PT212
A national survey of cadmium in potato tubers and soils

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HAL

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PT212

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1. EXECUTIVE SUMMARY

A Project, funded by the ***Horticultural Research and Development Corporation (HRDC)****,was conducted between October 1992 and September 1994 to investigate the link between soil characteristics and Cd concentrations in potato tubers. The* ***specific objectives of the study*** *were to investigate the following:*

(a) if regional differences in cadmium content of potato tubers are significant,

(b) if soil characteristics are important in determining cadmium uptake by potatoes, and if so,

(c) the most important soil characteristics to be measured for predicting potential problem soils.

Results are summarised below.

- *Three hundred and fifty two commercial potato crops and associated soils were sampled and tuber Cd concentrations determined in relation to soil characteristics.*

- *Concentrations of Cd in potato tubers differed widely between States and between regions within States.*

- *Potato tubers having Cd concentrations in excess of the maximum permitted concentration (MPC) of 0.05 mg kg^{-1} were found in all States, but the incidence of high Cd concentrations varied between States and between regions within States.*

- *The number of samples which exceeded the MPC was in line with violation rates recorded in other smaller surveys of potato tubers in Australia. However, potato tuber Cd concentrations were comparable or only slightly higher than concentrations found in other countries.*

- *A limit of 0.05 mg kg^{-1} for potato tubers may be too stringent given that good agricultural practices on low Cd soils leads to production of tubers exceeding the current Australian MPC, and given that other countries have less stringent or no Cd regulations for potatoes.*

1. EXECUTIVE SUMMARY (cont.)

- *There was a wide range in concentrations of extractable Cd in soil, with Tasmania having the highest median Cd concentrations in soil, and Queensland the greatest range in concentrations.*

- *Cadmium concentrations found in soils in all States were not high by world standards.*

- *High tuber Cd concentrations were principally related to high soil salinity, with low soil zinc, soil acidity (low soil pH) and potato cultivar also being important.*

- *On limited evidence from the literature and this study, Australian soils are more prone to produce mature potato tubers with higher internal concentrations of Cd than are soils used for potato production in USA or Europe.*

2. MAJOR FINDINGS/IMPLICATIONS OF THE STUDY

SUMMARY DATA - TUBER Cd

- Three hundred and fifty two commercial potato crops and associated soils were sampled over the period February 1992 to July 1993. The sites sampled represented the major potato production areas in Australia.

- Across all States, tuber Cd concentrations ranged from 0.004 to 0.232 mg kg^{-1} fresh weight (FW) with an overall mean value of 0.041 and a median of 0.033 mg kg^{-1} (FW). Approximately 92 samples out of 359 (or 25.6%) exceeded the current maximum permitted concentration of 0.05 mg kg^{-1} (FW) and 18 (5.0%) exceeded 0.1 mg kg^{-1} (FW).

- Potato tubers having Cd concentrations in excess of the MPC were found in all States, but the incidence of high Cd concentrations varied between States and between regions within States.

- Cadmium concentrations in potato tubers were similar to those found in other countries, although data fell in the upper end of the range reported overseas.

- A limit of 0.05 mg kg^{-1} for potato tubers may be too stringent given that good agricultural practices on low Cd soils can lead to production of tubers exceeding the current Australian MPC, and given that other countries have less stringent or no Cd regulations for potatoes.

SUMMARY DATA - SOIL Cd

- There was a wide range in concentrations of EDTA-extractable Cd in soil, with values varying from 0.01 mg kg^{-1} to 0.59 mg kg^{-1} and mean and median values of 0.136 and 0.097 mg kg^{-1}, respectively.

- Tasmania had the highest median Cd concentrations in soil, and Queensland the greatest range in concentrations with a minimum of 0.03 and a maximum of 0.59 mg kg^{-1}.

- Differences between States in soil Cd concentrations are presumed to be related to soil type and fertilizer histories, with high Cd concentrations in longer established areas having soils which have traditionally required higher rates of fertilizer P, and hence higher rates of Cd applied.

- Topsoils (0-150 mm) generally had higher Cd concentrations than subsoils (150-300 mm).

- Cadmium concentrations found in soils in all States were not high by world standards, confirming trends noted earlier in vegetable soils of Queensland.

LINK BETWEEN TUBER Cd CONCENTRATIONS AND SOIL CHARACTERISTICS

- There was a poor relationship between EDTA-extractable Cd concentrations in soil and tuber Cd concentrations.

- Statistical analysis of the data indicated that concentrations in the topsoil of chloride and zinc, soil acidity and potato cultivar explained a large percentage of the variation in tuber Cd concentrations.

- Chloride mobilises Cd in soil and increases concentrations of Cd in soil solution, thus increasing plant uptake.

- While tuber Cd concentrations were similar to or higher than those found overseas, soil Cd concentrations were lower. This apparent high soil-plant transfer of Cd in Australia compared to other countries may be because;

    - most of the Cd in Australian soils is anthropogenic, which is likely to be less strongly bound within minerals than geogenic Cd,

    - topsoils are generally lighter textured than those in Europe and North America,

    - soils are likely to be Zn deficient compared to soils in Europe and North America,

    - soils are more likely to be saline compared to soils in Europe and North America, and

    - soils generally have lower organic C contents than soils in Europe and North America.

3. CONCLUSIONS/RECOMMENDATIONS

1) Agronomic management practices need to be adopted which minimise Cd accumulation by potatoes. These have been identified under two previous HRDC projects (VG006 "Effect of soil conditions and fertilizers on cadmium in vegetables - a national approach" and PT107 "Development of crop management strategies for improved productivity and quality of potatoes grown on highly acid soils").

2) Research on management strategies to reduce Cd concentrations in potato tubers should focus on minimising further inputs of Cd to soil and deal with the issue of saline soils and waters, as elevated levels of chloride can enhance the availability and uptake of soil Cd.

3) The regulations for Cd in potatoes need to reviewed in the light of the findings here, where potatoes having Cd concentrations exceeding the MPC were found on soils with very low Cd concentrations and with good agricultural practice. Any review must begin with assessment of health risks associated with intake of potatoes at a Cd concentration higher than the current MPC (0.05 mg kg^{-1}).

4) A follow-up national survey of Cd in potatoes be conducted on-farm in 3-5 years, to determine if there are any trends, either upward or downward, in tuber Cd concentrations.

4. DIRECTIONS FOR FUTURE RESEARCH

- As identified under Project VG006, a diagnostic test is required to allow growers to identify high risk environments prior to planting of potato crops. This would allow selection of areas for potato production and could trigger extra ameliorative measures if high Cd risk was predicted. Such a test is being investigated under the current HRDC Project PT423 "A national strategy to reduce Cd accumulation in potato crops".

- The long-term availability of fertilizer Cd to crops needs to be determined. This is necessary if we are to know whether we can "run-down" available soil Cd concentrations after low Cd fertilizers are introduced and how long this will take. It will also allow assessment of the impact of continuing to add more Cd to soil than is removed in harvested produce.

- It is important that the reasons for the lack of any significant impact of soil pH on Cd availability be determined.

- It is imperative that strategies be developed to minimise Cd uptake by potatoes on saline soils.

5. ORIGINAL GRANT DETAILS 1992-94 - PT212

HORTICULTURAL RESEARCH AND DEVELOPMENT CORPORATION

1. **Project Title:** A national survey of cadmium in potato tubers and soils.
   HRDC Project No. PT 212

2. **Organisation:** CSIRO Division of Soils
   Postal Address: Private Bag No. 2, P.O., Glen Osmond, S.A. 5064
   Admin Contact: Ms H. Webster Phone: (08) 303 8403
   Fax: (08) 303 8550

3. **Project Chief Investigator:** Dr M.J.McLaughlin
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   Location of research:
   1) Adelaide Laboratories
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   2) Dept. Agriculture
      Institute of Plant Sciences
      Swan St
      Burnley, Vic 3121
   3) NSW Agriculture
      Biological and Chemical Research Institute
      PMB 10
      Rydalmere
      NSW 2116
   4) Queensland Dept. Primary Industries
      Meiers Rd
      Indooropilly, Qld 4068.
   5) West Australian Dept. Agriculture
      3 Baron-Hay Court
      South Perth, WA 6151

4. **Commencement date:** 1.10.92
   Completion date: 30.9.94

5. **Project cost (total):** $72,862

6. **Synopsis:**
   This project aimed to assess the current Cd status of the potato crop in all Australian States, and to evaluate the relationship between soil properties and potato tuber Cd content within a national framework.

