on either side of the seed. The Cd content of the ammonium sulphate and potassium chloride was not measured, but recently obtained samples contained 0.5 and 0.6 mg kg^{-1} respectively.

Crops on the research stations were managed by station staff, while CD6 and 7 were managed by the grower concerned as part of a commercial crop in that paddock. All crops were irrigated (40-50 mm every 8-10 days) from mid-December until they had senesced.

Harvest procedures

Petioles of the fourth or fifth leaf from the growing tip were sampled in all trials when the largest tuber was 5-10 mm long (Maier *et al.* 1989), determined by inspecting plants in buffer rows. There was no obvious difference in maturity between treatments. Thirty leaves were taken from each plot and the leaflets stripped by hand.

The trials were harvested after the haulms had died. The middle 5 m of the 2 centre rows of plots at CD3, CD6 and CD7, and the middle 4 m of the 4 centre rows of plots at CD2 were dug mechanically, weighed, and graded into processing (>100 g) and non-processing tubers (<100 g, or tubers with secondary growth). For each plot, samples of 10 processing tubers were taken at random for analysis.

Samples of soil were taken from the top 150 mm of the ridges of each plot about 7 weeks after planting. At CD3, soil was also taken from 150-300 mm. Each sample was a composite of 4 cores, with each core located in an individual row and midway between adjacent plants.

Tuber, petiole and soil analysis

Procedures for the preparation and analysis of tubers and petioles were the same as those described in Sparrow *et al.* (1992) except that deionised water was used instead of distilled water to rinse diced tubers, and that all tuber digests were analysed using flame atomic absorption spectroscopy with deuterium background correction employing a quartz atom concentrator tube to improve sensitivity (Brown and Taylor 1985). All concentrations in petioles and tubers are expressed on a dry matter basis.

Soils were analysed for pH (1:5 H_2O), sodium bicarbonate extractable P and K (Colwell 1963), organic carbon (Walkley and Black 1934), CEC (1 mol NH_4Cl L^{-1} at pH 7.0, after Gillman *et al.* 1982) and EDTA-extractable Cd (after Clayton and Tiller 1979 but with a 48 h shaking time).

Statistical analyses

Analyses of variance and simple and multiple linear regressions of response variates on phosphorus and lime rates were conducted using GENSTAT (GENSTAT 5 Committee 1987). Standard errors of differences (s.e.d.) are reported where F-tests from analyses of variance were significant ($P<0.05$). The significance of regression coefficients was assessed using t-tests, and regression models were fitted using appropriate error terms (Gates 1991).

3(b) iv Results

CD2, CD3 and CD6

Means for the lime and phosphorus treatments at CD2, CD3, and CD6 are shown in Tables 3 and 4. Analysis of variance showed no significant lime by P interactions. Yields at all sites were consistent with above average crops in Tasmania, and were not affected by lime except at CD6 where there was a small increase at the two highest rates (Table 3). However, all sites showed yield responses to phosphorus (Table 4). Yields with the high-Cd DSP at CD3 were not significantly different from those with the low-Cd DSP at the same rate of P.

Lime increased surface soil pH at all sites, and also increased subsoil pH where it was measured at CD3 (Table 3); re-sampling of surface soil after harvest at CD2 and CD3 showed that these effects had persisted. However, lime had no significant effect on either tuber or petiole Cd at any site, except for tuber Cd at CD3, where a small increase ($P<0.01$) was observed (Table 3). Tuber Cd did increase with increasing rate of P fertiliser at all sites (Table 4). The high-Cd DSP at CD3 gave higher tuber Cd concentrations than the low-Cd DSP at the same rate of P, but the differences were not statistically significant ($P>0.10$). The difference in petiole Cd between the fertilisers at CD3 was significant ($P<0.05$) at 240 kg P ha^{-1}, but there was no difference in petiole Cd between the rates of the low-Cd DSP (Table 4). At CD2 and CD6, P fertiliser increased petiole Cd, but the effect was significant only at CD6 ($P=0.02$).

Table 3. Effects of broadcast lime (t ha^{-1})

Lime	0	10	20	30	40	
Site			*Processing yield (t ha^{-1})*			s.e.d.
CD2	56.3	57.9	55.5	60.3		NS[A]
CD3	61.1	64.2	63.5	64.1		NS
CD6	50.3	50.0	52.6		52.7	1.11
			pH (1:5 H_2O; 0-150mm)[B]			
CD2	5.7	6.2	6.5	6.5		0.06
CD3	5.2	5.6	6.0	6.3		0.08
CD6	6.3	6.6	6.8		7.1	0.05
			pH (1:5 H_2O; 150-300mm)			
CD3	4.8	4.9	5.2	5.3		0.05
			Tuber Cd (mg kg^{-1})			
CD2	0.115	0.099	0.118	0.121		NS
CD3	0.085	0.084	0.100	0.098		0.0055
CD6	0.122	0.111	0.115		0.108	NS
			Petiole Cd (mg kg^{-1})			
CD2	2.10	2.09	2.05	2.00		NS
CD3	2.47	2.52	2.45	2.32		NS
CD6	1.77	1.85	1.90		1.78	NS
			EDTA-extractable Cd (mg kg^{-1}; 0-150mm)			
CD2	0.37	0.34	0.34	0.32		P=0.08
CD3	0.31	0.30	0.26	0.25		0.015[C]
CD6	0.42	0.38	0.38		0.35	0.016
			EDTA-extractable Cd (mg kg^{-1}; 150-300mm)			
CD3	0.25	0.23	0.22	0.26		0.015[C]

[A]not significant, $P > 0.05$. [B]Depth from top of ridge, approximately 100 mm above pre-plant soil surface. [C]s.e.d. for lime x depth.

Table 4. Effects of banded P (kg ha^{-1}) and Cd (g ha^{-1})

P	0	60	120	240	120[A]	240[A]	
Cd (CD2)	0	3.4	6.8	13.7			
Cd (CD3)	0	5.3	10.5	21.1	64	127	
Cd (CD6)	0	5.3	10.5	21.1			
Site				*Processing yield (t ha^{-1})*			s.e.d.
CD2	47.0	55.4	61.4	66.0			3.74
CD3	48.9	62.4	68.5	66.5	63.2	69.9	5.01
CD6	48.0	52.1	52.6	53.0			1.66
				Tuber Cd (mg kg^{-1})			
CD2	0.064	0.114	0.126	0.148			0.0075
CD3	0.055	0.081	0.083	0.109	0.102	0.122	0.0124
CD6	0.088	0.108	0.124	0.136			0.0132
				Petiole Cd (mg kg^{-1})			
CD2	1.83	1.95	2.22	2.25			NS
CD3	2.30	2.35	2.33	2.20	2.58	2.87	0.191
CD6	1.40	1.87	1.95	2.09			0.176
				EDTA-extractable Cd (mg kg^{-1}; 150-300mm)			
CD3	0.18	0.18	0.21	0.22	0.22	0.44	0.033

[A]DSP with 90 mg Cd kg^{-1}.

EDTA-extractable Cd in the surface soil decreased with increasing rate of lime at all sites (Table 3), but as expected there was no effect of P fertiliser at this depth (data not shown). In the subsoil at CD3, there was a trend to increasing EDTA-extractable Cd with rate of P fertiliser, but the effects were slight except at 240 kg P ha^{-1} of the high-Cd DSP (Table 4). Subsoil concentrations were less than those in the surface (Table 3).

Common scab (*Streptomyces scabies*) was not observed at any of the sites.

CD7

Banded lime had no significant effect on yield (P=0.09) or tuber Cd (P=0.26) (Table 5). The data were more variable than for the CD6 broadcast lime trial in the same paddock. Soil pH in the zone of lime and fertiliser placement increased with rate of banded lime, as did petiole Cd (Tables 5 and 6). Because the pH relationship reported is for the 150-300 mm depth, it seems probable that the effect of the lime immediately around the fertiliser band was even greater.

Table 5. Effect of banded lime (t ha^{-1}) at CD7

Banded lime	0	0.750	1.45	2.90	s.e.d.
Processing yield (t ha^{-1})	45.5	49.5	53.5	48.6	NS
Tuber Cd (mg kg^{-1})	0.16	0.13	0.11	0.17	NS
Petiole Cd (mg kg^{-1})	1.55	1.87	2.01	2.35	0.344
pH 150-300mm (1:5 H_2O)	5.5	5.6	5.8	6.1	0.22

3 (b) v Discussion

The failure of lime to decrease tuber Cd (Table 3) is disappointing, because liming was seen as a potentially effective measure which could be readily adopted. Studies with synthetic goethite in suspension have shown increased specific adsorption of Cd^{2+} as suspension pH increased from 5-8 (Forbes *et al.* 1976, Bruemmer *et al.* 1988). The mechanism is one where the Cd ion (Cd^{2+}) or hydroxy ion ($CdOH^{+}$) exchanges with protons on the oxide surface.

