PT107
Development of crop management strategies for improved productivity and quality of potatoes grown on highly acid soils

Norbert Maier
South Australian R&D Institute

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PT107

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ORGANISATION:	South Australian Research and Development Institute

PROJECT CO-ORDINATOR:	Mr N.A. Maier
PHONE:	(08) 3039423
FAX:	(08) 3039424
ADDRESS:	GPO Box 397, Adelaide SA 5001

FUNDING ORGANISATIONS:	Horticultural Research & Development Corporation Potato Industry Trust Fund Committee McCain Foods (Aust) Pty Ltd

RESEARCH & DEVELOPMENT TEAM

SARDI/PISA---PRIMARY PROJECT OFFICERS

Mr N. A. Maier Senior Research Scientist, South Australian Research and Development Institute (SARDI).

Mr M. Heap Senior Extension Specialist, Primary Industries (South Australia) (PISA)

Mr M. Butt Agricultural Officer, South Australian Research and Development Institute (SARDI).

CSIRO---PRIMARY PROJECT OFFICERS

Dr M. J. McLaughlin Principal Research Scientist, CSIRO Division of Soils/CRC for Soil and Land Management, Adelaide.

Ms M. Smart Technical Officer, CSIRO Division of Soils/CRC for Soil and Land Management, Adelaide.

SARDI/PISA---SUPPLEMENTARY PROJECT OFFICERS

Mr A. P. Dahlenburg Senior Research Scientist, South Australian Research and Development Institute (SARDI).

Dr C. M. J. Williams Senior Research Scientist, South Australian Research and Development Institute (SARDI).

SUMMARY

A Project funded by the **Horticultural Research and Development Corporation** (HRDC), the **Potato Industry Trust Fund Committee** of South Australia and **McCain Foods (Aust) Pty Ltd** was conducted between July 1991 to June 1994, to study the effect of soil acidity on potato yield, quality and chemical composition. The **specific objectives of the study** were to determine the effects of ameliorating acidity on: **i)** tuber yield and size distribution; **ii)** quality factors including specific gravity, french fry and crisp colour, after cooking darkening and internal browning disorders; **iii)** cadmium accumulation in tubers; **iv)** the incidence,of disorders, for example, common scab and nutritional leaf roll; and potato crop nutrition, and therefore fertiliser requirements. Both field and glasshouse experiments were conducted, and the main cultivars we sudied were **Russet Burbank, Atlantic, and Kennebec**.

Of the **11 field experiments** we conducted, the application of calcitic lime significantly increased total tuber yield in only 1 experiment In the **7 glasshouse experiments,** liming significantly increased yield in 2 experiments (G1 and G7), decreased yield in 2 experiments (G3 and G5) and did not significantly affect yield in 3 experiments (G2, G4 and G6). Based on data for all field and glasshouse experiments, the **relationships between rate of applied lime and tuber yield response were of little predictive value.**

Field data suggest that for **siliceous sand/sandy loam over clay (Dr/Db/Dy) and siliceous sand (Uc) soils**, yield reductions of 10-20% were associated with the incorporation of 15-20 t/ha calcitic lime (over-liming). For these soils there was **no significant relationship between tuber yield and pH_w over the range 4.8-7.0, and pH_{Ca} over the range 4.3-6.5.**

Using pH alone to predict the yield response of potatoes to liming is unreliable.

The **application of calcitic lime on tuber quality was inconsistent** between experiments. The application of lime significantly increased SG, and decreased after-cooking darkening and improved medulla crisp or fry colour.

Based on leaf chemical composition early in the growing season we conclude that for **crops adequately fertilised, the application of calcitic lime appears not to have induced nutrient deficiencies.**

The uptake of cadminm by tubers was affected by liming, nitrogen and potassium source, zeolite, depth of incorporation of lime, and varied between cultivars. **In the field,the application of lime was ineffective in reducing cadmium uptake.**

MAJOR FINDINGS AND PRACTICAL IMPLICATIONS OF THE STUDY

SOIL pH

- For siliceous sand/sandy loam over clay (Db/Dy/Dr) and siliceous sand (Uc) soils, incorporation of 10-15 t/ha calcitic lime 3-8 weeks before planting, increased pH_w from 4.5-5.5 to 6.5-7.5.

- In field experiments, pH of the surface (0-15 cm) soils were significantly higher (1.0-1.5 unit) after liming compared with the 15-30 cm depth. This shows the limitation of 'rotary hoeing' as a method of incorporation.

- **Temporal variation:** There were significant changes in pH (0.2-0.5 unit) between planting and harvest. These changes may be affected by the chemical composition of the irrigation water.

- pH measured in water (pH_w; 1:5 soil:water) was highly correlated with pH measured using 0.01M $CaCl_2$ (pH_{Ca}). Coefficients of determination (r^2) were in the range 0.873-0.995). A pH_{Ca} was 0.4-0.7 of a unit less than pH_w.

- **Spatial variation**

  . Sampling apparently uniform paddocks, coefficients of variation (CV) were in the range 2.4-12.3%.

  . Differences in pH_w of up to 0.4-1.0 unit occurred in apparently uniform potato paddocks.

EXTRACTABLE NUTRIENTS IN THE SOIL

- The effects of liming on extractable P and K (Colwell procedure), and DTPA extractable Cu, Zn and Fe were inconsistent, small and of little practical significance.

- In the surface (0-15 cm) soils, extractable Mn (DTPA extraction) and Al ($CaCl_2$ extraction) concentrations decreased with liming/reduced soil acidity. In unlimed plot, extractable Al concentrations were in the range 0.4-4.4 mg/kg and appear to be low.

- Application of calcitic lime increased exchangeable Ca levels (cited studies).

TUBER YIELD AND THE PREDICTION OF YIELD RESPONSE

- In the field, liming siliceous sand/sandy loam over clay (Dr/Db/Dy) and siliceous sand (Uc) soils, significantly (P<0.05) increased total tuber yield in only **1 out of 11** experiments.

- In glasshouse studies with potted plants, the application of calcitic lime significantly (P<0.05) **increased** tuber yield in 2 experiments, **decreased** it in another 2 and had **no effect** in 3.

- Based on data for all field and glasshouse experiments, the relationships between rate of applied lime and tuber yield response were of little predictive value.

- Field data suggest that for siliceous sand/sandy loam over clay (Dr/Db/Dy) and siliceous sand (Uc) soils, yield reductions of 10-20% were associated with the incorporation of 15-20 t/ha calcitic lime (over-liming).

- For siliceous sand/sandy loam over clay (Dr/Db/Dy) and siliceous sand (Uc) soils, there is no significant relationship between tuber yield and pH_w over the range 4.8-7.0, and pH_{Ca} over the range 4.3-6.5.

- Using pH alone to predict the yield response of potatoes to liming is unreliable.

TUBER QUALITY

After-cooking darkening (ACD)

- Blackening appears to be reduced at higher pH ranges.
- High rates of lime significantly (P<0.05) decreased darkening in 3 experiments.
- Based on those experiments with ACD indicies >150, there was a negative relationship between rate of applied lime and relative ACD index. The application of 10-15 t/ha lime reduced ACD indicies by up to 60-65%.

♦ Crisp/Fry colour

- Stem-end crisp/fry colour was not affected by the application of calcitic lime.
- In many experiments, although the effects were not statistically significant, there were negative trends in medulla colour indicies (CI) with increasing rates of calcitic lime. The application of 10-20 t/ha of lime reduced medulla CI by 40-100%

♦ Tuber specific gravity (SG)/Dry matter content (%)

- Based on data for the cvv. Russet Burbank, Atlantic, Kennebec and Crystal the application of calcitic lime significantly increased the SG or dry matter content of tubers in both glasshouse and field experiments. However, the magnitude of the increase varied greatly between experiments

- The positive effect of liming on SG/dry matter coontent is consistent with many similar reports in the scientific literature.

♦ Internal browning (internal brown spot)

- The incidence of internal browning was highly variable between treatments and sites. The percentage of tubers affected ranged from 0 to 63.6%.
- The application of calcitic lime did not significantly affect the incidence on internal browning in any experiment.

♦ Hollow heart

- The incidence of hollow heart was generally low, with the percentage tubers affected ranging from 0-23.8%
- The application of calcitic lime did not significantly affect the incidence on hollow heart in any experiment.

GROWTH AND DEVELOPMENT

♦ In those experiments where tuber yield was significantly affected by liming, **plant height, leaf, stem and leaf+stem yields (d wt basis)** were also usually affected.

- In 4 experiments, the application of calcitic lime significantly **decreased the number of tubers set per plant**. The number of tubers set by potted glasshouse plants (12-60) was much higher than set by field grown plants (7-15).