   Keywords:
   Potatoes, cadmium, cadmium uptake, soil chemistry

7. **Brief Statement of Objectives for Each Year of the Project:**
   Year 1 Carry out national sample collection. Initiate collaboration on quality assurance program.
   Year 2 Complete national sample collection. Complete soils analyses and collate results for statistical analysis.

8. **Project Milestones/Schedule of Operations**

Task description	Completion date
Complete tuber analysis quality assurance program	1/11/93
Complete tuber and soil sampling	31/3/94
Collate data from tuber analysis	30/6/94

6. Description of the Project

(i) General Objectives

The major aim is to assess the current cadmium status of the Australian potato crop, and to investigate the relationship between soil and growing conditions and Cd uptake. This may identify;

(a) if regional differences in cadmium content of potato tubers are significant,

(b) if soil characteristics are important in determining cadmium uptake by potatoes, and if so,

(c) the most important soil characteristics to be measured for predicting potential problem soils.

These aims are a subset of those identified as research needs by the HRDC sponsored workshop on "Cadmium in potatoes", held at CSIRO Division of Soils on 2-3rd October, 1991.

This project proposal links with HRDC project V/0006/RO (CSIRO Division of Soils), V/0011/R1 (Tas. DPI) and P/0102/RO (WADA) which aim to determine management strategies to reduce cadmium content of potato (and other) crops. Project P/0102/RO (WADA) has planned a small survey of tuber Cd in commercial crops in WA, therefore no extra resources are requested under this application for tuber collection or analyses. Project V/0006/RO (CSIRO) planned a survey of potato crops and soils in SA, with limited numbers of samples from other eastern States due to commitments to other project objectives. In collaboration with the Chemical Standards Branch of SADA the South Australian survey is more extensive than originally planned and is currently underway (see V/0006/RO progress report Feb. 1992). A survey of potato crops in Tasmania is also under way under project V/0006/RO in collaboration with project V/0011/R1 (Tas DPI) therefore no funds are requested under this application for SA or Tasmania. This application seeks funding to expand the current survey activities of the three projects currently funded and to extend the survey to Victorian, NSW and Queensland crops in collaboration with relevant State Departments.

(ii) The Problem

Nature of problem. Potatoes and other vegetables, notably the root and leafy vegetables, constitute an important part of the Australian diet (about 100kg/person/year) and all have cadmium concentrations well above the norm of most Australian foods (excepting animal offal products). The National Health and Medical Research Council have established maximum permissible concentrations (MPC) of cadmium in Australian foods which for potatoes is 0.05mg Cd kg^{-1} fresh weight. Unpublished information presented at the HRDC workshop "Cadmium in potatoes" held on 2-3rd October, 1991 indicated that a number of States have potato tubers above the NH&MRC limit. In WA the Manjimup/Pemberton area was identified as an area where potato tuber cadmium contents were high. In SA, 41 of the 90 tuber samples tested in the period to July 1991 exceeded the MPC for cadmium content. In Victoria, of the 92 samples analysed between 1987 and 1990 as part of a residue survey, 40% exceeded the MPC and a further 35% exceed half the MPC value. In NSW, only 10 samples from a total of 123 analysed to date have exceed the MPC for cadmium. In Queensland, in a small survey of potato tubers, no samples exceeded the MPC for cadmium.

Circumstances giving rise to the problem. There is concern worldwide for health issues related to food purity. Many countries are legislating both to limit the level of potentially toxic elements in foodstuffs, and to limit the concentration of these elements in soil amendments such as fertilizers, liming materials and organic wastes. In Australia the NH&MRC has legislated to restrict the cadmium concentration in vegetables to less than 0.05 mg kg^{-1} wet weight. Some potatoes are above this limit, due probably to the high requirement of this crop for fertilizer P, it's growth on many acidic soils and the propensity for root crops such as potatoes to accumulate cadmium. Furthermore, the source of phosphate rock used for fertilizer manufacture in Australia has traditionally been from high cadmium deposits such as Nauru and Ocean Island

(iii) Procedure

The proposed approach is to extend and integrate the current cadmium surveys of potato crops. Surveys of potato crops in WA, SA and Tasmania are currently underway as part of HRDC projects V/0006/RO (CSIRO) and P/0102/RO (WADA). Project V/0006/RO had a small national survey component included in its objectives for the first year of the project. Project P/0102/RO had a small tuber cadmium survey component of WA crops as part of its objectives for the first year of the project. It is proposed to:

(a) extend the WA survey to include sampling and analyses of soils associated with tuber samples,

(b) expand and extend the proposed national survey under project V/0006/RO to include Victoria, NSW and Queensland where there is only limited survey work was planned, and

(c) include State departments in the national survey project and integrate the results from all States into a national database and determine if links between soil or regional parameters and tuber Cd content exist.

As tuber and some soil analyses may be performed in different laboratories, a sample exchange and quality assurance program will form part of the first years' activities.

Tubers will be harvested at maturity from all the major potato growing areas in each State. Sampling may therefore extend through to the second half of the 1993 year (to fall in the 1993/94 financial year) depending on regional growing conditions. Additional information on potato cultivar, fertilizer applied, expected crop yield will be obtained from the grower before or at the time of sampling. Sampling will consist of "point sampling" where paired soil and tuber samples are taken. As large a cultivar of soil types will be included in any area. Tubers will be analysed in the relevant State Chemistry Laboratory, while soils will be despatched to CSIRO Division of Soils in Adelaide for analysis. Soils will be characterised using the following measurements - % clay, pH, EC, chloride, total C and N, soluble salts, extractable P, EDTA extractable Cd and Zn and a two point Cd sorption measurement. More detailed analyses such as mineralogy may be performed on a subset of the samples if important differences are found in the initial characterisation. Information relating to tuber cadmium contents will be collated by CSIRO and relationships with soil properties investigated.

7. CSIRO AND COLLABORATING PERSONNEL INVOLVED IN THE PROJECT

CSIRO

Dr M.J.McLaughlin
the late Dr K.G.Tiller
Mr R.H.Merry
Mr L.H.Smith
Ms M.K.Smart
Ms K.T.Sellar

SA Research and Development Institute/Primary Industries SA

Mr Norbert Maier
Mr Mark Butt
Mr Mark Heap
Mr Dick Henderson
Mr Chip Mawby

Agriculture, Western Australia

Mr Allan McKay

Agriculture Victoria

Mr Gordon Berg
Mr Peter Handson

Tasmanian Dept. Primary Industries and Fisheries

Dr Leigh Sparrow

NSW Agriculture

Mr Paul Milham

Queensland Dept. Primary Industries

Mr George Rayment
Mr Glenn Barry
Mr Alan Jeffrey
Mr Errol Best

8. SCIENTIFIC OUTCOMES

To date 7 papers detailing work carried out under this project and associated project VG006 have been published in, or submitted to, internationally refereed journals or books. A further 5 journal papers are currently in preparation. Two conference papers/abstracts have been published. In addition, a paper was delivered to the 2nd International Symposium on the Biogeochemistry of Trace Metals, Taipei, Taiwan in September 1993.