That there was no decrease in tuber Cd with lime at CD2, CD3, and CD6 might be attributed to a lack of influence of broadcast lime on the availability of Cd from the fertiliser band, but the result at CD7 (Table 5) suggests that mixing lime with the banded fertiliser will not help. The lack of lime by P interactions in these trials suggests that as well as not influencing Cd availability from the fertiliser band, lime had no influence on the availability of Cd in the soil. This may be because the krasnozems on which these trials were conducted are already restricting the availability of Cd in the soil through their high organic matter (Table 2) and iron oxide (Graley and Loveday, 1961) content. Tiller *et al.* (1984) concluded that organic matter and iron oxides can both adsorb Cd strongly; organic matter has greater affinity for Cd at pHs less than 6, and iron oxides more at pHs above 6.

The response to lime may depend on the amount of cadmium in the soil as well as the range of soil pH under study. Therefore soils with an initial pH of 5.5 and with higher concentrations of soil solution Cd than may have been the case in our study, may show some effect of lime. However, such soils would need to have had a history of heavy Cd addition in P fertiliser, and there are few heavily fertilised krasnozems in Tasmania with pH less than 6 because of the need to cater for acid-sensitive species such as onions and poppies (*Papaver somniferum*) in rotations. In any case, the observation by Bruemmer *et al.* (1988) that the relative adsorption of Cd decreases with increasing initial Cd concentration would argue against this scenario.

Soil pH measurements at CD3 indicated that our liming treatments, as expected, were more effective in the ridges than below (Table 3). EDTA Cd concentrations at 150-300 mm at CD3 (Table 3) were affected by the presence of the fertiliser at about 200 mm, and by the fact that soil below the depth of lime incorporation was not encountered until about 250 mm below the top of the ridge, yet they still showed a decrease from the concentrations in the top 150 mm of the ridge (Table 3). This suggests that the Cd added previously to this site in P fertiliser has remained near the surface, consistent with the finding of Williams and David (1976) for a Victorian krasnozem. Therefore, we do not expect that our tuber Cd results would have changed much had we limed the subsoil more effectively. We grew other crops at these sites to see if any further downward movement of lime altered its effectiveness (section 3(f)).

We did not measure soil pH in the period between lime application and early tuber growth (5-10 mm tubers, 7 weeks after planting). It is possible that lime was still equilibrating with the soil during this period, especially at CD2 and CD3 where the lime was applied only 4 and 6 weeks before planting respectively. Scott *et al.* (1992) showed that incorporated lime had almost fully reacted in 6 months, but earlier assessments were not made. The influence on tuber Cd of continued reaction of lime during early growth is likely to have been small because tubers were absent or only small. The crop canopy at this time was also small, having just closed within the rows, so the potential for gross effects of Cd retranslocation to tubers was low. The fact that soil pH measured in the following year at CD2 and CD3 showed inconsistent changes of only 0.1-0.3 units reassures us that pH changes after early tuber growth were minimal.

Our lime treatments produced a range of surface soil pH (pH 5.2-7.1) associated with potato production on krasnozems in many parts of Australia. More research is needed to confirm the apparent non-response of tuber Cd to increasing soil pH in krasnozems over the range pH 6.5 to 7.0, and to extend this range further. To lime to even higher pH is not only expensive but risky because of the possibility of induced deficiencies of trace elements such as boron (Pregno and Armour, 1992) and zinc, and of the increased incidence of common scab (Huber 1990). These possible side effects also need assessment. Research is also needed on krasnozems from northern Australia, which have less organic matter than those in Tasmania (Moody *et al.* 1990).

Even with P fertiliser relatively low in Cd, the addition of 240 kg P ha^{-1} in these trials still approximately doubled tuber Cd concentrations (Table 4). The increases in tuber Cd concentrations from addition of 240 kg P ha^{-1}, calculated from relevant regression equations, are less than those found previously (Sparrow *et al.* 1992) when TSP containing 151 mg Cd kg^{-1} was used (Table 6). This observation suggests an influence of fertiliser Cd concentration, but the fact that the 2 sets of data were obtained at different sites in different seasons using different P fertilisers, and also that fertiliser Cd concentration at CD3 had little effect, indicates that this subject needs further study. The following paper describes such a study.

Table 6. Regression equations

Site	Equation	F-prob	R^2	dCd^A
	Tuber Cd (mg kg^{-1}) and P rate (kg ha^{-1})			
CD2	$TuberCd=0.06728+0.000746Prate-0.0000017Prate^2$	<0.001	0.43	0.08
$CD3^B$	$TuberCd=0.06017+0.0002067Prate$	0.001	0.46	0.05
CD6	$TuberCd=0.09375+0.000192Prate$	0.005	0.23	0.05
A*	$TuberCd=0.07418+0.000704Prate$	<0.001	0.75	0.17
C*	$TuberCd=0.20232+0.00116Prate-0.00000224Prate^2$	<0.001	0.80	0.15
	pH (150-300mm) and petiole Cd (mg kg^{-1}) vs banded lime (t ha^{-1})			
CD7	$pH=5.443+0.23611Lime$	0.011	0.40	
	$PetioleCd=1.588+0.273Lime$	0.046	0.34	

[A]Tuber Cd(Prate=240)-Tuber Cd(Prate=0) in mg Cd kg^{-1}.
[B]Using low Cd DSP only.
*from Sparrow *et al.* (1992).

Tuber dry matter contents in our studies varied from 18-23% (Sparrow *et al.* 1992 and unpublished data). Assuming an average dry matter of 20%, the current MPC for potatoes in Australia of 0.05 mg Cd kg fresh wt^{-1} would equate to 0.25 mg Cd kg dry wt^{-1}. Despite the consistent influence of rate of P fertiliser on tuber Cd in this and the previous study (Sparrow *et al.* 1992), at only 1 site did P fertiliser cause tuber Cd concentrations in Russet Burbank to exceed 0.25 mg Cd kg^{-1}. This finding is in line with surveys of commercial Tasmanian Russet Burbank crops which show a violation rate of 10-15%, with almost all violations less than twice the MPC (section 3(a)).

3(b) vi Acknowledgements

This work was supported by funds from Edgell-Birdseye potato growers, Edgell-Birdseye Pty Ltd, Pasminco-EZ, Tasmanian Alkaloids Pty Ltd, Glaxo Pty Ltd, Beams Brothers Lime, and the Horticultural Research and Development Corporation. We would like to thank the staff of the

Department of Primary Industry and Fisheries who helped with the conduct of the trials and who analysed the soils, Bruce Cullen for the cadmium analyses, Pasminco-EZ for supplying the fertiliser, Beams Brothers Lime for supplying the lime and Don Stephenson for allowing us to use his farm.

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3(c) Field studies of cadmium in potatoes (*Solanum tuberosum* L.) II. Response of cv. Russet Burbank and Kennebec to two double superphosphates of different cadmium concentration.

3(c) i Summary

Separate field experiments were conducted with Russet Burbank and Kennebec potatoes on a basaltic krasnozem where tuber cadmium (Cd) responses were examined over 3 rates of banded phosphorus (P), supplied as double superphosphate (DSP) containing either 15 or 90 mg Cd kg^{-1}. In both cultivars tuber Cd concentrations increased with rate of DSP. This response was due more to the amount of P supplied in the DSP than the amount of Cd supplied in the DSP and may be a result of banded P encouraging root proliferation in the fertiliser band. Even with DSP at 15 mg Cd kg^{-1}, Cd additions at rates of DSP needed for high yields were 6-20 times higher than corresponding rates of Cd removal in tubers. Examination of data from all studies of Cd in Russet Burbank on Tasmanian krasnozems showed a significant relationship between petiole and tuber Cd concentrations, but the estimation of a petiole concentration associated with the critical tuber Cd concentration in Australia was subject to unacceptable uncertainty due to variation between sites.

3(c) ii Introduction

Concern about cadmium (Cd) in potatoes has prompted studies of the response of tuber cadmium to rate of phosphorus (P) fertiliser and to liming (Sparrow *et al.* 1992, 1993). However, the minimal tuber Cd decreases we found with liming, and the fact that most potatoes grown in the basaltic krasnozems where these studies were conducted still need more than 150 kg ha^{-1} of banded phosphorus for optimum economic yield (Sparrow *et al.* 1992), show a need for other remedial measures to be investigated.

It may be possible to achieve some reduction in tuber Cd concentrations by decreasing the concentration of cadmium in the P fertiliser. The fertiliser industry in Australia has already reacted to this issue by supplying fertilisers to the potato industry which are considerably lower in cadmium than they were in the 1980s. The commercial triple superphosphate (TSP) used in 1989 by Sparrow *et al.* (1992) contained 151 mg Cd kg^{-1}, and the Cd content of other concentrated P fertilisers available in Australia in the past has been of the order of 60-100 mg Cd kg^{-1} (Cook and Freney 1988). In contrast, TSP available now and used by Sparrow *et al.* (1993) contained 12 mg Cd kg^{-1}.

Evidence of decreased plant Cd concentrations when fertiliser containing lower Cd concentrations was used has been published by Reuss *et al.* (1978), who showed linear relationships between Cd applied in P fertiliser and Cd in radishes, lettuce and peas grown in pots. Mortvedt *et al.* (1981) showed a similar trend in wheat in an acid soil, but the increase in grain Cd was only statistically significant when Cd in diammonium phosphate was increased from 74 to 153 mg Cd kg^{-1}, and not when it was increased from 2 to 74 mg Cd kg^{-1}. Jaakkola (1977), also working with wheat in the field, found no difference between the grain Cd of plants supplied either 2 or 49 g Cd ha^{-1} in P fertiliser.