- Liming did not significantly affect the **number of stems per plant** in any experiment. The number ranged from 3-11.

LEAF CHEMICAL COMPOSITION (early tuber set)

- The effects of liming on leaf nutrient content were variable and often not consistent between experiments. Overall, the effects of applying calcitic lime on the concentration of leaf nutrients may be summarized as follows:

  . **Decreased** - P, S, Cl, B, Mn and Zn
  . **Increased** - Ca and Mg
  . **No consistent effect** - N, Na, K, Cu and Fe

- The effect of lime on nutrient uptake, and therefore on growth, yield and quality responses, **may depend on the external supply of that nutrient**, including rates supplied in fertiliser.

- In our experiments, based on both plant analysis and the absence of symptoms of nutrient stress, **liming does not appear to have induced nutrient deficiencies**. In all experiments plants were fertilized with N, P, K, S and Ca. Magnesium and trace elements were usually not applied.

TUBER CHEMICAL COMPOSITION

- Chemical composition of tubers is variable, depending on cv., nutrient supply, soil type, season and portion of the tuber analysed.

- The application of calcitic lime tended to **increase** Ca and Mg concentrations in tubers and **decrease** P, Cl, Zn and Mn concentrations.

- For both tuber and leaf, there were significant differences between glasshouse and field experiments in the magnitude of the effects.

INCIDENCE OF SCAB

- During the course of our study the **incidence of visible symptoms of scab was non existent/very low**, therefore, data on the effects of calcitic lime on the incidence of scab could not be collected.

- It should be noted that inspite of applying lime at rates up to 20 t/ha, high incidence of scab infections did not occur in our experiments. The crops were planted and harvested within 8-10 months of applying the lime.

NUTRITIONAL LEAF ROLL

- No symptoms consistent with nutritional leaf roll were observed in our study even though the soils were strongly acid sand/sandy loams.

CADMIUM CONCENTRATIONS

- Application of lime either had **no effect** on or **increased** tuber Cd concentrations under field conditions.

- Under glasshouse conditons application of lime significantly **decreased** tuber Cd concentrations in 5 out of the 6 experiments conducted.

- There was a close correlation (r^2=0.71) between Cd concentrations in tubers and Cl concentrations in tubers grown under field conditions. No other elements either in tubers or in leaves correlated closely with Cd in the tuber.

- Application of single superphosphate containing Cd at rates up to 100 kg P/ha increased tuber Cd concentrations at 3 out of 6 field sites and in 1 of 2 glasshouse trials. Use of low-Cd superphosphate significantly decreased tuber Cd concentrations in the 1 glasshouse trial. it was tested

- In glasshouse experiments, comparison of ammonium sulfate, urea, ammonium nitrate and calcium nitrate as the source of N showed that use of calcium nitrate resulted in tubers with higher Cd concentrations compared to other N sources.

- Zeolite was effective under glasshouse conditions in **reducing** tuber Cd concentrations, but the rate of zeolite required and the cost would prohibit adoption by growers.

- In glasshouse experiments, the critical role of chloride in irrigation water leading to high Cd concentrations in tubers was demonstrated. In comparison, other anions (sulfate, bicarbonate) in irrigation water have little effect.

CONCLUSIONS/RECOMMENDATIONS

- **The major pracical implications (see pp. 4-9) and reommendations of our work are discussed in Appendix 1 (pp.20-40), which is an overview of the effects of ameliorating soil acidty on potato yield, quality, growth and chemcal composition.**

- Overall, the results of our study indicate that there were no consistently significant agronomic benefits from ameliorating soil acidity by, for example, applying agricultural lime prior to planting a potato crop, if the soil's pH (water) was >4.8. Indeed liming of soils to pH (water) values above 6.5-7.0 resulted in significant reductions in yield of tubers. Soil pH is a poor predictor of crop response to lime.

- High rates of applied calcitic lime (10-20 t/ha) significantly reduced after-cooking darkening and increased SG or tuber dry matter content of tubers in some experiments. However, these rates of calcitic lime were often associated with reduced yields.

- Applications of lime cannot be recommended as a means to reduce tuber Cd concentrations. Indeed, according to our work, under field conditions the application of lime has a greater chance of increasing tuber Cd concentrations rather than decreasing them as is commonly believed.

- Poor irrigation water quality was the greatest factor involved in producing tubers with high Cd concentrations, with Cl being identified as the problem ion. Growers wishing to produce tubers with low Cd concentrations should therefore use good quality irrigation waters with low Cl concentrations.

EXTENSION/ADOPTION BY INDUSTRY

♦ EXTENSION

The fingings of the study have been, and will continue to be, extended to Industry and technical colleagues by:

1. FIELD DAYS

2. GROWER MEETINGS

3. GROWER ARTICLES

4. TECHNICAL WORKSHOPS

5. FINAL REPORT

6. SCIENTIFIC PAPERS

♦ FACILITATE ADOPTION BY INDUSTRY

Many of the findings will be included in the **information packages** for growers and technical staff being prepared as part of PROJECT **PT428**, which started in July 1994.

DIRECTIONS FOR FUTURE RESEARCH

- It is important that the reasons for the discrepancy between data obtained in glasshouse and field experiments be determined. Possible factors which could lead to the differences in results obtained under glasshouse and field conditions are:

  (a) Inadequate time allowed for reaction of lime with soil.
  (b) Differential soil moisture conditions between glasshouse and field situations. and/or
  (c) Differences in water quality between glasshouse and field situations.

- The mechanism whereby lime may increase crop Cd concentrations needs to be identified so that soil and environmental factors which lead to this phenomenon can be identified and appropriate remediation techniques developed for these situations.

BACKGROUND

Potatoes are the main vegetable crop grown in Australia, estimated to be worth $314 million in 1993-94. In many parts of Australia potato crops are grown on strongly acidic (pH< 5.5, 1:5 soil: water) soils. For example, (i) in the Mount Lofty Ranges of SA, 167 potato paddocks were surveyed in 1987/88 and 31 (19%) had surface soil pH (1:5 soil:water) values < 5.5. In the Lower South East, 26 (58%) of the paddocks surveyed had surface soil pH (1:5 soil:water) values, 5.5; (ii) In the Ballarat region of Victoria, 47% of the 375 paddocks sampled had soil pH (1:5 soil:water) values < 5.4. Other surveys showed that 30% of the soil samples from Gippsland had pH values < 5.1 and on the Bellarine Peninsula, 19% were below pH 5.1 (K. Peverill, National Potato Industry Conference, Warragul 1990); and (iii) in N.W. Tasmania, a survey of 41 krasnozen soils showed that 50% of the surface soil samples had pH (1:5 soil:water) values <6.1 (range 5.2 - 6.9).

In spite of the widespread cropping of highly acidic soils for potato production in S.E. Australia, no detailed study of the effect of soil acidity on potato productivity and quality has been undertaken in Australia.

Potato crops are frequently grown in rotation with improved pasture (as part of cereal and/or grazing enterprises of dairying) and high rates of ammonium fertilisers may be applied. Potatoes also take up high amounts of cations, especially potassium, from the soil. All these factors contribute to soil acidification. Soil acidification is now recognised as a serious soil degradation problem. It is therefore important to develop management strategies for potatoes grown on acid, especially strongly acid, soils to ensure not only maximum productivity and quality, but also that production is sustainable in the long term.

Overseas research has shown that ameliorating soil acidity (eg. by liming) can affect tuber yield, specific gravity, internal browning, fry or crisp colour, after-cooking darkening, the incidences of diseases, for example, common and powdery scab and the availability of many plant nutrients. However, the magnitude of these tuber yield and quality responses are dependent on many factors, including soil type, potato cultivar grown and crop management practices. Therefore, general recommendations based on overseas results cannot be confidently made. Localised research, combining soil types, potato cultivars and management practices is essential to develop crop management strategies for improved yield and quality of potatoes grown on strongly acid soils.

Circumstances giving rise to our study on the effects of soil acidity on potato productivity and quality were:

(a) **Expansion of the area cropped** - Many soils used for potato production are naturally very acidic. The expanding french fry and crisp industries in SA will be largely reliant on potatoes grown on strongly acid (pH 4.5 - 5.5; 1:5 soil:water) sand - sandy loam soils.

(b) **Cadmium** - An important problem concerning the potato and phosphate fertiliser industries nationwide is cadmium residues in tubers. Management practices which reduce/minimise cadmium uptake need to be identified. Liming soils may be one such practice.