Journal papers published/submitted

1) McLaughlin, M.J., Williams, C.M.J., McKay, A., Gunton, J., Jackson, K., Dowling, B., Kirkham, R., Partington, D., Smart, M.K. and Tiller, K.G. 1994. Effect of potato variety on cadmium accumulation in potato tubers. *Aust. J. Agric. Res.* 45: 1483-1495.

2) McLaughlin, M.J., Tiller, K.G., Beech, T.A. and Smart, M.K. 1994. Soil salinity causes elevated cadmium concentrations in field-grown potato tubers. *J. Environ. Qual.* 23(5): 1013-1018.

3) McLaughlin, M.J., Maier, N.A. Freeman, K., Tiller, K.G., Williams, C.M.J. and Smart, M.K. 1994. Effect of potassic and phosphatic fertilizer type, phosphatic fertilizer Cd content and additions of zinc on cadmium uptake by commercial potato crops. *Fert. Res.* 40: 63-70.

4) McLaughlin, M.J., the late Tiller, K.G., Naidu, R. and Stevens, D.G. 1996. Review: The behaviour and environmental impact of contaminants in fertilizers. *Aust. J. Soil. Res.* 34: 1-54

5) the late Tiller, K.G., Oliver, D.P., McLaughlin, M.J., Merry, R.H. and Naidu, R. 1996. Managing cadmium contamination of agricultural land. *In* 'Remediation of Soils Contaminated by Metals' Eds. I.K.Iskandar and D.C.Adriano. (Science and Technology Letters, Northwood, England. (in press).

6) the late Tiller, K.G., McLaughlin, M.J. and Roberts, A.N. 1995. Environmental impacts of heavy metals in agroecosystems and amelioration strategies in Oceania. *In* "Advances in Environmental Science - Remediation of Degraded Soils and Groundwaters, Volume 4 - Worldwide Perspectives on Soil and Groundwater Pollution: Asia, Africa and Oceania." Ed. P.M. Huang. Science Reviews, UK. (in press).

7) McLaughlin, M.J., the late Tiller, K.G. and Smart, M.K. 1996. Speciation of cadmium in soil solution of saline/sodic soils and relationship with cadmium concentrations in potato tubers (*Solanum tuberosum* L.). *Aust. J. Soil. Res.* (submitted)

Conference papers/abstracts

8) McLaughlin, M.J., Maier, N., Williams, C.M.J., Tiller, K.G. and Smart, M.K. 1993. Cadmium accumulation in potato tubers - occurrence and management pp.208-213 *In* Proc. 7th National Potato Research Workshop, Ulverstone, May 1993. Ed. J.Fennell. Tasmanian DPI, Launceston.

9) McLaughlin, M.J. and Tiller, K.G. 1994. Chloro-complexation of cadmium in soil solutions of saline-sodic soils increases phyto-availability of cadmium. pp.195-196. *In* Proc 15th Int. Congr. Soil Sci., Acapulco, Mexico, July 1994.

9. TECHNOLOGY TRANSFER/INDUSTRY LIAISON

1) Major meetings

During the course of the project a coordination meeting was held in Adelaide in collaboration with project VG006 to review the issues, determine research and management priorities and to pass information and research outcomes to industry.

The meeting "Cadmium Workshop for the Australian Potato Industry" was held on 5th-6th August 1993 at CSIRO in Adelaide. This meeting had significant industry representation and updated industry on research results, prioritised future research directions and developed a management plan to address the Cd issue. Proceedings of this workshop were published by HRDC in September 1993 (Document/Project PT 342). In addition, results from this project and VG006 were presented at the 7th National Potato Research Workshop, Ulverstone, in May 1993.

2) Grower meetings

A number of talks were given to growers as part of the project.

1) Cd update, SA Potato growers meeting, Adelaide, April 28th, 1993.

2) Tatiara Potato Growers meeting, Bordertown, October 10th, 1994.

3) Koo-wee-rup/Thorpedale crisping growers meeting, Coralyn, October 19th, 1994.

3) Industry liaison

Throughout the project, close contact has been maintained with the fertilizer industry through the Fertilizer Industry Federation of Australia, Ltd.

Close contact has also been kept with the National Food Authority (NFA). During July-August 1994, technical assistance was provided to the Australian Potato Industry Council to lodge a submission to the NFA to increase the maximum permitted concentration for Cd in potatoes.

Two meeings were held (09//08/95 and 23/08/95) where Mr George Rayment presented results to the Deciduous Sectional group (at Stanthorpe) and the Vegetable Sectional group (in Brisbane) of the Queensland Fruit and Vegetable Growers Association (QFVG) on Cd contamination of vegetables, including potatoes. In 1994 Mr Rayment also presented data to the Board of QFVG on cadmium in vegetables.

4) Articles/leaflets/media

Research results from the project have been reported in the following media

a) Article in Peelings Newsletter October 1993, "Cadmium accumulation in potatoes".

b) Article in Rural Research, Autumn 1994 edition, "Cadmium: a modern day problem".

c) Article in Rural Research, Autumn 1995 edition, "Keeping cadmium under control".

d) Article in Peelings Newsletter, December 1994, "Cadmium update".

5) Decision support software

Many of the findings will be included in information packages and decision support software for growers and technical staff being prepared as part of SARDI Project PT428, which started in July 1994

10. TECHNICAL PAPERS

APPENDIX 1	National survey of Cd in potato tubers and soils and comparison with international data sets

Introduction

Cadmium (Cd) concentrations in foods are regularly monitored in a number of countries, including Australia. In Australia, the National Food Authority (NFA) conducts the Australian Market Basket Survey (AMBS) of foods every two years, and analyses foods as consumed for a range of heavy metal and organic contaminants (Stenhouse, 1992). In addition, many State authorities and the National Residue Survey (NRS) (Anon, 1992a) monitor Cd concentrations in agricultural produce.

In Australia, the maximum permitted concentration (MPC) for Cd in potato tubers has been set by the Australian National Health and Medical Research Council (NHMRC) at a level of 0.05 mg kg^{-1} on a fresh weight basis (Anon, 1993). The AMBS and NRS surveys have identified potatoes as a food which exceeds Australia's MPC in about 15-20% of samples tested (Anon, 1992a; Stenhouse, 1991) and it has been estimated that potatoes constitute a considerable percentage of the adult male dietary Cd intake (Stenhouse, 1991, 1992). However, the number of samples in these surveys are small. For example AMBS data for potatoes are collated from a sample size of 32 (1990 and 1992) while NRS data are for 103 samples. Furthermore, few of these surveys are conducted from produce collected on-farm, where links between Cd in the produce, soil Cd concentrations and other soil and crop attributes can be investigated.

The aim of this project was to investigate the regional distribution of Cd in potato tubers with a view to establishing links between tuber Cd concentrations and soil and crop factors.

Materials and Methods

Sampling

Potato crops and soils were sampled by personnel of CSIRO and the relevant State Departments of Agriculture. Three hundred and fifty two commercial potato crops and associated soils were sampled over the period February 1992 to July 1993. The sites sampled represented the major potato production areas in Australia (Figure 1).