At one site in the previous study (Sparrow *et al.* 1993), there was little change in tuber Cd with a lower fertiliser Cd concentration in double superphosphate (DSP), although the response of tuber Cd to rate of P fertiliser in that study was generally less than in an earlier study where TSP with 151 mg Cd kg^{-1} was used (Sparrow *et al.* 1992). We wanted to extend our investigations over a wider range of P rates, in order to try and separate the effects of fertiliser P rate and fertiliser Cd rate, because both may be influencing Cd uptake. Williams and David (1977), working with subterranean clover in a P responsive soil in pot culture, showed that monocalcium phosphate banded with $CdCl_2$ enhanced Cd uptake more than when both were dispersed through the soil, an effect they attributed to the stimulation by P of root growth in the band. Neither Jaakkola (1977), Reuss *et al.* (1978) or Mortvedt *et al.* (1981) used a range of P rates in their studies.

Cultivar selection also offers potential to decrease tuber Cd concentrations. Studies with lettuce have shown marked differences in the Cd uptake of different cultivars (e.g. Xue and Harrison 1991). Unpublished data from potato cultivar trials in Australia have also indicated a wide variation in Cd uptake (M.J. McLaughlin, pers. comm.).

This paper reports on field experiments where Russet Burbank and Kennebec, 2 important cultivars in southern Australia, were grown at a range of rates of P. Two double superphosphates (DSP) with different cadmium contents were used.

3(c) iii Materials and Methods

The site was at Forthside Vegetable Research Station (FVRS, 41° 12'S, 146° 15'E), near Devonport, Tasmania. Two trials were situated immediately adjacent to the area used by Sparrow *et al.* (1993) for the CD2 lime by P trial. The soil characteristics for the CD2 site given in Table 2 apply also to the current site.

Experimental design

For logistical reasons, a separate trial was conducted for each cultivar. Both trials were split-plot designs, with fertiliser type as main plots (DSP with either 15 or 90 mg Cd kg^{-1}). Main plots were split for rates of banded P (60, 120 or 240 kg P ha^{-1}). Sub-plots were 4 rows by 12 m. There were 3 replicates. We did not include a zero P treatment because we wanted to maximise the number of fertiliser type comparisons in the space available.

Trial establishment

The trials were planted (25/10/90), maintained and harvested, and samples analysed as described in Sparrow *et al.* (1993), except that plant spacing for Kennebec was 185 mm, no soil samples were taken during the season, and the middle 6 m of the 2 centre rows was harvested.

Statistical analysis

Analyses of variance and simple and multiple linear regression were performed by GENSTAT (GENSTAT 5 Committee 1987). Standard errors of differences (s.e.d.) are reported where F-tests from analyses of variance were significant ($P<0.05$). The merit of individual variables in multiple regressions was assessed by t-tests of regression coefficients and by consideration of the amount of variation explained by their inclusion in the model. Because separate trials were conducted for each cultivar, comparisons of the cultivars were not assessed statistically.

3(c) iv Results

For both cultivars the mean yield increased with rate of phosphorus, but the trend was not significant for Russet Burbank (Tables 7 and 8). Petiole P concentrations also increased with rate of P (Table 7). Fertiliser type had no effect on either the yield or petiole P concentrations of either cultivar (Table 7).

Tuber Cd concentrations in both Kennebec and Russet Burbank increased ($P=0.003$ and $P<0.001$ respectively) with increasing P fertiliser rate (Tables 7 and 8). Regression analysis to apportion this response between effects of fertiliser P rate and fertiliser Cd showed that fertiliser P rate was a greater influence for both cultivars (Table 8). On its own, fertiliser P rate explained more of the variation in tuber Cd than did fertiliser Cd on its own, and when the 2 were combined there was little improvement over the models containing only fertiliser P rate (Table 8). Mean tuber Cd concentrations in Kennebec ranged from 0.20-0.34 mg kg^{-1}, and in Russet Burbank from 0.11-0.20 mg kg^{-1} (dry wt basis) (Table 7).

There was no effect of either P rate or fertiliser type on petiole Cd concentrations in either cultivar (Table 7).

Cadmium uptake was calculated from tuber Cd and total tuber yield, and reflected the great influence of P rate on these variables (Table 8). Mean uptake ranged from 1.22 to 2.42 g Cd ha^{-1} in Kennebec, and from 0.65 to 1.23 g Cd ha^{-1} in Russet Burbank (Table 7).

Table 7. Treatment means

Phosphorus rate (kg ha^{-1})	60		120		240		s.e.d.		
Fertiliser type	low	high	low	high	low	high	Prate	Type	PxT
Fertiliser Cd (g ha^{-1})	5.3	32	10.5	64	21	127			
Kennebec									
Processing yield (t ha^{-1})	53.0	57.3	63.7	66.5	64.4	68.4	2.04	NS[A]	NS
Petiole P (mg kg^{-1})	0.39	0.37	0.43	0.45	0.53	0.49	0.017	NS	NS
Tuber Cd (mg kg^{-1})	0.22	0.20	0.25	0.27	0.29	0.34	0.015	NS	NS
Petiole Cd (mg kg^{-1})	2.74	2.62	2.77	2.65	2.47	2.78	NS	NS	0.113
Cd uptake (g ha^{-1})	1.28	1.22	1.61	1.86	1.96	2.42	0.091	NS	NS
Russet Burbank									
Processing yield (t ha^{-1})	49.5	48.5	54.8	48.9	56.3	51.9	NS	NS	NS
Petiole P (mg kg^{-1})	0.27	0.26	0.34	0.30	0.41	0.39	0.020	NS	NS
Tuber Cd (mg kg^{-1})	0.13	0.11	0.15	0.18	0.19	0.20	0.009	NS	NS
Petiole Cd (mg kg^{-1})	2.80	3.12	2.92	3.64	2.88	3.48	NS	NS	NS
Cd uptake (g ha^{-1})	0.78	0.65	0.99	1.02	1.21	1.23	0.052	NS	NS

[A]NS=not significant, $P > 0.05$.

Table 8. Regression equations

		Fprob	R^2
	Kennebec		
Tuber Cd	Y=0.1825+0.00055Prate[A]	<0.001	0.62
	Y=0.2243+0.000813FertCd[B]	0.003	0.42
	Y=0.1824+0.000428Prate+0.000394FertCd	<0.001	0.69
Processing yield	Y=54.5+0.0552Prate	0.025	0.28
Petiole Cd	NS[C]		
Cd uptake	Y=1.025+0.005Prate	<0.001	0.68
	Russet Burbank		
Tuber Cd	Y=0.1100+0.0003571Prate	<0.001	0.58
	Y=0.1413+0.000433FertCd	0.028	0.27
	Y=0.1100+0.0003202Prate+0.00012FertCd	0.001	0.59
Processing yield	NS		
Petiole Cd	NS		
Cd uptake	Y=0.6073+0.00267Prate	<0.001	0.83

[A]kg P ha^{-1}. [B]g Cd ha^{-1}. [C]NS=no significant relationships.

3(c) vi Discussion

For both high- and low-Cd fertilisers used in this and previous studies (Sparrow *et al.* 1992, 1993), there has been a consistent effect of rate of banded P on tuber Cd. The results of this study suggest that on our sites the response of tuber Cd depended more on the amount of P than on the amount of Cd added in the fertiliser (Table 8). Greater root proliferation in the fertiliser band with increasing rate of P (Williams and David 1977; Marschner, 1986) on the P responsive sites we used may have been a factor. Root density was not measured.

The minor effect of fertiliser Cd on tuber Cd in these experiments is consistent with observations made at site CD3 in the previous paper (Sparrow *et al.* 1993), and is indicative of the low Cd uptake by potatoes relative to the amount of Cd applied in fertilisers in these experiments. The maximum calculated recovery of fertiliser Cd in tubers was 4.3% for Kennebec grown with the low Cd DSP (Table 9). No similar published data for potatoes is available, but Jaakkola (1977) and Mortvedt *et al.* (1981) reported recoveries by wheat of 0.1% and 0.5% respectively, the latter being cumulative recovery over 2 crops. The Cd added in fertiliser to give these recoveries was 49 and 74 g Cd ha^{-1}, respectively. Method of fertiliser application and species differences could account for the apparent higher recoveries of potatoes compared with wheat.

Table 9. Tuber Cd uptake in relation to Cd applied in fertiliser (g Cd ha^{-1})

	Kennebec		Russet Burbank	
	low Cd DSP	high Cd DSP	low Cd DSP	high Cd DSP
Cd_{upt}^{A}	0.68	1.20	0.43	0.58
Cd_{app}^{B}	16	95	16	95
% recovery	4.3	1.3	2.7	0.6

A (uptake at 240 kg P ha^{-1}) - (uptake at 60 kg P ha^{-1})
B (applied Cd at 240 kg P ha^{-1}) - (applied Cd at 60 kg P ha^{-1})

Fertiliser Cd concentrations may have to come down by another order of magnitude before a consistent and practical decrease in tuber Cd is gained when potatoes are grown with banded fertiliser. This is especially important for Russet Burbank, which generally needs at least 150 kg P ha^{-1} for optimum yield on krasnozems (Sparrow *et al.* 1992) and so offers less potential for decreased P application rates than Kennebec, which has a lower P requirement (P. Regel pers. comm.) Regardless of any lack of immediate decrease in tuber Cd, the use of low Cd P fertilisers in Tasmania has at least cut additions of Cd to soil considerably compared with the higher Cd fertilisers used previously. So far, no premium price has been demanded for low Cd fertilisers which might discourage their use.