(c) **Soil acidification** - Soils used for potato production are often light textured and naturally acidic. These soils are at risk from accelerated acidification, due to their use for agricultural production, for example, grazing, dairying and cropping. Management practices, such as the use of nitrogen fertilisers, the growing of clover based (improved) pastures and the removal of organic farm products (eg. hay or tubers), contribute to soil acidification. Soil acidification is an increasingly important problem and the development of management practices which minimise acidification and/or ameliorate soil acidity, is important to ensure sustainable production in 'sensitive' areas. For potatoes such strategies have not been developed.

(c) **Changes in grower practice** - For example, growers are now expected to grow new cultivars for specific end uses. Overseas studies have reported that cultivars may have different optimum or 'preferred' pH ranges. It is therefore particularly important to know the preferred pH ranges of cultivars grown for the major french fry and crisp manufacturers (eg. Russet Burbank and Atlantic) and important fresh market cultivars (eg. Crystal and Pontiac). These data will have implications for cultivar breeding and evaluation programs

OBJECTIVES

The overall aim of the project was to develop crop management strategies for improved productivity and quality of potatoes grown in highly acid soils and to integrate these strategies into existing crop production technology developed by the investigation team.

SPECIFIC RESEARCH OBJECTIVES WERE:

(a) To determine the effect of soil acidity on:

. Tuber yield (total, marketable and tuber size distribution).

. Tuber quality (for example, specific gravity, french fry and/or crisp colour, after-cooking darkening,internal browning disorders and hollow heart).

. Cadmium concentration in tubers

. The incidence of diseases, in particular, common scab.

. Variety performance.

(b) To asses the use of lime to ameliorate soil acidity in a potato production system. In particular, placement and timing of lime applications.

(c) To determine the effect of soil acidity on nutrient uptake by plants and the implications of this for crop nutrient management and fertiliser requirement.

(d) To study the relationship between soil acidity and nutritional leaf roll.

TECHNICAL PAPERS

Introductory technical information, research methodology, results and discussion of the data in relation to the objectives are presented in a series of papers which are listed below. The papers are grouped under the project objectives which they address.

To determine the effect of soil acidity on potato growth, yield, quality and chemical composition

APPENDIX 1 (Pages 20-40)

An overview of the effects of soil acidity and calcitic lime on extractable nutrients in the soil , and yield, quality, incidence of disease and chemical composition of potatoes (Solanum tuberosum L.)

APPENDIX 4 (Pages 76-91)

Effect of lime and nitrogen source on the yield, growth, leaf nutrient composition and cadmium concentrations in potatoes (Solanum tuberosum L.)

APPENDIX 7 (Pages 103-107)

Effect of current seasons gypsum and lime applications on the yield, quality, leaf chemical composition and cadmium concentrations in potatoes (Solanum tuberosum L.)

APPENDIX 8 (Pages 108-111)

Comparison of the effect of zeolite and lime on the yield, growth, leaf chemical composition and cadmium concentrations in potatoes (Solanum tuberosum L.)

To determine the effect of soil acidity on nutrient uptake and cadmium accumulation by potatoes

APPENDIX 2 (Pages 41-59)

Effect of current seasons lime applications on the yield and cadmium concentration of potato tubers (Solanum tuberosum L.)

APPENDIX 3 (Pages 60-75)

Effect of lime and phosphorus on the growth, yield and N, P, and Cd concentrations in potatoes (Solanum tuberosum L.)

APPENDIX 4 (Pages 76-91)

Effect of lime and nitrogen source on the yield, growth, leaf nutrient composition and cadmium concentrations in potatoes (Solanum tuberosum L.)

APPENDIX 5 (Pages 92-98)

Effect of lime, chloride concentration in irrigation water and soil type on the yield, growth, leaf nutrient composition and cadmium concentrations in potatoes (Solanum tuberosum L.)

APPENDIX 6 (Pages 99-102)

Further studies into the effects of anions added to irrigation water, lime and soil type on growth, yield and cadmium concentrations in potatoes (Solanum tuberosum L.)

APPENDIX 9 (Pages 112-115)

Effect of depth of incorporation of lime on soil pH and conductance, and cadmium concentrations in potato (Solanum tuberosum L.)

APPENDIX 10 (Pages 116-119)

Effects of sulfur and lime on soil pH, conductance, yield and cadmium concentrations in potatoes (Solanum tuberosum L.)

Compare methods of determination and assess sampling error

APPENDIX 11 (Pages 120-121)

Relationship between pH determined using water and calcium chloride.

APPENDIX 12 (Pages 122-123)

Variability in soil pH.

ACKNOWLEDGMENTS

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APPENDIX 1

AN OVERVIEW OF THE EFFECTS OF SOIL ACIDITY AND CALCITIC LIME ON EXTRACTABLE NUTRIENTS IN THE SOIL, AND YIELD, QUALITY, INCIDENCE OF DISEASE AND CHEMICAL COMPOSITION OF POTATOES (*SOLANUM TUBEROSUM* L.)

INTRODUCTION

the effects of calcitic lime (limestone), phosphorus (P), nitrogen (N) source, irrigation water quality, gypsum and zeolite on growth, yield, chemical composition and tuber quality. The main cvv. studied were Atlantic, Russet Burbank and Kennebec. **In this paper we discuss the effects of soil pH and lime on selected chemical properties of the soil, yield, tuber quality and chemical composition. Our findings are also compared with data from published studies and practical implications of the studies are emphasized.** Specific details and methodologies used in the experiments are presented in subsequent papers in this report.

The following points should be noted:

(I) The lime was incorporated into the soil 3-8 weeks before planting.

(ii) We conducted both pot (glasshouse) and field experiments. With pot experiments, we were able to achieve very thorough incorporation of the lime into the soil (see Appendix 2), lime the whole rooting volume of the plant and ensure an effective period of moist incubation. With field experiments, the lime was spread by hand and incorporated using a rotary hoe, which therefore limits incorporation to 15-20 cm.

(iii) All field experiments were conducted in South Australia and the soils for the glasshouse work were obtained from potato growing areas in the Mt Lofty Ranges

(Yundi and Forreston), lower South East and, for use in 1 experiment (experiment G7), from Ballarat in Victoria. *For the glasshouse studies, the soils from South Australia were sand-sandy loams (see Table 2, Appendix 1) and from Victoria a krasnozem. For the field experiments the soils were also siliceous sand/sandy loam over clay (Db/Dy/Dr) or siliceous sand (Uc) soils (see Table 2, Appendix 1).*

(iv) Depending on soil test data and soil type we applied N, as ammonium nitrate; K, as potassium sulfate; and P, as superphosphate in the basal dressing and as side-dressings of N and K to ensure these nutrients were not limiting yield response.

(v) The chemical analyses used are described in Appendix 1. Specific gravity was determined by the weight in air - weight in water method (Maier *et al.* 1986). For crisp colour determination, up to 10-15 tubers were selected from each plot, washed, and cut in half by cutting longitudinally through the stolon scar and bud-end of each tuber. A 10 mm slice was cut from one half for after-cooking darkening assessment and the other half was quartered by again cutting through the stolon scar and bud-end of the tuber. A 1 mm slice was cut from one quarter for cooking. The crisp colour assessment procedure and calculation of a colour index (CI) for the vascular ring and medulla region of the crisp were described in Dahlenburg *et al.* (1990). The after-cooking darkening (ACD) assessment procedure and calculation of an ACD colour index was described in Dahlenburg and Maier (1989). The greater the CI values the darker the crisps.

SOIL ACIDITY (pH)

Murphy *et al.* (1967) working in the USA, found that the application of 3.8 t/ha increased soil pH by 0.5-1.0 units and the application of 7.6 t/ha increased pH by only a further 0.2-0.4 of a unit. The pH values of the nil lime plots were in the range 4.7-5.5, depending on the year. There were no significant interactions between lime and the fertiliser treatments. Bolton (1977) reported that increasing the rate of applied lime from nil to 20 t/ha increased soil (0 - 20 cm) pH (in water) from 4.5 to 6.5 at 1 site, and from 4.8 to 6.7 at another. However, when a complete NPKMg fertiliser was applied the application of lime did not significantly affect yield at either site. Hossner and Doll (1970) reported the application of 6.7 t/ha of hydrated lime increased soil pH (1:1 soil:water ratio) after harvest from 4.7 to 6.0 in the first year of their study, and from 6.0 to 7.0 in the second. The application of lime did not significantly affect tuber yield in either year. However, in the first year there was a significant increase in yield due to the application of Mg fertiliser, this effect did not occur in the second year and this was attributed to the higher pH of the unlimed plots in that year.