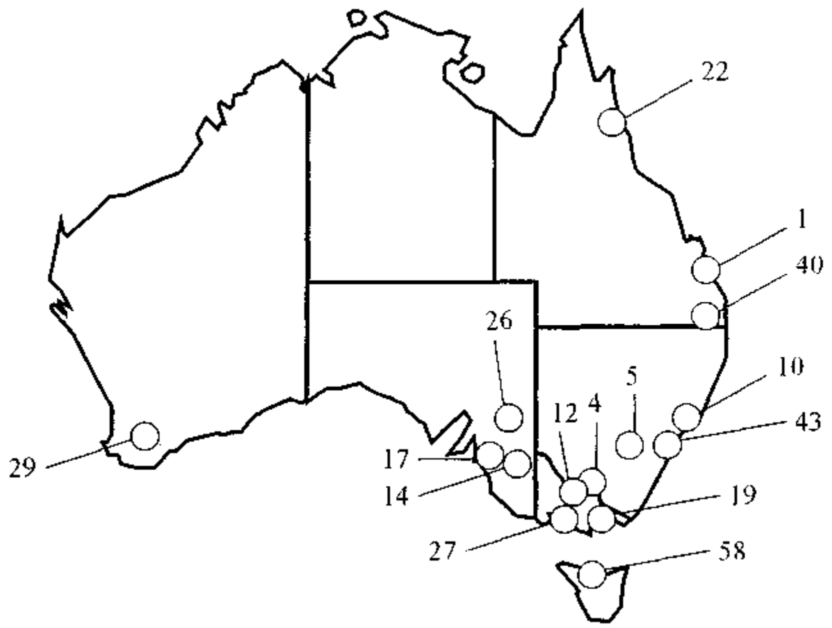

Figure 1. Location of sampling points.

The possibility that local spatial variability might confuse the relationships between soil characteristics and tuber Cd concentrations was minimised by sampling tubers and soils from the exact same location at each site.

Potato crops were sampled by hand digging tubers from two to three metres of row after haulms had senesced. Twelve to 15 tubers in the size range 80-450 g were collected, with any severely diseased or damaged tubers discarded. Potato cultivar was noted and tubers were brushed free of soil and transported to the laboratory for analysis.

Soil Orders (Soil Survey Staff, 1992) sampled included Alfisols, Vertisols, Oxisols, Ultisols, Mollisols and Inceptisols with a wide range of physical and chemical characteristics.

Soils were sampled from the same length of crop row from which tubers were removed. Soil in the ridged rows down to the furrow depth was thoroughly mixed and a one kilogram sample taken by compositing four subsamples. As potato growers normally form the top 150 mm soil into ridges at planting or during crop growth, this sample is subsequently referred to as *topsoil*. The topsoil was pushed aside and a minimum of four subsamples of soil taken to a depth between 150 - 300mm using a stainless steel auger and composited into a single sample. These samples are subsequently referred to as *subsoils*. Soils were air-dried and crushed to pass a 2 mm sieve prior to analysis. All soils were analysed at the laboratories of the CSIRO Division of Soils in Adelaide.

Analysis

Potato tubers were analysed in the laboratories of CSIRO Division of Soils, Adelaide, State Chemistry Laboratories of SA, WA, Victoria, the Biological and Chemical Research Institute Laboratories (Rydalmere) of NSW Agriculture Department and Queensland Department of Primary Industries Resource Management Institute. A quality assurance program was undertaken to ensure that methods of analyses of potato material for Cd in these various laboratories yielded comparable results. To check digestion procedures and instrumental techniques, two homogenised potato materials were circulated to all laboratories for analysis.

Tubers were generally rinsed first in tap water and then scrubbed gently using a nylon brush in deionised water to remove adhering soil. Tuber eyes and imperfections were removed using a stainless steel knife and either the whole tuber used or a 10-20 mm longitudinal slice taken from the stem end to the bud end. (Concentrations of Cd in a tuber slice were found to be identical to that of the whole tuber). Tuber material was then either homogenised or oven dried and ground < 250 μm prior to digestion.

A subsample of the homogenate or ground dried material was digested by boiling under convection or microwave heating with either concentrated HNO_3, HNO_3+H_2O_2 or HNO_3+$HClO_4$ acids until the digest mixture was clear. The solution was then made up to volume with dilute HNO_3 acid and Cd concentration in the solution determined either by inductively-coupled plasma (ICP) mass spectroscopy using indium as an internal standard, or by graphite furnace atomic absorption spectrophotometry. Analysis of standard reference materials by the various laboratories and methods gave Cd concentrations not significantly different from certified values. All tuber Cd concentrations are expressed on a fresh weight (FW) basis as Cd food standards in Australia relate to metal concentrations in foods *as consumed*.

Soil pH, electrical conductivity (EC) and extractable Cl were determined in a water suspension of soil using a 1:5 soil:solution ratio (Rayment and Higginson, 1992). Chloride in the filtered solution was determined using an automated ferricyanide method (APHA, 1992). Phosphorus was extracted from the soils by shaking for 16 hr with 0.5 *M* $NaHCO_3$ at a soil:solution ratio of 1:100 (Colwell, 1963). Cadmium and Zn were extracted by shaking soils for seven days with 0.05 *M* EDTA (pH 6.0) using a soil:solution ratio of 1:2.5 (Clayton and Tiller, 1979). Total P and Zn in soils was determined by digestion of soil by boiling with concentrated HNO_3+$HClO_4$ acids until the digest mixture was colourless. Solutions were made up to volume in 0.016M HNO_3 acid. Concentrations of Cd and Zn in extracts were determined using a Varian Spectra AA-40 flame atomic absorption spectrophotometer using deuterium background correction. Concentrations of P in extracts were determined using the method of Murphy and Riley (1962). Total C was determined using a LECO CR-12 furnace at 1200^{O}C (Rayment and Higginson, 1992).

Data analysis

The relationship between the concentration of Cd in the tubers, potato cultivar and soil characteristics was determined by linear and step-wise (forward) multiple regression analyses. The factors included were cultivar, pH_{water}, EC, extractable-Cl, extractable-P, EDTA-extractable Zn, total Zn, EDTA-extractable Cd, total-P and total C in both the topsoil and subsoil. To normalise the skewed distribution of some of the data sets, data were transformed (square root or logarithm) where appropriate.

Results

Tuber analysis

Results of the quality assurance program indicated that all laboratories involved in tuber analysis obtained comparable data for the two homogenised tuber materials (Table 1), indicating that data from the different laboratories could be compiled and analysed as a single set.

There was a wide range of potato cultivars sampled (Table 2). However, the number of observations for some cultivars was insufficient to make any comparison of cultivar mean Cd concentrations. Within each cultivar there was a very wide range in tuber Cd concentrations found, due to differences in soil and environmental conditions.

Across all States, tuber Cd concentrations ranged from 0.004 to 0.232 mg kg^{-1} (FW) with an overall mean value of 0.041 and a median of 0.033 mg kg^{-1} (FW) (Table 3). Ninety two samples out of 359 (or 25.6%) exceeded the current MPC of 0.05 mg kg^{-1} (FW) and 18 (5.0%)

exceeded 0.1 mg kg^{-1} (FW) (Figure 2). The relevant data for the various States are shown in Table 3. Potato tubers having Cd concentrations in excess of the MPC were found in all States, but the incidence of high Cd concentrations varied between States and between regions within States.

Table 1. Analysis of two homogenised tuber materials for Cd in different laboratories.

Laboratory	Sample 1 Mean	Sample 1 SD (n)	Sample 2 Mean	Sample 2 SD
	mg kg^{-1} (FW)‡			
1 (CSIRO)	0.213	0.019 (142)	0.099	0.008 (142)
2 (SCL - SA)	0.198	0.007 (5)	0.088	0.002 (5)
3 (NSW - BCRI)	0.210	0.015 (6)	0.100	0.007 (6)
4 (QDPI - RMI)	0.201	0.013 (8)	0.092	0.008 (8)
5 (SCL - Vic.)	0.230	0.013 (3)	0.120	0.004 (3)
Mean	0.210		0.100	
SD	0.013		0.012	
CV (%)	6.2		12.0	