The effect of P fertiliser rate on petiole Cd in both this and the previous study (Sparrow *et al.* 1993) has been minimal compared to its effect on tuber Cd, a result consistent with the findings of Sparrow *et al.* (1992). However, a pooling of data for Russet Burbank from all of these studies produced a significant relationship between petiole and tuber Cd (Fig 1). The relationship relies on data only from site C in Sparrow *et al.* (1992) for points above 4 mg petiole Cd kg^{-1}, and predicts a 95% confidence interval for 0.25 mg tuber Cd kg^{-1} of 3.0-5.0 mg petiole Cd kg^{-1}. This concentration of tuber Cd corresponds approximately to the dry weight equivalent of the National Health and Medical Research Council (NH&MRC) maximum permitted concentration (MPC) for food as consumed (NH&MRC 1988). More data is needed, especially in the upper range of petiole Cd, if petiole Cd is to be used to identify potentially violative Russet Burbank crops. The inclusion of site in the model explained a further 29% of the variation (equation not shown), suggesting that site characteristics, together with petiole Cd, would provide better tuber Cd predictions than would petiole Cd alone. Surface soil pH would not appear to be a critical site characteristic (Sparrow *et al.* 1993).

The relative behaviour of the 2 cultivars used cannot be assessed statistically, but the large difference in tuber Cd is noteworthy (Table 7). In surveys of commercial potato crops in northern Tasmania we have measured higher average tuber Cd concentrations in Kennebec (0.24 mg Cd kg^{-1}, n=15) compared with Russet Burbank (0.15 mg Cd kg^{-1}, n=69). Kennebec, a determinate cultivar, may have a more shallow rooting habit and so feed more from the fertiliser band than the indeterminate Russet Burbank, but we have no data to support this. Variation in Cd uptake between cultivars and breeding lines deserves further attention as part of breeding programs. The apparent higher petiole Cd in Kennebec compared with Russet Burbank (Table 7), together with the finding that these 2 cultivars have different critical petiole potassium concentrations (Chapman *et al.* 1992), suggests that relationships between petiole and tuber Cd concentrations will vary with cultivar.

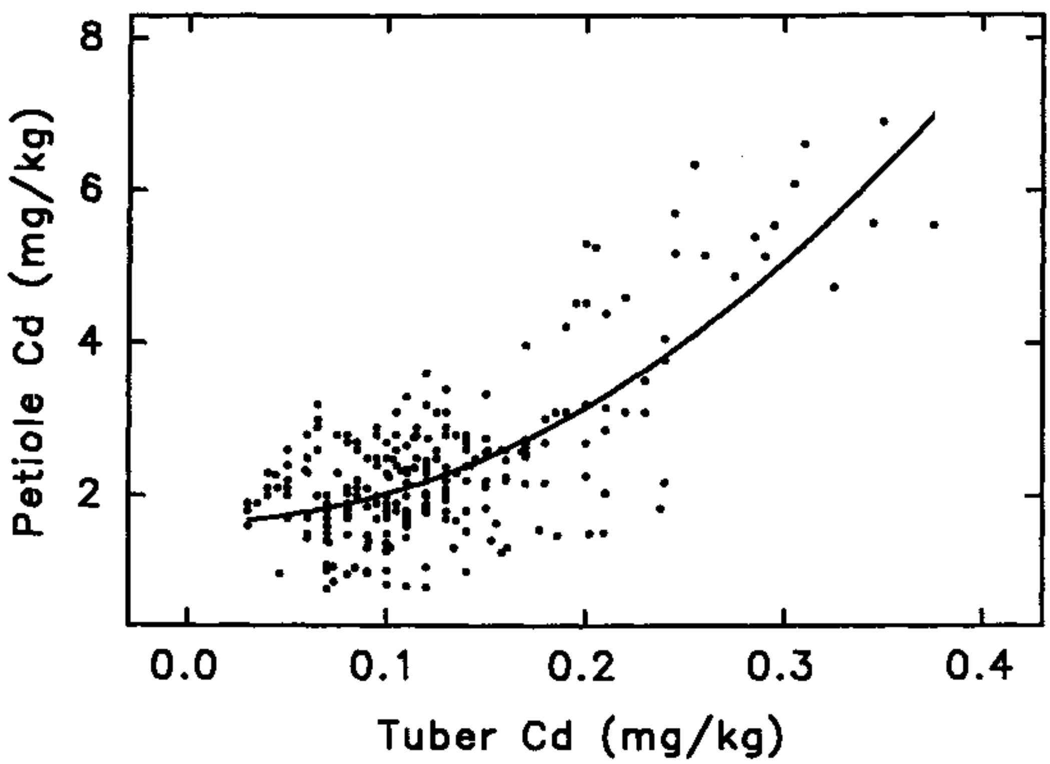

Fig 1. Petiole vs tuber Cd for Russet Burbank trials on Tasmanian krasnozems. Regression equation is: Petiole Cd = 1.6551+37.62tuberCd^2, $P<0.001$, $R^2=0.57$, n=262.

3(c) vii Acknowledgements

This work was supported by funds from Edgell-Birdseye potato growers, Edgell-Birdseye Pty Ltd, Pasminco-EZ, Tasmanian Alkaloids Pty Ltd, Glaxo Pty Ltd, Beams Brothers Lime, and the Horticultural Research and Development Corporation. We would like to thank the staff of the Department of Primary Industry and Fisheries who helped with the conduct of the trials and who analysed the soils, Bruce Cullen for the cadmium analyses, and Pasminco-EZ for supplying the fertilisers. Special thanks go to Dr D Ratkowsky and Mr R Corkrey for help with the statistical analyses and their reporting.

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3(d) Field Studies of Cadmium in Potatoes (*Solanum tuberosum* L.). III. Response of cv. Russet Burbank to sources of banded potassium.

3(d) i Summary

Six field experiments were conducted where Russet Burbank potatoes were grown with banded fertilizer consisting of diammonium phosphate (DAP) and either potassium sulphate (K_2SO_4) or potassium chloride (KCl). At each site, rates of nitrogen (N), phosphorus (P) and potassium (K) were matched as closely as possible for each K fertilizer treatment. At four of the six sites, potatoes grown with K_2SO_4 had tuber and petiole cadmium (Cd) concentrations 20-30% lower than did potatoes grown with KCl. The use of K_2SO_4 instead of KCl appears to offer considerable promise as a means of decreasing tuber Cd uptake. Sulphate ions presumably promote increased soil adsorption of soil and/or fertilizer Cd compared with chloride ions, and so decrease Cd availability. We attributed the lack of difference in tuber and petiole Cd between K sources at two sites to either leaching, chloride in irrigation water, or at one site to a higher than desired rate of NPK fertilizer with the sulphate treatment. Any one of these may have offset decreases in Cd uptake due to the presence of sulphate ions.

3(d) ii Introduction

Potato growers in Australia are seeking management practices which will decrease the uptake of Cd by their crops (Sparrow *et al.* 1993*a*). Previous studies of Cd in potatoes have shown that neither liming nor decreased fertilizer Cd concentrations resulted in decreased tuber Cd concentrations in the short term (Sparrow *et al.* 1993*a*,1993*b*). Other short-term options are needed.

In many parts of Australia, including Tasmania, KCl is the source of fertilizer K for potatoes, but in South Australia growers prefer K_2SO_4 (Maier 1986). Source of fertilizer K could influence tuber Cd concentrations because high rates of fertilizer K are generally applied to potatoes (Maier 1986; Chapman *et al.* 1992), and because SO_4-ions have been shown to promote stronger Cd sorption by soil than have Cl-ions (O'Connor *et al.* 1984). Furthermore, Salardini *et al.* (1993) showed in pot culture that poppies (*Papaver somniferum*) had higher seed Cd when fertilised with KCl compared with K_2SO_4 under non-leaching conditions, but that the reverse happened with plants grown under leaching conditions. Thus, rainfall and irrigation management may interact with K source to influence Cd uptake.

In this study, six field trials were conducted with cv. Russet Burbank. Banded KCl and banded K_2SO_4 were compared for their effects on tuber and petiole Cd concentrations and on yield and tuber dry matter.

Table 10. Site details and selected surface soil (0-150 mm) characteristics

Site	Lat/Long	Soil type[A]	pH ($1:5\ H_2O$)	Extractable[B] P (mg kg^{-1})	Extractable[B] K (mg kg^{-1})	Organic Carbon (%)	Sand:silt:clay	EDTA-Cd[C] (mg kg^{-1})
1.	41°45'S 147°10'E	Orthic Tenosol	5.8	67	445	1.4	78:5:17	0.13
2.	41°35'S 147°13'E	Brown Sodosol	5.1	55	240	4.1	66:17:17	0.10
3.	41°15'S 146°31'E	Red Ferrosol	6.6	220	369	4.7	30:20:50	0.43
4.	41°13'S 146°14'E	Red Ferrosol	6.4	115	220	3.8	22:21:57	0.48
5.	41°13'S 146°27'E	Red Ferrosol	6.2	83	75	5.3	22:29:49	0.38
6.	41°30'S 146°40'E	Red Ferrosol	6.5	144	451	7.8	34:39:27	0.45

[A]Isbell (1992). [B]Colwell (1963). [C]after Clayton and Tiller (1979) but with 48 h shake.