In our glasshouse experiments the pH of the unlimed pots were in the range 4.3-5.1 and the application of 10-20 t/ha lime increased the pH to 6.6-7.4 (Figure 1). Similarly in the

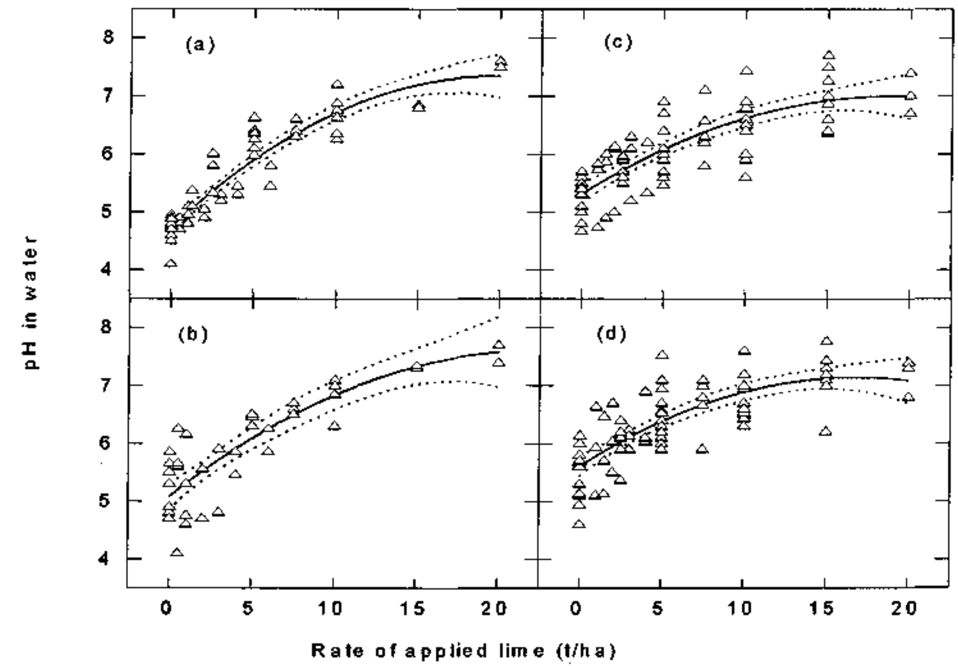

Figure 1. Effect of applied lime on pH_w determined at planting (a,c) and harvest (b,d) for glasshouse (a,b) and field experiments (c,d). For the field experiments, data are for the 0-15 cm soils.

field experiments, pH in the surface 0-15 cm increased from 4.7-5.7 to 6.4-7.7. In Experiment G6, there was a significant difference between soil types in the rate of lime required to increase pH. For example, increasing the rate of lime from 0, 2.5, 5 and 10 t/ha increased the pH of the sand from 4.7, 6.0 and 6.9, respectively; for the loamy sand, the corresponding pH values were 4.9, 5.3 and 6.6.

In the field experiments, the pH of the 16-30 cm layers were significantly lower compared with the 0-15 cm soil layers (see Appendix 2). This shows the limitations of the method of incorporation (rotary hoeing) used in these experiments. There were also significant changes in pH between planting and harvest. However, these changes were small compared with the effects of lime and soil depth in the field experiments (see Appendix 2).

EXTRACTABLE NUTRIENTS IN THE SOIL

Murphy *et al.* (1967) showed that the application of lime significantly increased extractable P and exchangeable Ca in the soil and decreased exchangeable K (P<0.05) levels. Bolton (1977) reported that the application of lime, at rates up to 20 t/ha, did not affect exchangeable K and Mg, and extractable P concentrations in the soils at 2 sites. Exchangeable Ca and Mn concentrations were significantly (P<0.05) increased. Hossner and Doll (1970) found that liming increased exchangeable Ca levels in both years of their study and increased exchangeable K in the first year. Lee and MACDonald (1977) reported that the application of dolomite significantly decreased extractable Al and Mn concentrations. van Lierop *et al.* (1982) found that liming decreased the mean extractable Mn and Al (1 *N* KCl) concentrations by 12-15% and 53%, respectively and increased exchangeable Ca from 0.07-2.1 meq to 1.4-3.3 meq/100 g.

In our study the effects of liming on extractable P and K (Colwell method) and DTPA extractable Cu, Zn and Fe were inconsistent, small effects of little practical significance (data not presented). In contrast, liming significantly (P<0.05) decreased the amount of extractable Mn and Al ($CaCl_2$ extraction) (Table 1). Extractable Al concentrations were relatively low and consistent with values reported for sand/sandy podzolic soils by Richards (1992).

Table 1. Effect of applied lime on extractable Mn and Al concentrations

	Glasshouse experiments				Field experiments		
	G1	G2	G3	G4	F1	F2	F3
	DTPA-extractable Mn (mg/kg)						
0	0.98	2.33	13.03	1.93	3.2	14.7	23.0
1	0.98	2.03					
5	0.67				2.3	8.3	14.3
7.5			1.93				
10	0.42	1.78					
15		1.90		1.22	2.2	7.3	6.3
l.s.d. (P=0.05)	*0.42*	*n.s.*	*0.29*	*0.45*	*n.s.*	*6.2*	*9.2*
	$CaCl_2$-extractable Al (mg/kg)						
0	1.60	2.88	n.a.	n.a.	0.40	0.87	4.4
0.5	1.03	6.78					
1	2.20	4.00					
5	0.15				0.20	0.27	0.63
10	0.09	0.25					
15		0.33			0.17	0.23	0.17
l.s.d. (P=0.05)	*0.60*	*2.26*			*0.20*	*0.51*	*0.78*

YIELD AND THE PREDICTION OF YIELD RESPONSE

Murphy *et al.* (1967) have reviewed early studies into the effects of lime on potato yield. Their discussion showed that the effect of lime was not consistent between studies. For example, the rates of lime required to optimise yield and the soil pH at which significant responses occurred varied significantly. They also reported that the incorporation of up to 7.6 t/ha of lime into the surface layer significantly reduced the tuber yield of Katahdin and Russet Burbank potatoes. They could not provide an explanation for the inverse lime - yield relationship. Jackson *et al.* (1982) working in Oregon with soils derived from pumice-volcanic ash parent material, found that tubers yields decreased significantly as pH increased from 4.5 to 6.4. The application of lime did not affect the K response and the lime x K interaction was not significant.

Bolton (1977), working in Britain, reported that for the cv. Pentland Crown grown in a sandy-clay loam, total tuber yield was not affected by liming at 2 sites if a complete NPKMg fertiliser was applied. Mean yields in 1974 were 56.4 and 57.6 t/ha at the 2 sites. However, on plots to which no P fertiliser has been applied since 1962, tuber yields were lower on acid plots and yields were increased by liming to near pH 6.0. Response to P fertiliser was reduced by liming. Response to Mg and K fertilisers was also found to be pH dependent. For example, responses to applied K were larger on the limed than unlimed soils. On plots which received no fertiliser K, yields were decreased by liming at the 2 sites.

MacLean *et al.* (1967) found that liming acid peat soils (Histosols) to pH (in water) above 4.1-4.3 did not increase yield. These soils may be low in extractable Al and Mn. Hossner and Doll (1970) studied the effects of applied lime and Mg, and soil K concentrations on the yield of potatoes (cv. Sebago) grown in a loamy sand. In 2 experiments over 2 years the application of 6.7 t/ha of hydrated lime did not significantly increase tuber yield. However, in 1 experiment the application of Mg significantly increased yield and the relative increase was greater on unlimed than on limed plots. The application of lime also reduced the yield depression due to the application of high rates of K in 1 experiment.

Lee and MACDonald (1977) used pot experiments to study the growth and yield of the cvv. Netted Gem, Sebago, Katahdin and Green Mountain grown in loam soil (Ultisol) at pH 4.6, 5.3 and 5.7 (1:1 soil:water ratio). Dolomite was added to the soil in each pot to obtain the higher 2 pH levels. In both experiments raising the pH of the soils from 4.6 to 5.3 or 4.6 to 4.9 significantly increased tuber yield. Raising the pH to 5.7 or 5.2 did not result in a further increase in yield. In 1 experiment healthiest tops were observed at pH 5.3 and plants growing in soil at pH 4.6 exhibited typical Mn toxicity symptoms (Black specks on lower stems and petioles and leaves dropped prematurely).

van Lierop *et al.* (1982) reported on a pot experiment which studied the effects of liming on tuber (cv. Kennebec) yields. Eight sandy soils (Spodosols) typically used for potato production in Quebec were used. The pH (1:1 soil:water ratio) of the unlimed soils ranged from 4.6 to 5.0. The application of lime significantly increased tuber yield (mean of 40%) on 3 of the 8 soils. Increases in yield did not generally occur above pH 4.9. However, the use of pH to predict yield response was limited, for example, plants growing in 1 strongly acid (pH 4.4) soil did not respond to liming. They suggested to more reliably predict yield response to liming a triple-norm classification (pH, extractable-Al and extractable-Mn) should be used.