NR = not reported

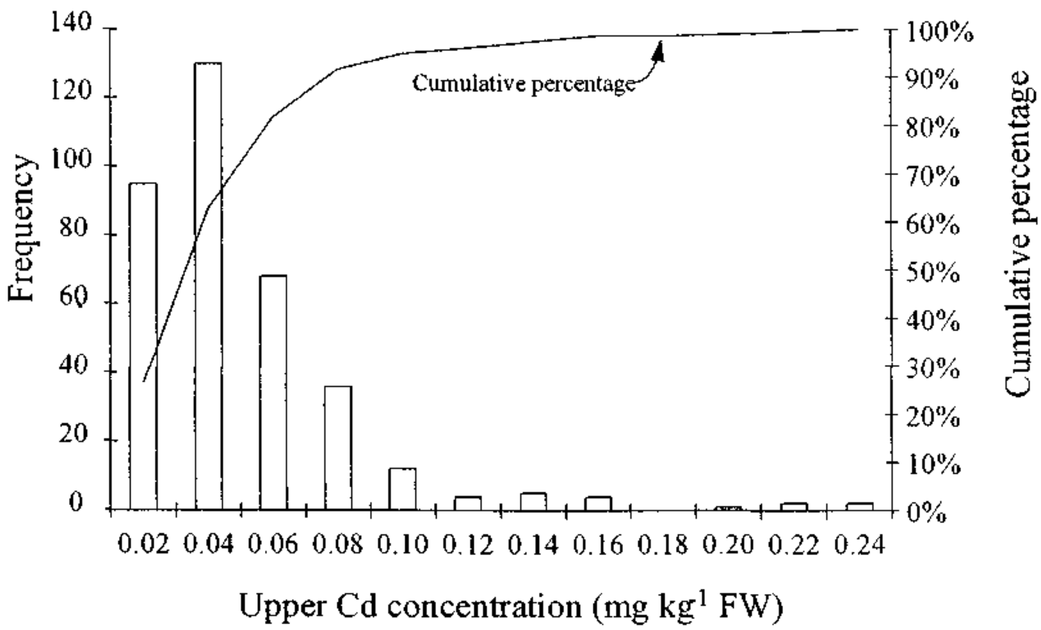

Figure 2. Frequency histogram for tuber Cd data - all States.

Table 2. Summary data for Cd concentrations in cultivars.

Cultivar	Mean	SD†	Min	Max	No.
	mg kg^{-1} FW‡				
Atlantic	0.041	0.048	0.004	0.206	47
Bison	0.086				1
Coliban	0.019	0.018	0.005	0.070	17
Crystal	0.013	0.011	0.005	0.021	2
Desiree	0.018	0.013	0.005	0.036	4
Exton	0.022	0.008	0.010	0.036	7
Kennebec	0.063	0.048	0.006	0.232	69
Norchip	0.010				1
Pontiac	0.051	0.034	0.006	0.123	27
Rideau	0.032				1
Russet Burbank	0.043	0.018	0.007	0.096	84
Sebago	0.029	0.016	0.006	0.066	71
Sequoia	0.042	0.008	0.030	0.053	8
Shepody	0.018	0.010	0.011	0.025	2
Snowchip	0.007				1
Tarago	0.043	0.008	0.037	0.048	2
Wilcrisp	0.026				1
Winlock	0.023	0.010	0.008	0.038	6
Wontscab	0.015				1
Unknown	0.021	0.012	0.011	0.042	7
Total					359

† SD = standard deviation
‡ FW = fresh weight

Table 3. Range, mean and median tuber Cd concentrations in Australian States†.

	NSW	QLD	VIC	WA	SA	TAS	ALL
	mg kg^{-1} (FW)‡						
Mean	0.029	0.020	0.037	0.050	0.066	0.038	0.041
Median	0.027	0.018	0.036	0.048	0.059	0.037	0.033
Minimum	0.008	0.004	0.006	0.022	0.005	0.010	0.004
Maximum	0.065	0.069	0.103	0.096	0.232	0.084	0.232
No. samples	62	63	58	29	89	58	359
No. > MPC§	6	2	14	13	49	8	92

† NSW = New South Wales, QLD = Queensland, VIC = Victoria, WA = Western Australia, SA = South Australia and TAS = Tasmania.
‡ FW = fresh weight
§ MPC = maximum permitted concentration (0.05 mg kg^{-1})

Soil analysis

The soils had a wide range of values for measured properties (Table 4).

Table 4. Characteristics of soils.

Characteristic	Depth (mm)	Range	Median	Mean
pH (water)†	0-150	4.4-9.0	5.7	6.0
	150-300	4.3-9.3	5.6	5.9
EC (dS/m)†	0-150	0.03-1.45	0.19	0.26
	150-300	0.04-1.58	0.18	0.23
Total C (%)	0-150	0.1-15.5	2.5	3.1
	150-300	0.1-14.1	2.1	2.8
Extractable Cl (mg kg^{-1})†	0-150	4-1819	64	142
	150-300	1-1225	58	114
Total P (mg kg^{-1})‡	0-150	27-4321	744	965
	150-300	20-4561	649	933
EDTA-extractable Cd (mg kg^{-1})§	0-150	<0.03-0.590	0.097	0.136
	150-300	<0.03-0.613	0.081	0.122
EDTA-extractable Zn (mg kg^{-1})§	0-150	<0.7-29.9	4.2	5.7
	150-300	<0.7-41.7	3.7	5.4

† 1:5 soil:water ratio.
‡ determined by digestion with conc. $HNO_3/HClO_4$ acids.
§ according to the method of Clayton and Tiller (1979).

Soil pH values varied from highly acidic (pH 4.3) to highly alkaline and sodic (pH 9.3) and some soils were highly saline with electrical conductivity values > 0.4 ds/m and extractable-Cl concentrations > 1000 mg kg^{-1}. There was also a wide range in concentrations of EDTA-extractable Cd and Zn in soil, with Tasmania having the highest median Cd concentrations in topsoil, and Queensland the greatest range in concentrations with a minimum of 0.03 and a maximum of 0.59 mg kg^{-1} (Table 5).

Topsoils generally had higher Cd concentrations than subsoils, although there was a close relationship between Cd concentrations in these two strata (Figure 3). There was no relationship between concentrations of Cd and Zn extractable by EDTA in topsoils (Figure 4) or subsoils (data not shown).

Table 5. Range, mean and median EDTA-extractable Cd concentrations in topsoils (0-150 mm) in Australian States†.

	NSW	QLD	VIC	WA	SA	TAS	ALL
				mg kg^{-1}			
Mean	0.109	0.109	0.147	0.168	0.076	0.261	0.136
Median	0.091	0.078	0.099	0.160	0.069	0.248	0.097
Minimum	0.013	0.030	0.030	0.050	0.030	0.030	0.013
Maximum	0.514	0.590	0.460	0.303	0.185	0.543	0.590
No. samples	62	63	58	29	88	58	358

† NSW = New South Wales, QLD = Queensland, VIC = Victoria, WA = Western Australia, SA = South Australia and TAS = Tasmania.

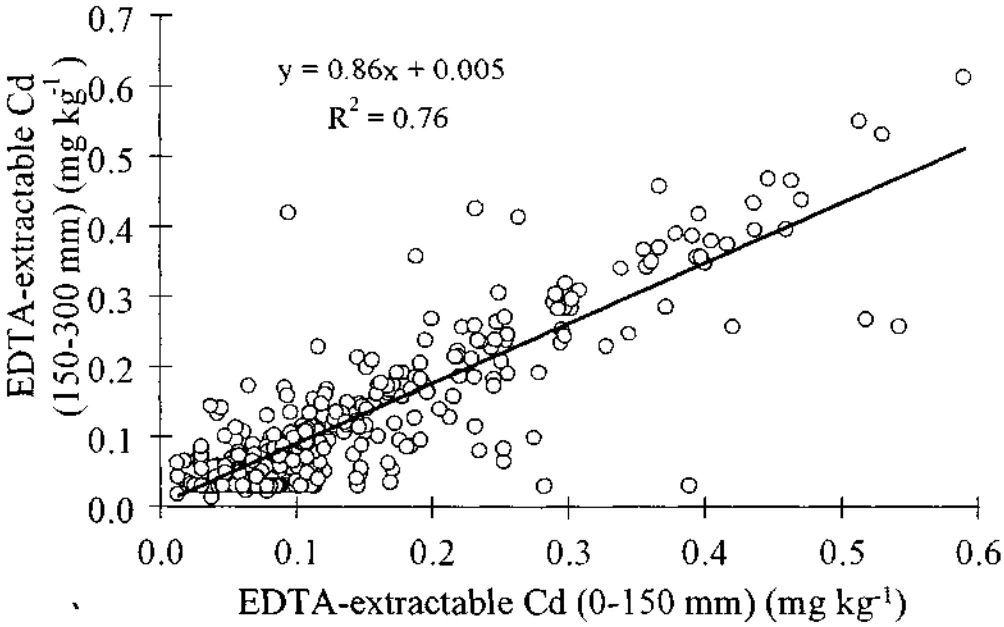

Figure 3. Relationship between EDTA-extractable Cd concentrations in topsoils (0-150 mm) and subsoils (150-300 mm).