Table 11. Some trial details

Site	Planting date	Tuber length at petiole sampling (mm)	Harvest date	N-P-K (kg ha^{-1}) applied with each K source	
				Potassium chloride[A]	Potassium sulphate[B]
1.	30 October 1992	15-20	1 April 1993	151-167-279	159-176-274
2.	1 December 1992	5-10	16 April 1993	119-133-221	126-140-218
3.	2 December 1992	5-10	2 April 1993	186-207-346	199-221-345
4.	2 December 1992	5-10	16 April 1993	212-236-197	218-241-201
5.	22 October 1992	30-40	2 April 1993	160-177-296	184-204-318
6.	22 October 1992	20-25	1 April 1993	175-194-162	209-232-193

[A]Fertilizer mix was 3:2 DAP:KCl for sites 1,2,3 and 5, and 3:1 DAP:KCl for sites 4 and 6.

[B]Fertilizer mix was 4:3 DAP:K_2SO_4 for sites 1,2,3 and 5, and 5:2 DAP:K_2SO_4 for sites 4 and 6.

3(d) iii Materials and Methods

The sites were in commercial potato crops in northern Tasmania (Table 10). Fertilizers were mixtures of commercial grade DAP (18% N, 20% P, 12 mg Cd kg^{-1}) with either commercial grade KCl (50% K, <0.1 mg Cd kg^{-1}) or commercial grade K_2SO_4 (41.5% K, <0.1 mg Cd kg^{-1}) in ratios which gave N-P-K concentrations in the final product which closely approximated the "11-12-19" and "14-16-11" commonly used in potato production in Tasmania (Table 11).

The experimental design was a randomized block with four replicates. Plot size was 20-40 m, depending on the site, by 4 rows. Trials were planted using the growers' or contractors' planters under commercial conditions. Fertilizer was weighed before and after planting to enable application rates to be calculated. After planting, all irrigation and pest and disease management were by the growers. Petioles of the youngest fully expanded leaves were sampled (30 per plot) at the stages shown in Table 11, which also shows the times of planting and harvest. Tubers from the middle 10 m of the two centre rows of each plot were harvested when the haulms had died, and were graded into processing (>100 g) and non-processing tubers. At sites 2, 4, 5 and 6 a sample of ten processing tubers was taken from each plot for Cd analysis. At sites 1 and 3, tubers for Cd analysis were sampled before harvest. Ten tubers were taken from the upper 75 mm of the ridges of the two centre rows of each plot, and a matching 10 tuber sample was taken near the fertilizer band, about 200 mm below the ridge top. Methods for petiole and tuber analysis have been described previously (Sparrow *et al.* 1992, 1993*a*). All Cd concentrations are expressed on a dry matter basis.

Results were subjected to analysis of variance, using Genstat 5 (Genstat 5 Committee 1987), and a 5% or lower *F*-test probability was taken to be evidence of a significant treatment effect.

3(d) iv Results

At four of the six sites, mean tuber and petiole Cd concentrations were significantly less with K_2SO_4 compared with KCl (Fig. 2). Decreases with K_2SO_4 occurred on both light-textured (site 1) and heavy-textured soils (sites 3, 4 and 5). They were also observed when the level of tuber Cd was relatively low (sites 3 and 4), and when it was relatively high (sites 1 and 5) (Fig. 2a). The highest tuber Cd was found at site 5, the site with the lowest extractable K (Table 10). The position of the tubers in the ridge influenced neither the relativity between K sources nor the absolute tuber Cd levels at the two sites at which it was a variable. At site 1 the mean tuber Cd concentrations for upper and lower positions were 0.184 and 0.180 mg kg^{-1} respectively. At site 3 the values were 0.081 and 0.083 mg Cd kg^{-1} respectively.

Source of potassium had a significant effect ($P<0.05$) on yield only at site 6, where K_2SO_4 gave a higher processing yield (Fig. 3). At site 6 and site 5 the application of the K_2SO_4

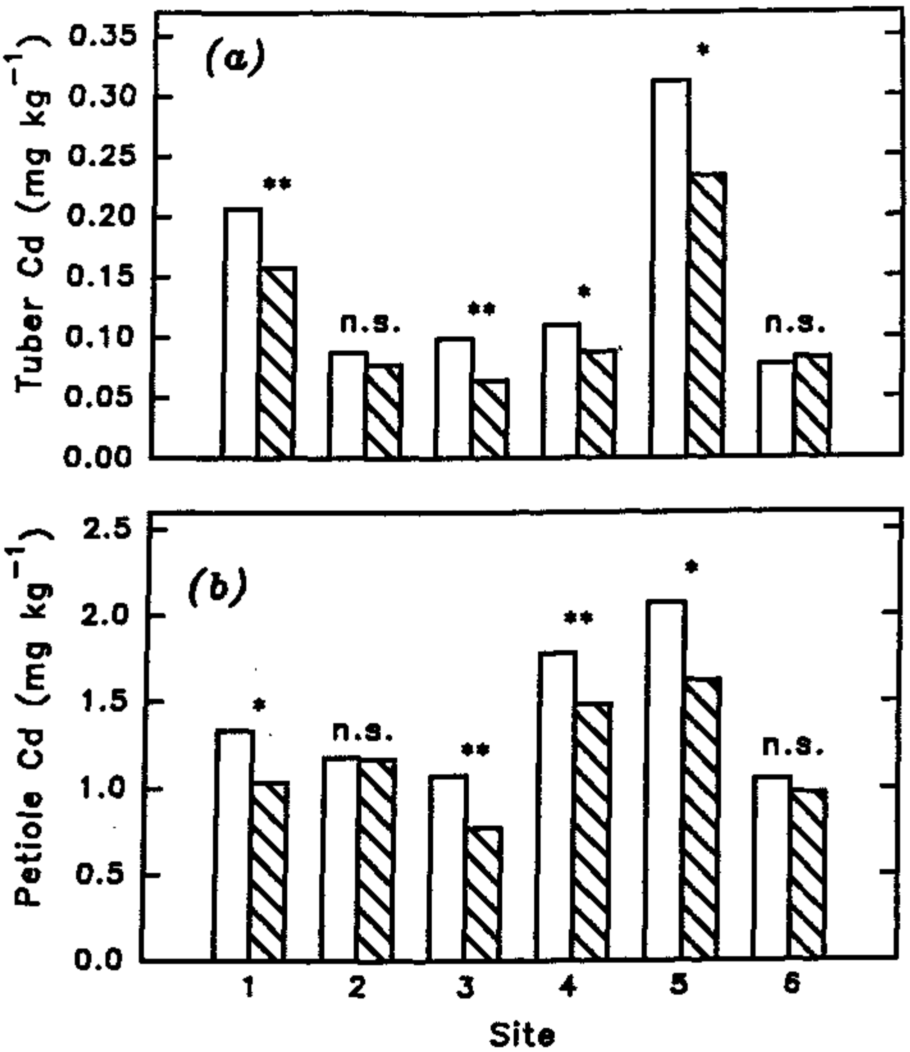

Fig 2. Effect of KCl (plain bars) v. K_2SO_4 (hatched bars) on (a) tuber Cd and (b) petiole Cd (n.s. = $P > 0.05$, $*P < 0.05$, $**P < 0.01$).

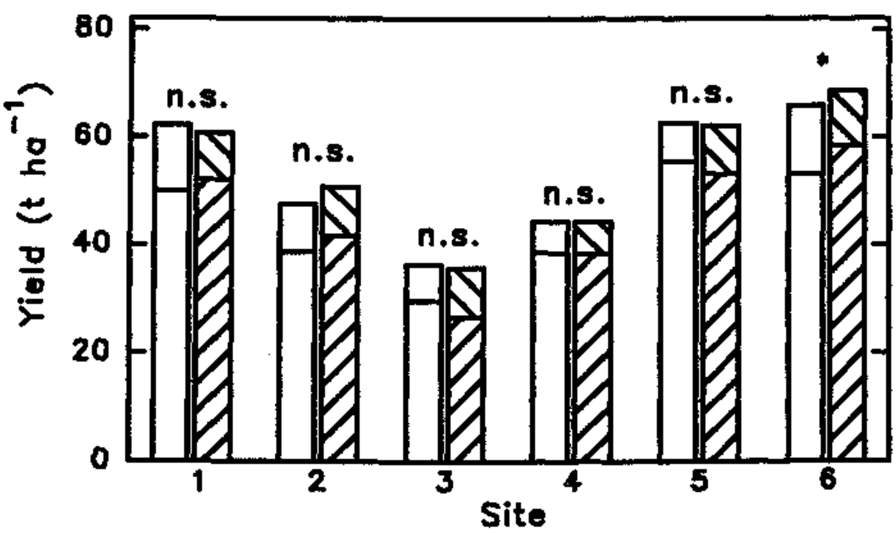

Fig 3. Effect of KCl (plain bars) v. K_2SO_4 (hatched bars) on processing (lower bars) and total (upper bars) tuber yield (n.s. = $P > 0.05$, $*P < 0.05$ for processing yield only).

mix was at a rate higher than desired, resulting in NPK rates 15-20% greater than in the KCl treatment (Table 11). At sites 1-4, rates of NPK for the K_2SO_4 treatment were within 7% of the corresponding KCl treatment (Table 11). At sites 2, 4, 5 and 6, K source had no significant effect on tuber dry matter (Table 12). Dry matter was not measured at sites 1 and 3.