The references cited show that the predictability of yield responses to the application of lime is complex. This may be due in part to the multiplicity of problems associated with acid soils or factors affected by liming (Helyar 1987). For example:

- toxicities (Al, H^+ and Mn).
- Deficiencies (Ca, Mg and Mo)
- soil structure
- microbial activity/incidence of disease

Of the 11 field experiments we conducted, the application of lime significantly ($P<0.05$) increased total tuber yield in only 1 experiment (F9) (see Appendix 2). In this experiment increasing the rate of applied lime from nil to 5 t/ha increased yield from 50.3 to 63.9 t/ha in 1992/93 (see Appendix 2). However, the application of lime at 10 t/ha significantly decreased yield to 54.4 t/ha. The experiment was repeated in 1993/94, and again increasing the rate of lime from nil to 5 or 10 t/ha significantly increased the yield of the cvv. Atlantic and Russet Burbank from 88.1 to 94.6, and 64.1 to 90.3 t/ha, respectively. At all other sites the effect of lime was not significant. **In the 7 glasshouse experiments, liming significantly increased yield in 2 experiments (G1 and G7), decreased yield in 2 experiments (G3 and G5) and did not significantly ($P>0.05$) affect yield in 3 experiments (G2, G4 and G6)** (see Appendix 2). The yield responses are discussed below in relation to leaf nutrient composition.

We found that for potatoes grown in sand/sandy duplex soils (e.g. red or yellow podzolic), **the relationships between rate of applied lime and yield response were poor for both field and glasshouse experiments** (Figure 2). For the field experiments, the data suggest that yield depression was associated with the application of 15 or 20 t/ha lime (over liming) (Figure 2).

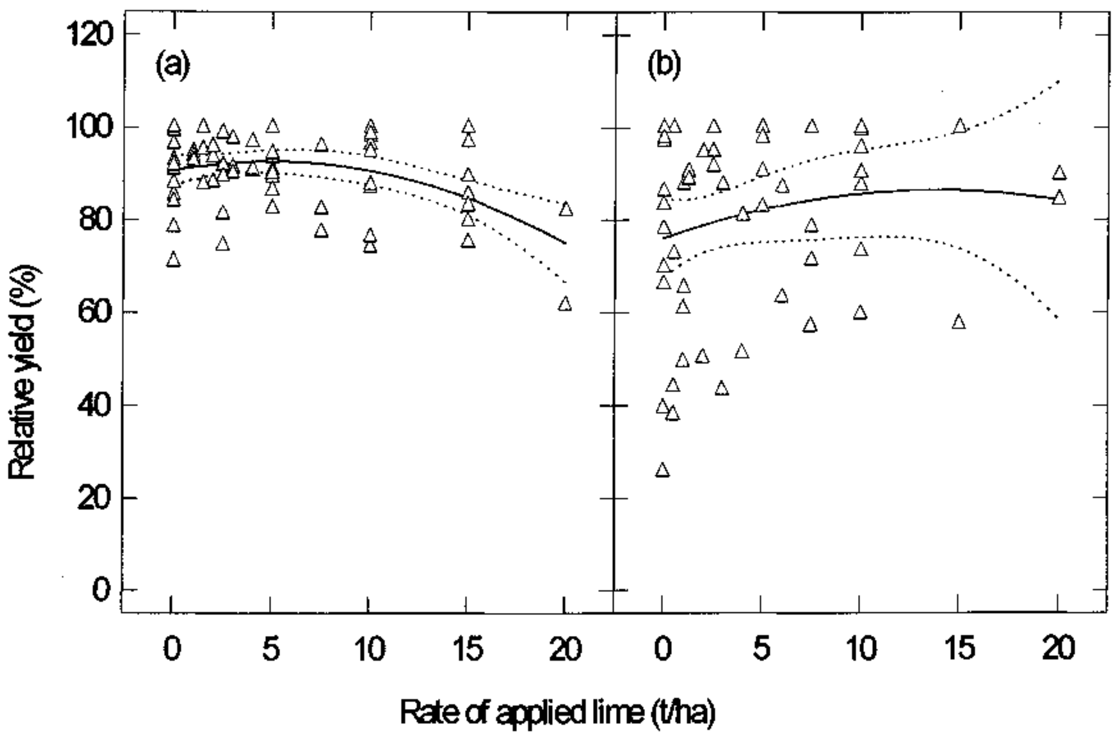

Figure 2. Relationships between rate of applied lime and relative yield for (a) field and (b) glasshouse experiments. Data are based on all experiments over the 3 years of the study.

Based on all field experiments, the relationships between yield response and pH_w (4.7-7.7) and pH_{Ca} (4.2-6.9) in the surface (0-15 cm) soil were poor (Figure 3).

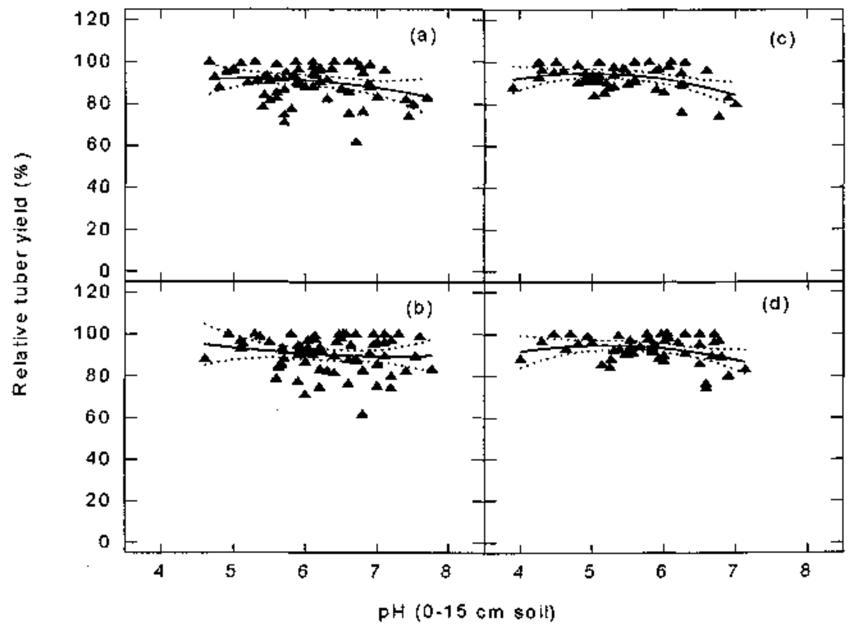

Figure 3. Relationships between pH_w (a,b) and pH_{Ca} (c,d) determined at planting (a,c) and harvest (b,d). Data are based on all field experiments and for 0-15 cm soils.

The data suggest that liming to pH_w=7.5 or pH_{Ca}=7 was associated with yield reductions of approximately 20%. For the glasshouse experiments, the relationships were similarly poor and the data are not presented.

Based on our work, and the references cited, **we conclude that using pH alone to predict yield response of potatoes to liming is unreliable.**

TUBER QUALITY

Murphy *et al.* (1967) reported that the application of 3.8 t/ha of lime significantly reduced SG of Katahdin potatoes from 1.075 to 1.074. For the cv. Russet Burbank, the application of lime up to 7.7 t/ha increased SG from 1.066 to 1.068. They concluded that the changes were not of sufficient magnitude to be of practical significance. Mondy *et al.* (1987) for the cv. Katahdin grown in a fine sandy loam found that banding dolomite (56 kg/ha

MgO) a planting discoloured more, were higher in phenols and lower in Mg content compared with control tubers. Smith and Nash (1940) found that there were significant relationships between soil pH and SG and degree of mealiness. Increasing the pH ranges from 4.9-5.3, 5.9-6.4 to 6.6-7.2, mean SG increased from 1.084, 1.085 and 1.087, respectively. The degree of mealiness also increased. In the pH range 6.7-7.6 the degree of blackening was significantly reduced. Smith (1977) concluded that the per cent starch of tubers from plants grown in a soil with pH 5.6-6.1 was higher compared with plants grown at either pH 4.7-4.9 or pH 7.2-7.5. Lee and MACDonald (1977) reported a significant soil pH x cv. interaction for SG. The application of dolomite increased SG from 1.072 to 1.085-1.086 depending on rate.