Relationships between tuber Cd concentrations and soil and crop characteristics

Therre was no relationship between Cd concentrations in soil and tubers (Figure 5). South Australia had the lowest Cd concentrations in soil, yet had the highest tuber Cd concentrations (Tables 3 and 5).

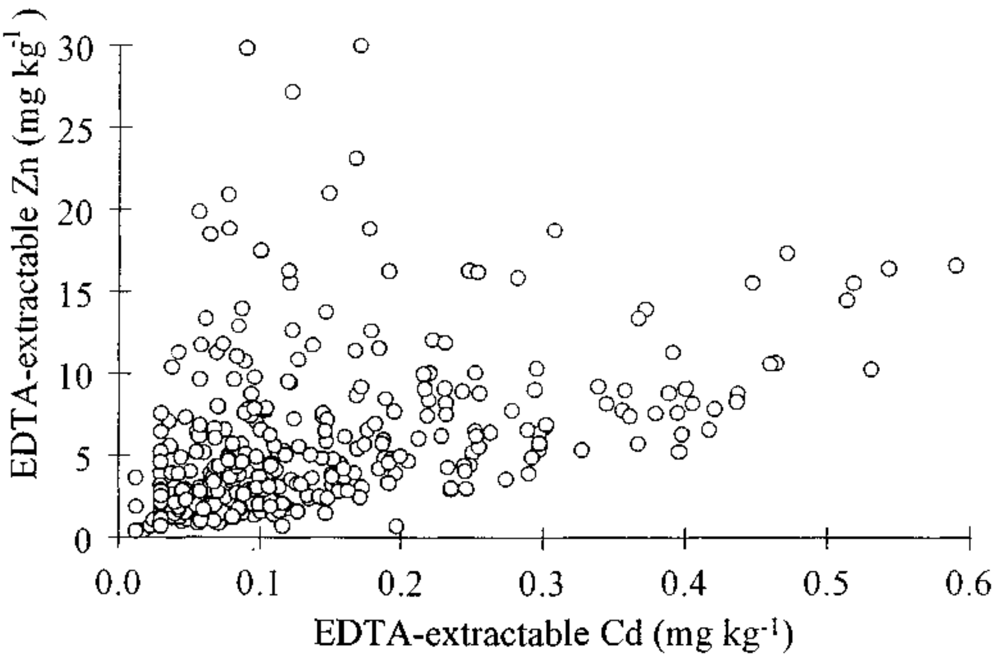

Figure 4. Plot of EDTA-extractable Cd and Zn concentrations in topsoils (0-150 mm).

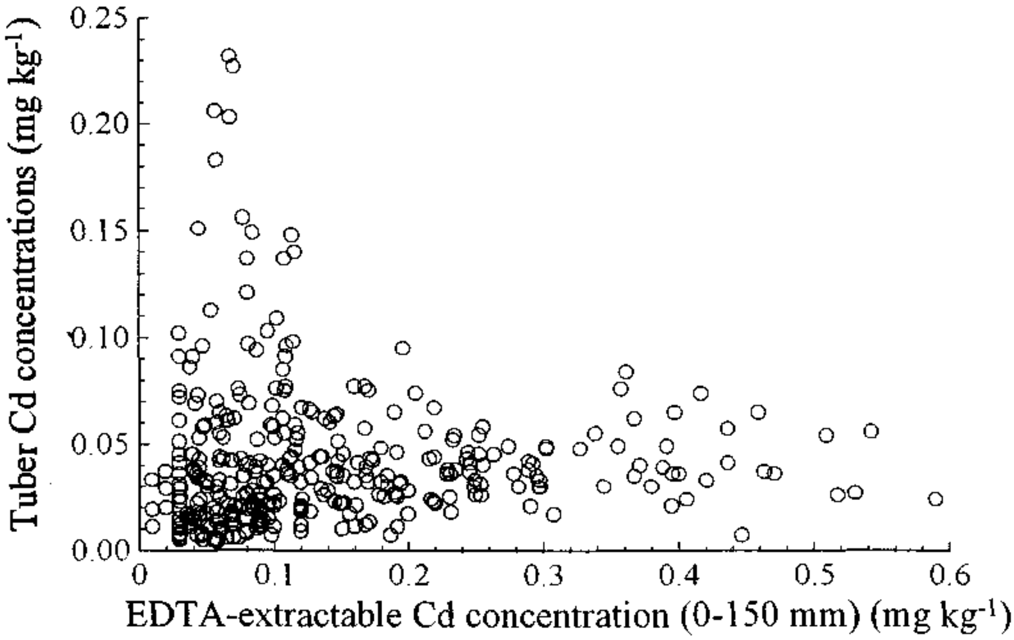

Figure 5. Plot of EDTA-extractable Cd in soil (0-150 mm) and tuber Cd concentrations.

Step-wise forward multiple regression analysis of the data indicated that Cl and Zn concentrations in the topsoil, soil pH and potato cultivar accounted for 57% of the variation in tuber Cd concentrations (Table 6, Figure 6).

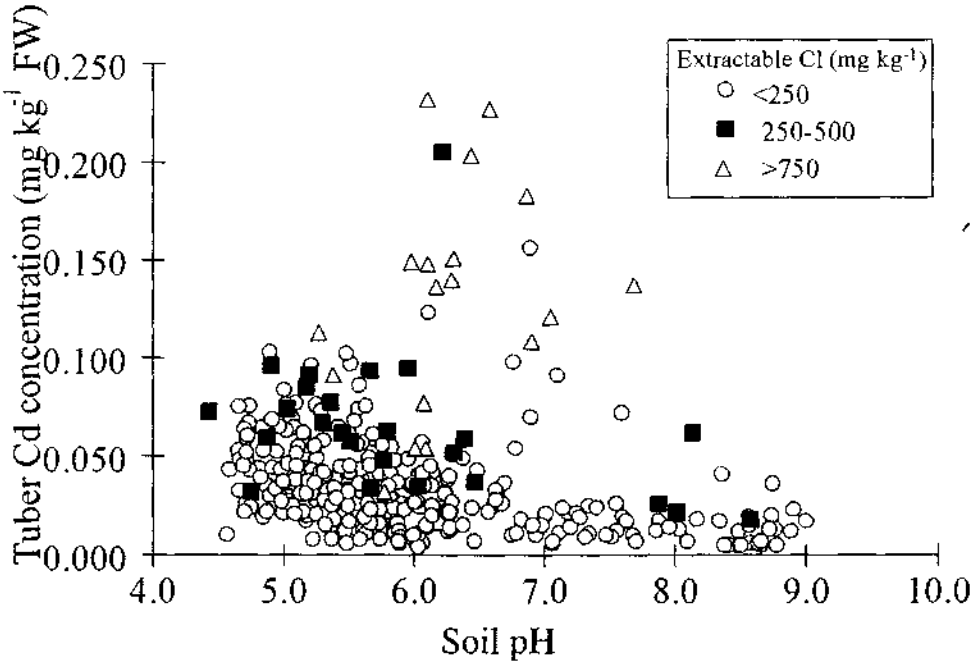

Figure 6. Plot of tuber Cd concentrations vs. soil pH for 3 classes of water-extractable Cl concentrations in soil (0-150 mm).