Table 12. Effect of K source on tuber dry matter (%)

Site	K source		s.e.d[A]
	Chloride	Sulphate	
2.	15.3	17.6	1.00
4.	16.8	17.3	0.29
5.	18.7	19.7	0.58
6.	18.8	18.7	0.20

[A]standard error of difference.

3(d) v Discussion

This study has shown that the use of K_2SO_4 instead of KCl in potato fertilizer is a promising alternative for growers wishing to take steps to immediately lower the Cd concentration in their potato crops. Decreases were observed on both of the main potato soils in Tasmania, and K_2SO_4 was effective where tuber concentrations with KCl were both relatively high and relatively low (Fig. 2a). Decreases were also found where the rate of fertilizer K was higher than that of fertilizer N and P (sites 1, 3 and 5) and where it was less (site 4) (Fig. 2a, Table 11).

At the moment a major disincentive to the use of K_2SO_4 is cost. Taking into account its cost per tonne (about twice that of KCl) and its K content (41.5% c.f. 50%), the use of K_2SO_4 instead of KCl in Tasmania's potato fertilizers (11.12.19 and 14.16.11) would add about 40% and 30% to their prices respectively. The higher cost is countered by the value of sulfur in K_2SO_4; this sulfur could be an important supplement because high analysis P fertilizers have replaced superphosphate as a P source for most Tasmanian crops and for many pastures.

There would appear to be little agronomic disadvantage to the use of K_2SO_4 instead of KCl. Working on sandy soils in South Australia, Maier (1986) showed that yields with K_2SO_4 were as high and sometimes higher than with KCl, and Maier *et al.* (1986) found little difference between the K sources in the size of tubers they produced. Maier *et al.* (1986) also found that while K_2SO_4 was less effective than KCl at reducing the susceptibility of tubers to bruising, on K-responsive soils, K_2SO_4 gave higher tuber specific gravity. On K-responsive clay loam Ferrosols in Tasmania, K_2SO_4 also tended to give higher tuber specific gravity than did KCl, but there was no other difference in tuber yield or quality (Chapman and Sparrow, unpublished data).

If K source affects tuber specific gravity on K-responsive soils then it should affect tuber dry matter in the same way because the two are closely related (Rastovski *et al.* 1981). The lack of effect of K source on tuber dry matter at sites 2 and 6 in this study (Table 12) may have been because these sites were not K-responsive (Table 10; Maier 1986; Chapman *et al.* 1992); the results at sites 4 and 5 cannot be explained in this way. Any effect of K source on tuber dry matter is important because the maximum permitted concentration (MPC) for Cd in potatoes is 0.05 mg Cd kg^{-1} of edible product (National Health and Medical Research Council 1988), which is usually taken to be the *fresh* tuber. An increase in dry matter from 20% with KCl to 21% with K_2SO_4 would mean that a 20% decrease in dry matter tuber Cd with K_2SO_4 would be only 16% when tuber Cd was expressed on a fresh weight basis. Maier *et al.* (1986) observed a 0.003-0.005 increase in tuber specific gravity with K_2SO_4 instead of KCl, which equates to a 0.6-1.0% increase in dry matter (Rastovski *et al.* 1981).

There were two sites where there was no effect of K source on either tuber or petiole Cd (Fig. 2). At site 6, the lack of difference may have been because about 20% more fertilizer N, P and K was applied with the K_2SO_4 treatment than with the KCl treatment (Table 11). The greater fertilizer addition was associated with greater processing yield (Fig. 3). Results from Sparrow *et al.* (1992) and Chapman *et al.* (1992) indicate that a yield response on this site was more likely to P than K, although responses to N and S cannot be ruled out. If tuber yield at site 6 did respond to the extra P in the sulphate treatment, it is likely that tuber Cd also increased with the extra P (Sparrow *et al.* 1992, 1993*a*, 1993*b*). Such a tuber Cd response may have been sufficient to offset any decreased Cd uptake due to the presence of sulphate instead of chloride. At site 5, where fertilizer NPK was also considerably more with the K_2SO_4 treatment than with KCl (Table 11), it is possible that the tuber Cd response to extra P fertilizer was limited by the lack of a yield response (Fig 3).

The response to sulphate is probably due to increased adsorption of Cd compared to the chloride treatment (O'Connor *et al.* 1984), although whether the source of the Cd is primarily from fertilizer or soil is not clear. If sulphate and chloride exert different effects on Cd availability to potatoes then sources of these ions other than fertilizer may be important influences on final uptake in certain situations. Additions of these ions in rainfall and irrigation water may override the effect of fertilizer in some areas. Such effects may have been responsible for the lack of tuber or petiole Cd differences between K sources at sites 2 and 6, but we have no data to confirm or refute this. Soil electrical conductivity and chloride concentrations in irrigation water in Tasmania are generally below 0.1 dS m^{-1} and 50 mg L^{-1} respectively (unpublished data), and would not be expected to be a strong influence, even in sandy soils.

Salardini *et al.* (1993) showed that leaching interacted with K source to affect Cd in poppy seed. Without leaching, poppies grown with KCl had higher seed Cd than those grown with K_2SO_4, presumably because the sulphate ions allowed more Cd to be adsorbed to the soil and less to be available to plants. However, with leaching, poppy seed grown with KCl had a lower Cd concentration than seed grown with K_2SO_4. In this case, greater removal of Cd in the leachate from the KCl-treated soil was suspected. No rainfall or irrigation records were kept for the potato trials in this study, so it is not possible to say whether leaching was a likely factor in these experiments. Further work on the effects of soil K level and leaching is planned.

3(d) vi Acknowledgments

This work was supported by funds from Edgell-Birdseye potato growers, Edgell-Birdseye Pty Ltd, Pasminco-EZ, Tasmanian Alkaloids Pty Ltd, Glaxo Pty Ltd, Beams Brothers Lime, and the Horticultural Research and Development Corporation. We would like to thank Bruce Cullen for the cadmium analyses, other staff of the DPIF for help with trials and analyses, and Pasminco-EZ for fertilizer. Dr K S R Chapman provided helpful comments on the manuscript.

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3(e) Effects of potassium and zinc fertilizers, gypsum and leaching on cadmium in the seed of poppies (*Papaver somniferum L.*).

3(e) i Summary

We examined the effects of additions of KNO_3, K_2SO_4 , KCl, $ZnSO_4$ and $ZnCl_2$ on the Cd concentration of the seed of poppies grown in pots in the presence or absence of gypsum and leaching. In the absence of leaching KCl gave the highest seed Cd concentration followed by K_2SO_4 followed by KNO_3. With leaching, KCl gave the lowest seed Cd concentration, 39% less than in the unleached KCl treatment. Application of gypsum increased seed Cd concentration irrespective of other treatments. Seed Cd concentration was decreased by $ZnSO_4$ and $ZnCl_2$ in the absence of leaching and was greater in the presence of leaching . The results suggest that the Cl-ion mobilises Cd in soil more than the SO_4-ion which in turn confers greater mobility than the NO_3-ion. In soils where leaching is not great, use of K_2SO_4, KNO_3 and/or $ZnSO_4$ may give lower Cd uptake than would use of their chloride couterparts. Conversely, in leaching environments use of KCl may help remove Cd from the root zone.

3(e) ii Introduction

Cadmium (Cd) as a contaminant in food is of increasing concern, and has been linked to Cd impurities in phosphate fertilizer (Williams and David 1976, Sparrow *et al.* 1993). Cadmium adsorption-desorption in soil and its uptake by plants are controlled by soil properties such as pH, cation exchange capacity, organic matter content and the presence of other ions including Ca and Zn (Jastrow and Koeppe 1980, Pickering 1980) and the presence of complexing ligands (O'Conner *et al.* 1984). O'Conner *et al.* (1984) using different Ca salts, showed that in the presence of Cl-ions the Cd sorption by a calcareous soil was less than in the presence of SO_4- and ClO_4-ions. The more mobile ions and complexes, such as Cd chlorocomplexes, can be removed from the root zone by leaching (Pickering 1980). Comparisons between different counter ions have not extended to include studies of plant uptake.

The objectives of this work were to examine the effect on Cd uptake of the addition of Zn and K as nitrate, sulphate or chloride salts in the presence or absence of both gypsum and leaching. Field poppy was chosen because it is an important cash crop in Tasmania and its seed is a valued edible by-product of pharmaceutical production. Poppy seed is a relatively high accumulator of Cd (Chizzola 1989).

3(e) iii Materials and Methods

A pot experiment was conducted with field poppy (*Papaver somniferum L.*) grown in 4-L pots containing 3.5 kg soil (oven dry basis). A clay loam krasnozem (red, dystrophic ferrosol; Isbell 1992), the soil type commonly used for crop production in northern Tasmania, was used. The soil had a pH (1:5 soil/water) of 6.1, bicarbonate-extractable P and K (Colwell 1963) of 124 and 462 mg kg^{-1} respectively, organic carbon of 5.5% and EDTA-extractable Cd (Clayton and Tiller 1979) of 0.50 mg kg^{-1}.