After-cooking darkening (ACD): High rates of applied lime (10-20 t/ha) significantly reduced the ACD indices from 166 to 106 in experiment G2; and in experiments F1 and F2 from 201 to 86, and 213 to 144, respectively. In many other experiments, although the effects were not statistically significant, there were negative trends in ACD due to the application of lime. Based on those experiments were the maximum ACD index was >150, there was a significant negative relationship between rate of applied lime and relative ACD index (Figure 4). The application of 10-15 t/ha lime reduced ACD indices by up to 60-65% in some experiments. Smith and Nash (1940) also reported reduced blackening at higher pH ranges (see above).

Crisp/fry colour: Analysis of variance showed that there were no consistent significant effects on medulla or stem-end crisp or fry colour indices due to liming in our study (data are not presented). However, at many sites, although the effects were not statistically significant, there were negative trends with increasing rates of lime. Based on both glasshouse and field experiments, the data show that the application of 10-20 t/ha lime decreased medulla colour indices by 40-100% (Figure 4). The application of lime did not significantly reduce stem-end browning in the cv. Russet Burbank (Figure 4).

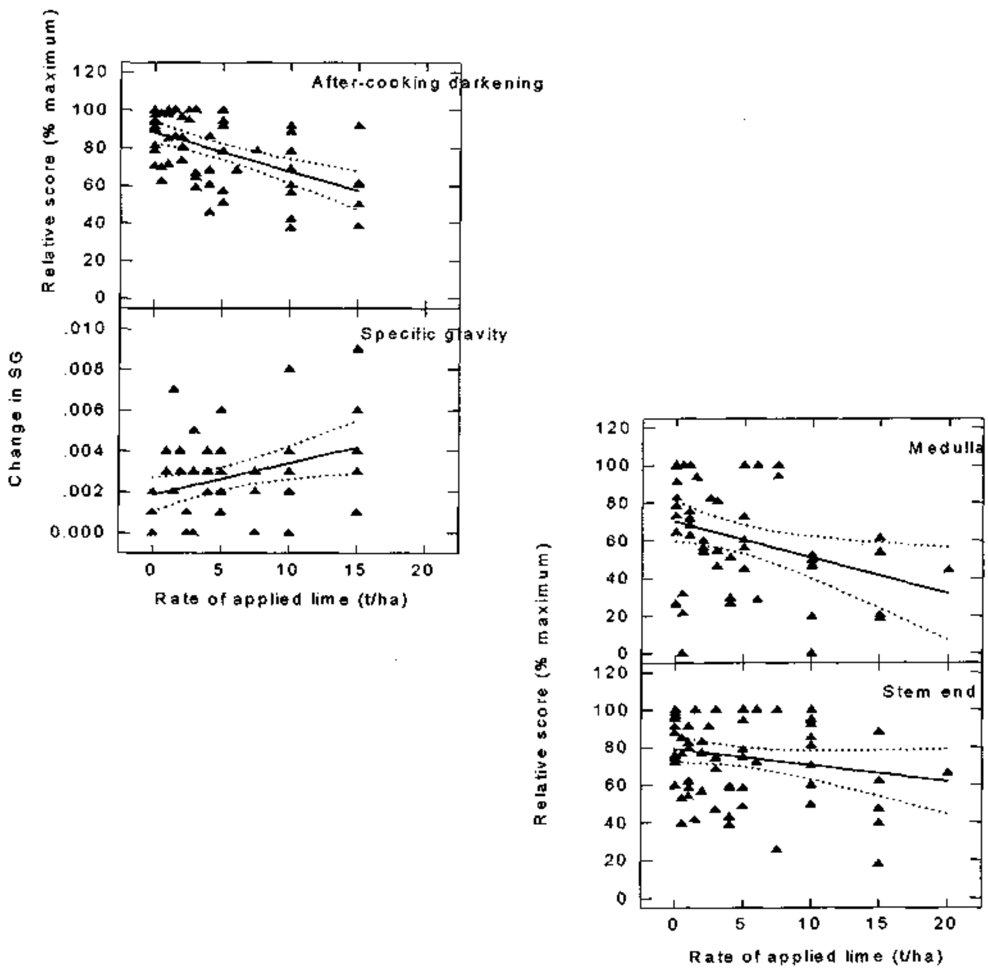

Figure 4 Relationships between rate of applied lime and relative crisp colour and after-cooking darkening indices, and changes in specific gravity. Data are for glasshouse and field experiments and mainly for the cvv. Russet Burbank, Atlantic and Kennebec.

Specific gravity (SG) or dry matter(%): Based on the cvv. Russet Burbank, Atlantic and Kennebec and Crystal, the application of lime significantly increased the SG or dry matter content of tubers in both glasshouse and field experiments (Table 2).

Table 2. Effect of applied lime on SG or dry matter content (%) of tubers for glasshouse and field experiments

Rate	Glasshouse		Field				
(t/ha)	G2	G5	F2	F4	F5	F7	F9
0		20.1	1.078	1.076	1.078	1.062	1.078
1			1.079				
2			1.080				
5		24.0	1.082		1.080	1.066	1.080
7.5				1.078		1.065	
10		22.5	1.084		1.077		1.080
15			1.085	1.080		1.068	
20		23.0					
l.s.d.(P=0.05		*1.9*	*0.006*	*0.002*	*0.002*	*0.003*	

However, the magnitude of the increase varied considerably between experiments (Figure 4) and in some cases were not of sufficient magnitude to be of practical significance.

The positive effect of liming on SG is consistent with many reports of similar effects in the scientific literature (see above). We cannot explain this effect, however, it is of interest that the application of lime also reduced Cl concentrations in leaves and tubers (Tables 5 and 6). Reduced Cl uptake is important because SG has been reported to be inversely correlated with leaf or tuber Cl concentrations.

Internal browning: The incidence of internal browning varied considerably between lime rates and experiments. For example for each experiment, the variation between the different rates of lime in the per cent tubers showing internal browning symptoms was: G4 and F4, 0%; G5, 0-63.6%; G6, 0-16.3%; F1, 15.6-35.0%; F3, 0-18.8%; F5, 42.2-48.4%; and F9, 4.8-7.8%. However, **liming did not significantly affect the incidence of internal browning at any site**, and therefore, accounted for very little of the variation found. Reports on work in America suggest that the incidence of internal browning can be reduced by ...' enhancing Ca nutrition' (Thorne 1991).

Hollow heart: The incidence of hollow heart was negligible in most experiments and **was not significantly (*P*>0.05) affected by rate of applied lime.** Depending on the lime treatments, the percentage of tubers showing hollow heart was 0% in experiments F4, G4 and G5, and ranged from: G6, 0-10%; F1, 02.2-6.7%; F4, 0-2.1%; F5, 15.2-23.8%; and F9, 0-1.5%.

GROWTH AND DEVELOPMENT

Growth and development data for example, plant height and weight of leaves, stems and total tops, were collected during many of experiments. These data are reported in detail in later sections of this report. In this section we only discuss the effects of liming on the number of stems and tubers per plant.

Tubers/plant: The effect of applied lime on the number of tubers/plant was determined in 5 glasshouse and 5 field experiments. **In 4 experiments liming significantly decreased the number of tubers set.** For example, the application of 15 or 20 t/ha of lime decreased the number of tubers per plant from 60 to 35 in experiment G2; 18 to 12 in G3; 31 to 9 in G5; and 10 to 8 in F6. It should also be noted that the number of tubers set by glasshouse plants (12-60) was much higher than set by field plants (7-15).

Stems/plant: The application of lime did **not significantly affect the number of stems per plant in any experiment.** Depending on the lime rates, the number of stems per plant ranged from: G1, 5-6; G2, 6-8; G4, 9-11; G5, 3; G6, 6-7; F1, 4; F5, 4; and F6, 4-5.

LEAF OR PETIOLE CHEMICAL COMPOSITION

Jackson *et al.* (1982) reported that at low pH (pH=4.5) nitrate-N in petioles was reduced. They suggested this may be due to reduced nitrification of ammonium-N applied. Bolton (1977) found that increasing rates of lime increased P concentrations in leaves especially if P fertiliser was omitted. At nil P, concentrations increased from 0.15-0.16 to 0.20-0.25% P. Magnesium and Ca concentrations also significantly increased. For example, for Mg concentrations increased from 0.06-0.29% at nil lime to 0.12-0.47% at 20 t/ha. Similarly for Ca, concentrations increased from 0.95-1.13% to 1.88-2.42%. In contrast, K concentrations in leaves significantly decreased from 1.39-6.28% to 0.52-4.98% K with increasing rates of lime. Hossner and Doll (1970) reported that the liming increased Ca concentrations in petioles sampled 6 and 16 weeks after planting. For example, at 6 weeks concentrations increased from 0.22-0.38% at nil lime, to 0.36-0.50% at 6.7 t/ha hydrated lime. The effects of lime on Mg and K concentrations were not significant (P>0.05) in either year.