Table 6. Analysis of variance table for multiple regression of tuber Cd concentration (mg kg^{-1} fresh weight basis) on water-extractable Cl, total Zn, soil pH and potato cultivar.

Change in factor	Degrees of freedom	Sum of squares	Mean Square	Variance ratio	% Variation
+ Cl†	1	0.1881	0.1881	367.4***	45.5
+ pH‡	1	0.0280	0.0280	54.8***	6.8
+ Zn§	1	0.0134	0.0134	26.1***	3.2
+cultivar	19	0.0172	0.0009	1.8*	4.2
Residual	325	0.1664	0.0005		40.3
Total	347	0.4132	0.0012		100.0

† Cl = water-extractable Cl (mg kg^{-1}) in topsoil (0-150 mm)
‡ pH (water) of topsoil (0-150 mm)
§ Zn = total zinc (mg kg^{-1}) in topsoil (0-150 mm)
*,*** = significant at the $P<0.05$ and 0.001 levels, respectively.

Discussion

Cadmium in soils

Cadmium concentrations found in soils in all States ranged from <0.03 to 0.61 mg kg^{-1}, which would not be considered high by world standards. Maximum (total) Cd concentrations found in agricultural soils in other countries range from 1.5 mg kg^{-1} (Roberts *et al.*, 1994) to 14.0 mg kg^{-1} (Wiersma *et al.*, 1986). The EDTA procedure used in this study is designed to extract all Cd bound to soil surfaces, but minimise dissolution of Cd and Zn within silicate or other crystalline lattices. Cadmium and Zn within these structures are more likely to be geogenic rather than anthropogenic and are thought to be less available for uptake by plants or for leaching (Clayton and Tiller, 1979). This procedure extracts approximately 93% of the total Cd in broadacre agricultural soils (McLaughlin et al., unpublished data) and therefore can be compared to total Cd concentrations reported in other studies. The range of Cd concentrations found was small compared to other comparable survey data for agricultural soils (Frank *et al.*, 1976; Andersson, 1977; McGrath, 1986; Wiersma *et al.*, 1986; Merry and Tiller, 1991; Holmgren *et al.*, 1993; Roberts *et al.*, 1994). Merry and Tiller (1991) examined Cd concentrations in 516 pasture soils in the area east of Adelaide, South Australia using the same EDTA procedure as used in this investigation. Cadmium concentrations ranged from 0.01 to 0.73 mg kg^{-1}, with mean and median values of 0.18 and 0.16 mg kg^{-1} (0-50 mm), respectively, and 0.09 and 0.08 mg kg^{-1} (50-100 mm), respectively. These data are comparable to the values we found here for horticultural soils. Mean (total) Cd concentrations reported in broadacre agricultural soils in other countries range from 0.265 mg kg^{-1} (Holmgren *et al.*, 1993) to 0.9 mg kg^{-1} (McGrath, 1986), so Cd concentrations in Australian agricultural soils appear to be lower than those in other countries. There is no good data set on concentrations of Cd for non-agricultural soils in Australia, so that it is difficult to determine if low Cd concentrations in Australian agricultural soils are due to low levels prior to fertilization and atmospheric inputs from anthropogenic sources, or due to the generally low rates of phosphatic fertilizer (and hence Cd) addition in Australia in comparison to other northern hemisphere countries (McLaughlin *et al.*, 1992). As there was some correlation (R^2=0.21, P<0.01) between total P and EDTA-extractable Cd (data not shown), it is likely that phosphatic fertilizer is a significant source of Cd in the soils, which accords with conclusions from other Australian studies examining soil P and Cd concentrations (Merry, 1988) and from Cd budgets (McLaughlin *et al.*, 1996; Jinadasa *et al.*, 1996).

Regional trends in soil Cd concentrations were evident. Mean and median Cd concentrations were relatively high in WA, possibly because the samples came from an area of horticultural soils which had been under potato and other vegetable production for over 60 years. For the other States, Tasmania and Victoria had the highest mean and median Cd concentrations in topsoils. This may be due to the greater areas of Oxisols and Ultisols under potato production in these States. High P (and hence Cd) applications rates have historically been used on these soils, due to their high P fixation capacities. Cadmium concentrations in SA soils were low. This may be a reflection of the generally lighter textured soils under potato production in this State, lower P (Cd) application rates and possibly some leaching of Cd from the profile.

Cadmium in potato tubers

Cadmium concentrations in potato tubers were in the upper end of the range of those found in surveys in other countries (Table 7).

In most of these studies, there is little indication if sites sampled were subject to atmospheric or industrial inputs of Cd. Nevertheless, reported median Cd concentrations range from 0.010 mg kg^{-1} (Zawadzka *et al.*, 1990) to 0.030 mg kg^{-1} (Wiersma *et al.*, 1986; Weigert *et al.*, 1984), which are slightly lower than those found in this study. This result contrasts with the data for soil Cd concentrations, where Australian soil Cd concentrations appeared to be lower than those reported in other countries.

We could only find two other studies which have specifically examined soil and potato tuber Cd concentrations simultaneously (spatially and temporally). Rayment (1994) examined 21 soils in Queensland and related potato tuber Cd concentrations to concentrations of Cd extracted from soil using EDTA (4 hour extraction). The transfer coefficients (TCs), calculated from the data of Rayment (1994) as tuber Cd concentration divided by soil (0-100 mm) Cd concentration (EDTA) varied from 0.06 to 0.36. Gerritse *et al.* (1978) examined 20 Dutch soils and related soil Cd concentrations to Cd concentrations of potato tubers grown in pots under glasshouse conditions. No information was given in relation to potato variety or to growth conditions or soil chemical analyses. The soils varied in texture from sands to clays, pH varied from 4.3-7.9 and total Cd concentrations varied from 0.05-4.6 mg kg^{-1}. The transfer coefficients (TCs), calculated from the data of Gerritse *et al.* as tuber Cd concentration divided by soil Cd concentration (total) varied from 0.002 to 0.2, with an approximate mean value around 0.05 and a median of 0.03 (data interpolated from Figure 5a in Gerritse *et al.*, 1978). In our study, the TCs calculated using EDTA-extractable Cd (which is similar to total Cd in these soils) varied from 0.02 to 4.5, with mean (±SD) and median values of 0.50(±0.60) and 0.26 (Figure 7).

Table 7. Concentrations of Cd reported in potato tubers in various countries.

		Cd concentration in fresh potatoes (mg kg^{-1} FW)				Reference
Country	No. Sites	Median	Mean	Min.	Max	
Australia*	359	0.033	0.041	0.004	0.232	This study
Australia	21	0.020	-	-	-	Anon (1987)
Australia	21	0.016	-	-	0.110	Anon (1988)
Australia	21	0.013	0.015	-	0.046	Anon (1990)
Australia	24	0.020	0.040	-	0.170	Stenhouse (1991)
Australia	32	-	0.033	0.013	0.068	Stenhouse (1992)
Aust. - Qld.	21	-	0.018	0.009	0.031	Rayment (1994)
Aust. - WA	116	0.030	0.035	0.005	0.120	Anon (1992b)
Germany	133	0.030	0.047	<0.013	0.200	Weigert *et al.* (1984)
Germany	100	-	0.020	-	-	Ocker *et al.* (1984)
Netherlands	94	0.030	0.030	0.002	0.090	Wiersma *et al.* (1986)
Poland 1986	70	0.006	0.010	0.001	0.067	Zawadzka *et al.* (1990)
Poland 1987	94	0.014	0.013	0.001	0.080	Zawadzka *et al.* (1990)
Poland 1988	90	0.010	0.018	0.001	0.090	Zawadzka *et al.* (1990)
Spain	8	-	0.013	0.008	0.017	Zurera *et al.* (1987)
Sweden	62	-	0.016	0.005	0.055	Jorhem *et al.* (1984)
Switzerland	101	0.013	0.015	0.003	0.044	Andrey *et al.* (1988)
UK	19	-	0.080	0.010	0.170	Thomas *et al.* (1972)
UK	20	-	<0.100	<0.010	0.060	Anon (1983)
USA	297	0.028	0.031	0.002	0.182	Wolnik *et al.* (1983)