The experiment was a completely randomised 2×2×6 factorial design with two rates of gypsum, two levels of leaching and 6 Zn and K fertilisers. There were 4 replicates. All pots received 240 mg P kg^{-1} soil as double superphosphate containing 90 mg Cd kg^{-1}. Gypsum (< 0.1 mg Cd kg^{-1}) was applied at nil and 2.5 g kg^{-1} soil. The K and Zn treatments comprised 3 sources of K (KCl, KNO_3 or K_2SO_4) at 200 mg K kg^{-1} soil, 2 sources of Zn ($ZnCl_2$ or $ZnSO_4$. $7H_2O$) at 40 mg Zn kg^{-1} soil and a control with neither Zn nor K. All chemicals used in the study were analytical grade except the double superphosphate and the gypsum which were commercial grade. The chemicals were finely ground and mixed with air-dried soil prior to being placed in polythene-lined pots. Prior to sowing, the filled pots were steam pasteurised for 3 hours at 70°C. The pots were sown on 1 October 1992 and watered to 80% FC during growth until 30 days after planting, when plants were thinned to three per pot and the leaching treatment was applied. During growth the closed (unleached) pots were watered to 80% FC when they reached 50% FC. The leached pots were watered to 105% FC on the same date. At maturity, 125 days after planting, plants were cut 10 mm above the soil surface, dried at 60°C, and the dry weights of seeds, capsules and shoots were recorded. Seeds were digested, without grinding, using a HNO_3 and $HClO_4$ mixture. The concentration of Cd in plant digests and soil extracts was determined by atomic absorption spectrometry.

Actual concentrations of seed Cd are not reported because of commercial confidentiality, but the control (no added Zn or K) concentration was of the order reported by Chizzola (1989). The mean seed Cd concentration in the control was set at unity and the concentration of Cd in the other treatments was calculated relative to this concentration.

3(e) iv Results

Yields of total above ground material and capsules were only influenced by the application of K which increased them by 26 and 44% respectively, but there was no difference between the sources of K. Seed yield was not affected by any treatment and averaged 6.9 $\pm$ 1.4 g pot^{-1}.

The influence of Zn and K fertilizers on seed Cd concentration varied with leaching (Fig. 4; fertiliser by leaching interaction $P < 0.001$). In the absence of leaching, KNO_3 gave lower seed Cd than K_2SO_4, and K_2SO_4 in turn gave lower concentrations than either KCl or the control (Fig. 4). However, with leaching KCl gave a lower Cd concentration than the control or the other potassium sources (Fig. 4). Relative to controls, zinc sulphate decreased seed Cd concentration by 40% in the absence of leaching, but increased seed Cd when leaching occurred (Fig. 4). Zinc chloride followed the same trend but with smaller magnitude (Fig. 4). Leaching exerted most effect on the potassium chloride, control and zinc sulphate treatments (Fig. 4).

Gypsum increased seed Cd concentration by an average of 28% ($P<0.001$). The increase due to gypsum varied with fertiliser (Fig. 5; gypsum by fertiliser interaction $P < 0.001$), with potassium nitrate and zinc chloride showing only small, non-significant increases (Fig. 5).

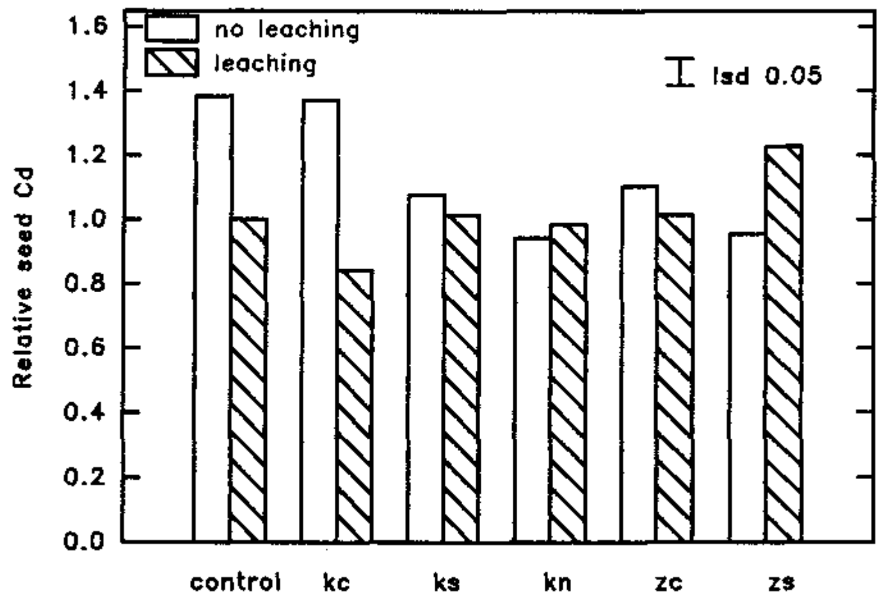

Fig 4. Effect of KCl (KC), K_2SO_4 (KS), KNO_3 (KN), $ZnCl_2$ (ZC) and $ZnSO_4$(ZS) on relative poppy seed Cd under two leaching regimes.

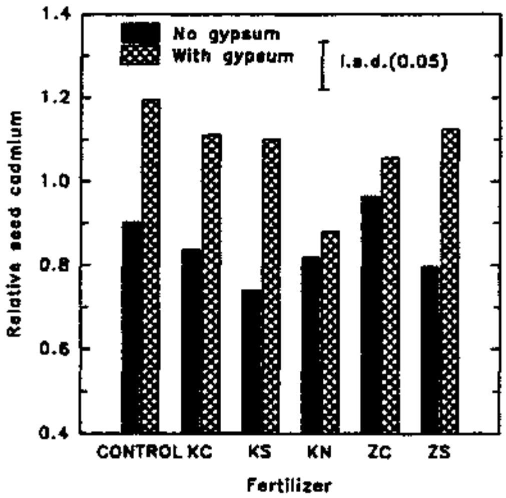

Fig 5. Effect of sources of K and Zn on relative poppy seed Cd in the presence or absence of gypsum (for legends see Fig. 4).

3(e) v Discussion

The significantly higher uptake of Cd by plants grown with KCl than K_2SO_4 in the absence of leaching (Fig. 4), agrees well with the findings of Garcia-Miragaya and Page (1976), O'Connor *et al.* (1984) and Hirsch *et al.* (1989). These authors suggested that formation of selective, strong and stable chlorocomplexes with Cd was the cause of reduced adsorption of Cd by the solid components of soil and of an increased Cd concentration in the soil solution. Higher uptake of Cd with application of KCl compared to the other K sources suggests that these complexes may be readily available to plants. Complexes of Cd with SO_4-ions, while apparently not as available as chlorocomplexes, would appear to confer some increased availability on Cd, because of the higher seed Cd with K_2SO_4 than with KNO_3 (Fig. 4). Comparison of the seed Cd concentrations of the K sources with the control is inappropriate because of the likely lower ionic strength of the soil solution of the control, and also because of the large vegetative growth response to K observed in the experiment.

The low seed Cd concentration in the leached KCl treatment (Fig. 4) supports the suggestion that Cd chlorocomplexes may be readily leached from the soil profile and result in decreased Cd concentrations in the soil solution (Garcia-Miragaya and Page 1976). While there was no significant effect of leaching on seed Cd in the K_2SO_4 treatment (Fig. 4), the small decrease observed suggests that Cd may also be leached from the soil as sulphate complexes, but not as readily as chlorocomplexes. This accords with the data from the unleached pots, which showed K_2SO_4 to be intermediate between KCl and KNO_3 in its effect on seed Cd and presumably Cd mobility. The magnitude of leaching effects will depend on the severity of leaching.

The increase in seed Cd concentration with gypsum may be the result of an increase in Cd-ion availability due to the influence of both Ca-ion concentration and the ionic strength of the soil solution. Garcia-Miragaya and Page (1976) showed that an increase in ionic strength decreased the amount of Cd adsorbed on clay surfaces. Calcium ions in high concentration can displace adsorbed Cd (Tiller *et al.* 1979) and render it available to plants. The results above with K_2SO_4 also suggest a direct effect of SO_4-ions in increasing Cd availability. The concentration of SO_4-ions added as gypsum was about six times greater than that added as K_2SO_4.

A significantly lower seed Cd concentration in the unleached $ZnSO_4$ treatment compared with $ZnCl_2$ (Fig. 4) supports the data from the K sources. We postulate that competition from Zn has resulted in the lower seed Cd in these treatments compared to the unleached control, but that the Cl-ions were able to offset this more than were the SO_4-ions. The increase in seed Cd with leaching of the Zn treatments (Fig. 4) is difficult to reconcile because we expected leaching to remove more Cl- and SO_4-ions than Zn-ions, thus allowing competition by Zn to be accentuated.

The findings of this study may have significant implications for the control of Cd uptake by crops and for the leaching of Cd from the root-zone of contaminated soils. In soils where leaching is not great, the use of K_2SO_4, KNO_3 and/or $ZnSO_4$ may reduce Cd uptake compared with chloride counterparts. Potassium chloride could be a more appropriate K source for winter crops under high rainfall by helping to remove Cd from the root zone.