Lee and MACDonald (1977) found that the application of dolomite significantly decreased Al, Mn and K concentrations in leaves of plants grown in pots. They sampled the 3rd leaf when 10% of the plants were flowering). The Mn concentration in leaves of plants grown with nil dolomite (pH 4.6) was 1,764 mg/kg. When dolomite was applied concentrations were 482 or 320 mg/kg. The application of dolomite significantly increased Ca (1.10 to 1.35%) and Mg (0.20 to 0.51%) concentrations and did not affect P (0.24-0.26%) concentrations. van Lierop *et al.* (1982) also reported that liming significantly decreased Mn concentrations in whole tops. For example, for the soils with which yield responses occurred, mean Mn concentrations in tops decreased from 970 to 390 mg Mn/kg.

Nitrogen: Liming did not significantly affect N concentration in the 5th leaf at any site, and at nil lime, concentrations ranged from 4.9-6.6% (Table 3). In the glasshouse experiments, increasing the rate of applied lime from nil to 10 t/ha significantly decreased N concentrations from 7.4 to 5.7%. Nitrogen concentrations in the range 5.0-6.5% at early tuber set indicate adequate N nutrition (MACKay et al. 1966; Piggott 1986). These standards show that the N nutrition of our plants was adequate and not limiting yield or growth responses.

Phosphorus, sulfur and chloride: Helyar (198) reported that ... 'the capacity of a soil to retain anions increases with increasing acidity'. Our results (Table 3) were consistent with this suggestion. Depending on the study P concentrations in the range 0.2-0.4% (Piggott 1986), 0.35-0.55% (Piggott 1986) and 0.39-0.46% (MACKay et al. 1966) have been reported to indicate adequate P nutrition. These data suggest that at nil and maximum rates of lime P nutrition of the plants was adequate. Our results for P contrast with those of Bolton (1977) who reported increasing concentrations with liming, depending on P supply.

Sodium: Liming did not significantly affect Na concentrations in any experiment. Sodium concentrations varied greatly between experiments. For example, at nil lime Na concentrations ranged from 0.004 to 0.188% in the glasshouse experiments and from 0.03 to 0.173% in the field experiments. Quality of irrigation water may be a significant factor in explaining this variation.

Potassium: Liming significantly decreased K concentrations in only 1 experiment (F7, 6.1 to 4.8%). The range in K concentrations in the 5th leaf (Table 3) show that at nil and maximum rates of applied lime K concentrations were adequate when compared with standards reported by Piggott (1986; 3.5-5.0;4.5-6.5%) and MACKay *et al.* (1966; 2.6-3.1%). Bolton (1977) suggested that at the 10% flowering stage, yield responses were associated with K concentrations <4% in youngest fully mature leaves. In our study, all K concentrations were greater than this value (Table 3).

Table 3. Mean (s.e.m.) and ranges for nutrient concentrations in 5th leaf at nil and maximum (10, 15 or 20 t/ha) rates of applied lime

Nutrient	Lime rate	Glasshouse (n=3-4) Mean	s.e.m	Range	Field (n=9) Mean	s.e.m	Range
N (%)	Nil	6.4	0.5	5.8-7.4	5.6	0.2	4.9-6.6
	Max.	6.1	0.2	5.7-6.4	5.6	0.5	4.8-6.2
P (%)	Nil	0.76	0.08	0.73-0.45	0.44	0.02	0.34-0.59
	Max.	0.60	0.09	0.53-0.45	0.42	0.02	0.32-0.58
K (%)	Nil	6.0	0.6	4.9-7.6	5.8	0.2	4.8-6.8
	Max.	6.4	0.8	5.2-8.6	5.5	0.2	4.7-6.7
Na (%)	Nil	0.058	0.043	0.004-0.188	0.075	0.018	0.030-0.173
	Max.	0.024	0.008	0.005-0.045	0.083	0.024	0.033-0.257
Cl (%)	Nil	0.88	0.20	0.50-1.12	1.68	0.29	0.73-3.04
	Max.	0.71	0.11	0.49-0.87	1.43	0.33	0.72-3.89
Ca (%)	Nil	0.47	0.14	0.27-0.89	1.04	0.11	0.58-1.55
	Max.	1.03	0.21	0.67-1.58	1.27	0.09	0.89-1.54
Mg (%)	Nil	0.32	0.05	0.23-0.44	0.51	0.05	0.22-0.71
	Max.	0.41	0.03	0.35-0.48	0.52	0.06	0.23-0.77
S (%)	Nil	0.85	0.28	0.42-1.62	0.41	0.03	0.28-0.57
	Max.	0.57	0.04	0.46-0.64	0.40	0.03	0.27-0.53
B	Nil	26	2	24-30	25	2	20-35
(mg/kg)	Max.	15	2	12-19	22	2	9-36
Cu	Nil	10	2	8-15	10	1	5-20
(mg/kg)	Max.	11	2	4-22	9	1	5-15
Mn	Nil	120	8	95-132	152	26	55-253
(mg/kg)	Max.	57	7	43-74	82	15	18-143
Zn	Nil	122	30	71-208	35	3	26-52
(mg/kg)	Max.	71	15	38-108	31	2	24-48
Fe	Nil	133	28	105-189	231	47	96-549
(mg/kg)	Max.	123	37	84-197	230	39	110-423

Calcium and magnesium: The application of lime increased Ca concentrations in the 5th leaf and the effect was greater for the glasshouse experiments compared with the field experiments (Table 3). In experiments G1, G5, F2 and F7 liming significantly increased Mg concentrations in the 5th leaf. Bolton (1977) suggested a critical Mg concentration of 0.18% in leaves sampled at the 10% flowering stage. The range in Mg concentrations presented in Table 3 show that concentrations in our study were higher than 0.18% at all sites

Boron: The application of lime significantly decreased B concentrations in some experiments (Table 4). In our study, the application of 10-20 t/ha lime resulted in leaf B concentrations as low as 9-12 mg /kg (Tables 3 and 4). Boron concentrations of 25-30 mg /kg in leaves sampled early in the season are considered adequate (Harrison *et al.* 1982; Piggott 1986).

Table 4. Effect of applied lime on boron concentrations (mg/kg) in 5th leaf for glasshouse and field experiments

Rate	Glasshouse			Field						
(t/ha)	G1	G2	G5	F1	F2	F3	F4	F5	F7	F8
0	30	24	26	20	26	25	25	22	35	20
1	25	30		20	24	23				
2		21		19	25	25				
5	20		25	18	24	23		21	34	13
7.5							20		34	10
10	14	17	20	16	23	23		19		
15		12		17	22	22	19		36	9
20			19							
l.s.d. (P=0.05)	*7*	*8*	*7*	*(1)*	*(1)*	*n.s.*	3	*1*	*n.s.*	5

Copper and iron: The application of lime did not consistently affect Cu concentrations in the 5th leaf. Concentrations in the range 5-15 mg/kg in leaves sampled early in the season appear to adequate for optimum growth. The range of concentrations at nil and maximum rates of applied lime fall within this range (Table 3). Liming did not significantly Fe concentrations at any site, and the range in concentrations are presented in Table 3.

Manganese: The application of lime significantly decreased Mn concentrations in 5th leaf in 4 glasshouse and 7 field experiments (Tables 3 and 5). Lee and MACDonald (1977) potatoes grown in a Caribou loam soil at pH 4.6 exhibited typical Mn toxicity symptoms and the Mn concentrations in leaves were 1,764 or 2,879 mg/kg. Liming reduced concentrations to 320 or 624 mk/kg. van Lierop *et al.* (1982) also reported Mn concentrations in potato tops in the range 100-1500 mg/kg. The leaf Mn concentrations obtained in our study (Table 3) were lower than values reported in the 2 studies cited.

Table 5. Effect of applied lime on manganese concentrations (mg/kg) in 5th leaf

Rate	Glasshouse				Field						
(t/ha)	G1	G2	G4	G5	F1	F2	F3	F4	F5	F8	F9
0	124	129	132	95	110	233	253	193	78	243	55
1	170	133			96	158	273				
5	135			29	90	80	163		67	45	27
10	74	71		50	83	94	150		64		18
15		45			84	92	143	130		19	
20			59	49							
l.s.d. (P=0.05)	*70*	*41*	*21*	*8*	*(7)*	*(42)*	*90*	*32*	*9*	*107*	*18*

Zinc: For the glasshouse experiments, increasing the rate of applied lime from nil to 10-20 t/ha decreased the mean Zn concentration from 122 to 71 mg/kg (Table 3). In the field experiments the changes were small and of little practical significance. For both field and glasshouse grown plants the range in Zn concentrations are similar to those reported by Piggott (1986) and Harrison *et al.* (1982). Christensen and Jackson (1981) reported that for the cv. Russet Burbank, deficient potato plants had Zn concentrations in leaves which ranged from 16-21 mg/kg. Plants with Zn concentrations of 25 mg/kg appeared normal.