* All States

Thus, it would appear that there is a higher soil-plant transfer of Cd to potatoes in Australian soils. This may be a reflection of a number of factors;

(a) most of the Cd in Australian soils is anthropogenic, which is likely to be less strongly bound to soil than geogenic Cd which often occurs structurally within soil minerals,

(b) topsoils are generally lighter textured than those in Europe and North America,

(c) soils are likely to be Zn deficient compared to soils in Europe and North America,

(d) soils are more likely to be saline compared to soils in Europe and North America, and

(e) soils generally have lower organic C contents than soils in Europe and North America.

The highly skewed nature of the TC data (Figure 7), was due to high TC values for a small set of soils, linked principally to conditions of high soil salinity (see below).

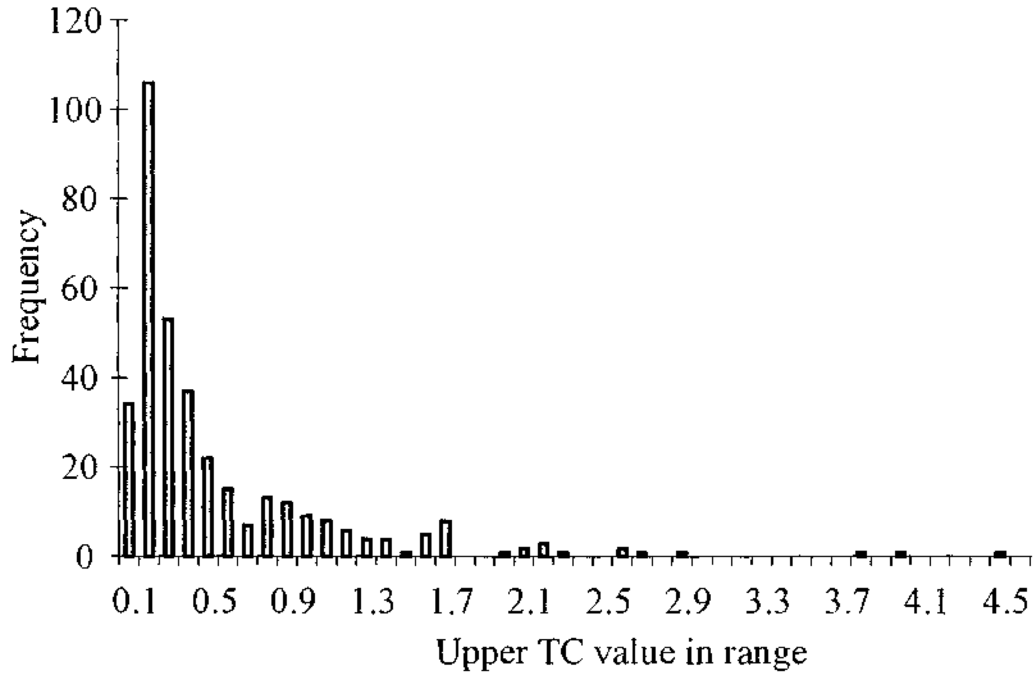

Figure 7. Frequency histogram for transfer coefficient (TC) values (tuber Cd/soil Cd).

The number of samples which exceeded the current NFA limit of 0.05 mg kg^{-1} was in line with violation rates recorded in other smaller surveys of potato tubers in Australia (Anon, 1992b; Stenhouse 1992). This raises the question as to whether the NFA limit of 0.05 mg kg^{-1} for "all other foods", into which potato tubers fall, is too stringent for potatoes given that good agricultural practices on low Cd soils leads to production of tubers exceeding this value. Few other countries have such stringent limits for Cd in potatoes, or other vegetables. In Germany the "Richtwert" for Cd in potatoes is 0.1 mg kg^{-1} (Ocker *et al.*, 1984). The Netherlands has a "monitoring" level for Cd in potatoes of 0.1 mg kg^{-1} and Denmark a "guideline" level of 0.06

mg kg^{-1}. The UK and USA have no food Cd standards, while NZ and Brazil have blanket limits of 1.0 mg kg^{-1} for "other foodstuffs" not covered specifically in their regulations (Walker, 1988). Given the stringent regulatory level in Australia and the incidence of Cd concentrations in potatoes exceeding 0.05 mg kg^{-1} in both Australia and overseas, it would appear that some review of the regulations may be appropriate.

Links between tuber Cd and soil characteristics

The concentrations of Cd found in potato tubers in Australia varied widely according to geographic location, with the major determinants of Cd accumulation in tubers related to soil rather than plant or climatic factors. Regionally high Cd concentrations in tubers were principally related to concentration of Cl in soil, with saline regions generally having higher tuber Cd concentrations. This result agrees with previous findings in South Australia (McLaughlin *et al.*, 1994a). Soil salinity impacts on Cd uptake by plants through chloro-complexation of Cd ions in soil solution (Hahne and Kroonjte, 1973; Lindsay, 1979);

$$Cd^{2+} + Cl^{-} \leftrightarrow CdCl^{+} \quad \log K = 2.0 \tag{1}$$

$$CdCl^{+} + Cl^{-} \leftrightarrow CdCl_2^{0} \quad \log K = 2.6 \tag{2}$$

$$CdCl_2^{0} + Cl^{-} \leftrightarrow CdCl_3^{-} \quad \log K = 2.4 \tag{3}$$

$$CdCl_3^{-} + Cl^{-} \leftrightarrow CdCl_4^{2-} \quad \log K = 2.5 \tag{4}$$

The lower charge on the Cd ion allows greater concentrations of $CdCl_n^{2-n}$ species in soil solution (McLaughlin and Tiller, 1994), which enhances plant uptake of Cd from solution (Smolders and McLaughlin, 1996a), either through alleviation of a diffusional limitation to Cd transport in the root apoplast, or through direct uptake of the $CdCl_n^{2-n}$ ions (Smolders and McLaughlin, 1996b).

Soil pH, concentrations of soil Zn and potato cultivar were also found to explain small amounts of the variation in tuber Cd concentrations. Soil pH is generally regarded as the major variable controlling Cd uptake by plants (Chaney and Hornick, 1978; Jackson and Alloway, 1992), but it is evident that in irrigated potato soils in Australia, soil salinity dominates any impact of soil pH on Cd availability. It has been known for some time that soil

Zn plays an important role in mediating Cd uptake by plants (Abdel-Sabour *et al.*, 1988) and applications of Zn have been found to reduce Cd uptake by potatoes (McLaughlin *et al.*, 1995). Similarly, potato cultivar is known to be an important determinant of tuber Cd concentration (McLaughlin *et al.*, 1994b). It is important to note that the ranking of the cultivars by mean tuber Cd concentration is different to that found previously (McLaughlin *et al.*, 1994b), because not all cultivars were well represented across all soil environments in the present study. For example, low Cd concentrations in Sebago (Table 3), compared to previous results (McLaughlin *et al.*, 1994b), are probably because this cultivar was present only in environments predisposed to low Cd uptake. Cultivar comparisons need to account for site and environmental interactions if meaningful rankings are to be produced (McLaughlin *et al.*, 1994b). Hence the cultivar rankings produced previously across a wide range of soil and growing conditions (McLaughlin *et al.*, 1994b) should be used in preference to those reported here.

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