3(e) vi References

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3(f) Field studies of the effects of residual lime and phosphorus on cadmium in potatoes and poppies.

3(f) i Introduction

The lack of a decrease in tuber Cd due to lime (section 3(b)) may have been because the lime had not been mixed with or had not had time to move to sufficient depth. Harvesting the potatoes at the sites in that study mixed the soil to a depth of about 250-300 mm, which was deeper than the initial incorporation and cultivation, so it is possible that crops grown after this may show a different response to the lime. We tested this by growing poppies at sites CD2 and CD3 in 1991/2, and by growing a second crop of potatoes at site CD2 in 1992/3. These studies also enabled examination of residual effects of P fertilizer, which had increased tuber Cd greatly in the year of application.

3(f) ii Materials and Methods

Poppies were sown at CD2 and CD3 in September 1991 using a seeding rate of 950 g ha^{-1}. Seed was applied with a mixture of 50% lime and 50% superphosphate at a rate of 100 kg ha^{-1}. Fertilizer containing 14%N, 16%P and 11%K was applied to all plots at a rate of 250 kg ha^{-1}. Nitrogen at 30 kg ha^{-1} was topdressed as urea at the hook stage, 1-2 weeks before flowering. Plants were irrigated as required.

At maturity, $2m^2$ from each plot was harvested by hand and the yield of capsules and seed recorded. Seed was subsampled and analysed for Cd by the methods described previously. Cadmium concentrations are expressed as mg Cd kg fresh $seed^{-1}$. Capsules were analysed for morphine by Glaxo Pty Ltd.

Site CD2 was replanted to potatoes, cv Russet Burbank, on October 28, 1992. Prior to planting, soil from the nil and 30 t ha^{-1} treatments was sampled in 50 mm increments to 300 mm and analysed for pH to determine the depth of influence of lime. Fertilizer, irrigation, pest and disease management were as for the previous potato crop at this site, except that 2 rows in each plot received 240 kg P ha^{-1} banded as double superphosphate (DSP) containing 15 mg Cd kg^{-1}, while the other 4 rows received no P. Harvest procedures and tuber analysis were the same as for the 1990/91 crop but in addition to the tubers sampled at harvest, extra tubers were sampled prior to harvest from the nil and 30 t ha^{-1} treatments. Samples were taken from both the top 75 mm of ridges and from near the fertilizer band, about 200 mm below the ridge top.

3(f) iii Results and Discussion

Lime maintained soil pH above that of the unlimed control during the poppy trials in 1991/92 (Table 13). The range in surface soil pH at both sites was similar to that for 1990/91 (section 3(b)). Despite the maintenance of pH differences, lime had no effect on seed Cd at either CD2 or CD3 (Table 13), although it did decrease poppy petiole Cd at CD3, and also increased morphine yield at both sites (Table 13). Poppy yield responses to lime on krasnozems are well known (Temple-Smith et al. 1983), and result from alleviation of aluminium toxicity. There was no effect of residual P on yield at either site, nor on seed Cd at CD2 (data not shown), but at CD3, 240 kg residual P ha-1 gave seed Cd levels 63% above the nil P treatment ($P<0.05$).

Fig 6 shows that just prior to planting potatoes at CD2 in 1992/3, the 30 t ha^{-1} lime treatment had significantly increased soil pH to a depth of 250 mm. Average pH in the top 150 mm at this time was similar to that of the previous year (Table 13), and generally a little lower than measured in year 1 (section 3(b)). This suggests that the harvesting of the first potato crop mixed the lime deeper, which may be why lime significantly decreased tuber Cd in the second potato crop at CD2 (Table 13). Lime had no effect on tuber yield (Table 13), consistent with previous results. There was no effect of residual P on tuber yield or tuber Cd (results not shown), but freshly applied P at 240 kg ha^{-1} increased yield from 31.8 to 35.1 t ha^{-1} ($P<0.05$) and increased tuber Cd from 0.09 to 0.14 mg kg^{-1} ($P<0.05$). There was a statistically significant ($P<0.003$) effect of ridge position on tuber Cd, but the difference between upper (0.11 mg kg^{-1}) and lower (0.10 mg kg^{-1}) zones was small.

If the harvesting of the first potato crop was responsible for deep mixing of the lime, it suggests that the poppies in 1991/2 were not able to take advantage of this like the potatoes in 1992/3 were. We conclude that poppies probably absorb Cd by a different mechanism to potatoes.

Lime increased the incidence of common potato scab (*Streptomyces scabies*) at CD2 (Table 13), such that tubers from the 20 and 30 t ha^{-1} treatments were not marketable. Effects of lime on common scab are well documented (Huber 1990), and the incidence of scab is not surprising given that, including our trials, potatoes were grown at the site three times in five years. The scab effects are confounded with the effects on tuber Cd, and it is possible that the presence of scab lesions on the tuber surfaces was the sole cause of restricted Cd uptake. Further confirmation of the residual effects of lime is warranted, as are basic studies of the physiology of Cd absorption by potato tubers, so that this can be clarified.

Table 13. Residual effects of broadcast lime (t ha^{-1})

Lime	0	10	20	30	
Site					
	pH (1:5 H_2O; 0-150mm)				s.e.d.
CD2	5.5	5.9	6.2	6.5	0.04
CD2[A]	5.5	5.8	6.1	6.5	0.11
CD3	5.3	5.9	6.1	6.3	0.11
	Morphine Yield (kg ha^{-1})				
CD2	42	47	53	51	3.5[B]
CD3	29	31	35	34	2.1
	Relative Poppy Seed Cd[C]				
CD2	1.00	0.82	0.85	0.79	NS[D]
CD3	1.00	0.92	0.90	0.94	NS
	Poppy Petiole Cd (mg kg^{-1})				
CD2	0.04	0.04	0.05	0.05	NS
CD3	0.11	0.07	0.06	0.06	0.008
	Processing yield (t ha^{-1})				
CD2[B]	33.0	34.2	33.7	33.1	NS
	Tuber Cd (mg kg^{-1})				
CD2[B]	0.14	0.11	0.12	0.10	0.011
	Comon Scab Index[E]				
CD2[B]	92	128	190	213	15.9

[A]Potato trial 1992/93.. [B] P=0.068. [C]nil lime set to unity. [D]not significant, P>0.05. [E]>150 is unmarketable

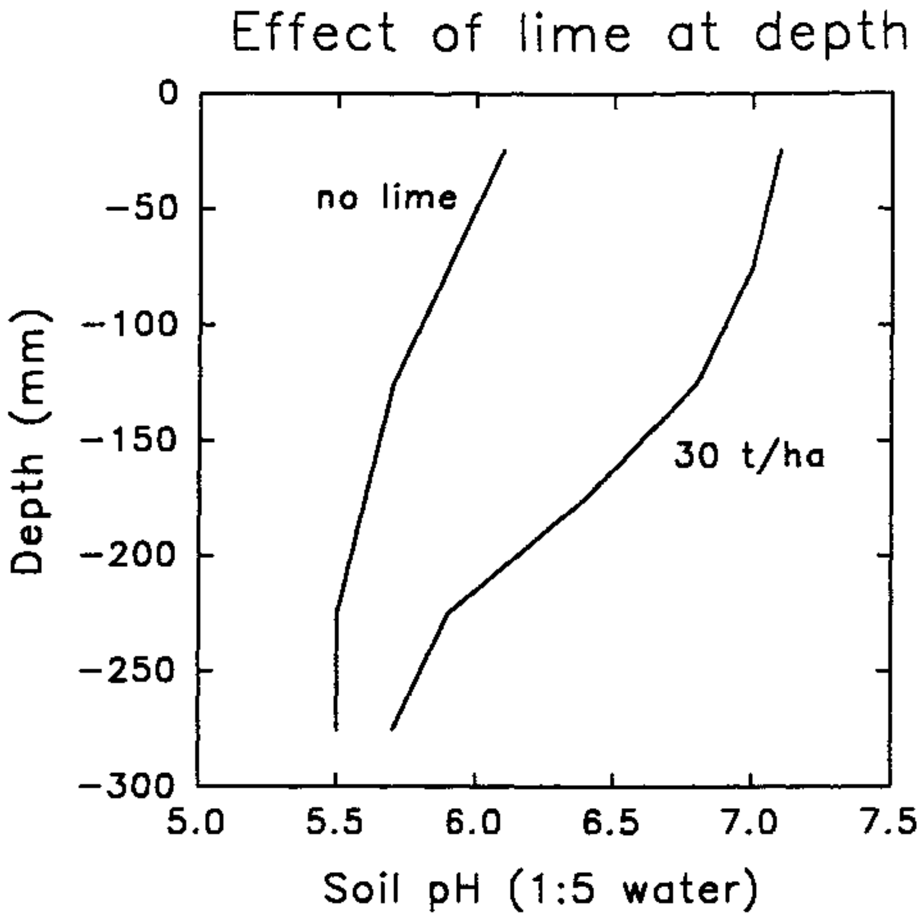

Fig. 6. Effect of lime on soil pH in surface 300 mm of CD2 in 1992/93 (l.s.d. $P<0.05$ = 0.24 pH units).

3(f) iv Referenecs

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