Based on leaf chemical composition early in the growing season we conclude that for crops adequately fertilised, liming appears not to have induced nutrient deficiencies. However, for some nutrients the effect of lime on uptake, and therefore growth, yield and quality responses, may depend on the external supply of that nutrient, including rates supplied in fertilisers.

TUBER CHEMICAL COMPOSITION

Murphy *et al.* (1967) reported that the application of lime significantly ($P<0.001$) increased mean P concentrations in tubers of the cv. Katahdin from 0.20 to 0.21%. For the cv. Russet Burbank, in 1 out of the 3 years the application of lime significantly decreased P concentrations (0.23 to 0.21%). Potassium concentrations were not affected by liming and mean concentrations ranged from 2.08-2.40% for the cv. Katahdin, and 1.77-2.32% for the cv. Russet Burbank. Bolton (1977) for the cv. Pentland Crown, found that increasing the rate of applied lime from nil to 20 t/ha increased P, Ca, K and Mg concentrations in tubers. However, the effects on K and Mg concentrations were small and not consistent between sites or nutrient supply.

The chemical composition of potato tubers is variable, depending on cv., nutrient supply, soil type, season and region of the tuber analysed. Ranges in nutrient concentrations in tubers reported in the literature are: N, 1.4-1.9%; P, 0.11-0.34%; K, 1.1-2.8%; Ca, 0.019-0.83%; Mg, 0.065-0.637%; Na, 0.021-0.022%; Cl, 0.10-0.33%; S, 0.15-0.17; Cu, 0.7-1.7 mg/kg; and Fe, 14-16 mg/kg. The concentrations obtained in our study, are in reasonable agreement with these ranges, except that Cl and Fe concentrations are much higher (Table 6).

Table 6. Mean (s.e.m.) and ranges for nutrient concentrations in tubers at nil and maximum (10, 15 or 20 t/ha) rates of applied lime

		Glasshouse (n=2)		Field (n=9)		
Nutrient	Rate	Mean	Range	Mean	s.e.m	Range
N (%)	Nil	n.a.		1.8	6.4	1.7-1.9
	Max.	n.a.		1.8	0.09	1.7-1.9
P (%)	Nil	0.34	0.28-0.40	0.21	0.02	0.14-0.32
	Max.	0.24	0.14-0.33	0.21	0.02	0.14-0.30
K (%)	Nil	1.7	1.5-2.0	2.0	0.2	1.1-3.3
	Max.	1.8	1.5-2.1	2.0	0.2	1.1-3.0
Na (%)	Nil	0.080	0.067-0.092	0.051	0.010	0.011-0.117
	Max.	0.080	0.053-0.060	0.059	0.014	0.014-0.140
Cl (%)	Nil	0.55	0.55-0.55	0.83	0.13	0.39-1.33
	Max.	0.40	0.40-0.40	0.60	0.10	0.32-1.10
Ca (%)	Nil	0.02	0.03-0.06	0.02	0.01	0.00-0.03
	Max.	0.05	0.04-0.05	0.04	0.01	0.02-0.08
Mg (%)	Nil	0.08	0.08-0.09	0.10	0.01	0.07-0.12
	Max.	0.10	0.08-0.12	0.10	0.01	0.08-0.13
S (%)	Nil	0.19	0.15-0.23	0.18	0.01	0.14-0.20
	Max.	0.20	0.20-0.20	0.18	0.01	0.15-0.21
B	Nil	4	4-4	5	0.5	2-6
(mg/kg)	Max.	4	3-4	4	0.6	1-6
Cu	Nil	2	2-2	4	0	2-6
(mg/kg)	Max.	2	2-2	3	0	1-5
Mn	Nil	7	5-8	9	1	6-15
(mg/kg)	Max	6	5-8	7	1	5-11
Zn	Nil	38	38-38	24	2	19-36
(mg/kg)	Max	18	17-18	21	2	13-29
Fe	Nil	30	30-30	58	12	38-78
(mg/kg)	Max	31	31-31	45	6	37-56

Calcium and magnesium: Liming increased Ca concentrations in tubers, with mean concentrations being atleast doubled (Table 6). The application of lime significantly increased Mg concentrations in 5 experiments, however, the increase was small, particularly when compared with the variation between experiments.

Phosphorus and chloride : The application of lime decreased Cl and P (in the glasshouse experiments) concentrations in tubers (Table 6).

Zinc and manganese: In experiments G5, G6, F1, F2, F3, F8 and F9, increasing rates of lime significantly decreased Zn concentrations in tubers (Table 6). In the field experiments, Mn concentrations were also reduced. However, overall the changes in Mn concentrations were small compared with the unexplained variation between sites.

Other nutrients: There were no consistent significant effects of liming on the concentrations of other nutrients in tubers.

INCIDENCE OF SCAB

The use of lime in potato production is limited because of the effect of lime on the outbreak and occurrence of common scab (*Streptomyces scabies*) (Odland and Allbritten 1950; Doyle and MACLean 1960).

In our study the incidence of visible symptoms of scab was so low that data on the effects of lime on the incidence of scab could not be collected.

Volod'ko (1982) reported that scab infection was not increased with lime applied during the growing period, but increased if it was applied on earlier dates *(Abstract: Lime and potato quality)*. Shil'nikov *et al.* (1978) found that actinomyces scabies infection of tubers was 10% in the first year of applying lime and 80-90% in the eighth year *(Abstract: Lime effect on yield and quality of potatoes)*.

INCIDENCE OF NUTRITIONAL LEAF ROLL

Nutritional leaf roll (NLR) has been reported to occasionally affect potato crops in the lower south East. Cultivars which have been affected include pontiac, kennebec, sebago and coliban. Symptoms may become apparent 3-4 weeks after planting, the young leaves start to curl (leaves roll upward and inward towards the midrib) and may develop a purple colour. The plants eventually collapse and senesce prematurely. If a crop is affected early in the growing season total crop failure can occur.

Soil and plant sampling of affected and healthy crops has been conducted by the authors. This preliminary work showed that NLR was associated with: I) strongly acid soils (e.g. 0-15 cm, pH_w 5.3-5.7; 16-30, 5.1; and 30-40, 5.1-5.6); ii) sand/coarse grain sand soils; and iii) affected plants showed depressed NO_3-N and K concentrations, and elevated P, Cl, S, Mn and Mg (?) concentrations. The disorder has also been reported overseas, for example, Volk and Gammon (1952; 1954). They recommended that the soil pH be maintained between 5-5.5 and that part of the basal N be supplied as NO_3 and the crop also be side-dressed with NO_3.

In our study, no plants were affected by nutritional leaf roll even though the soils were strongly acid sand/sandy loams.

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APPENDIX 2

EFFECT OF CURRENT SEASONS LIME APPLICATIONS ON THE YIELD AND CADMIUM CONCENTRATION OF POTATO TUBERS (*SOLANUM TUBEROSUM* L.)

INTRODUCTION

Cadmium (Cd) has accumulated in many agricultural soils in Australia due to fertilisation with phosphatic fertilisers containing high concentrations of Cd (Tiller et al 1994). In southern Australia, Cd concentrations in potatoes often approach or exceed the Australian Maximum Permitted Concentration (MPC) of 0.05 mg kg^{-1} fresh weight (FW) (Anon 1992a,b,c; Morgan 1989; Stenhouse 1991; NFA, 1993). It is therefore necessary to investigate farm management practices which could be used to reduce Cd accumulation in potato crops. Soil pH is regarded as the major factor controlling the plant availability of Cd in soil, with use of agricultural lime being the main management option suggested for minimizing Cd uptake by agricultural crops (Page and Bingham 1973; Chaney and Hornick 1978; Alloway 1990). In southern Australia, potatoes are often grown on acidic soils, so that the use of lime to raise soil pH may control Cd accumulation in potato tubers in these areas.

Murphy *et al.* (1967) reported that the incorporation of up to 7.6 t/ha of lime into the surface layer significantly reduced the tuber yield of Katahdin and Russet Burbank potatoes. They could not provide an explanation for the inverse lime - yield relationship. Jackson *et al.* (1982) working in Oregon with soils derived from pumice-volcanic ash parent material, found that tubers yields decreased significantly as pH increased from 4.5 to 6.4. Bolton (1977), working in Britain, reported that for the cv. Pentland Crown grown in a sandy-clay loam, total tuber yield was not affected by liming at 2 sites if a complete NPKMg fertiliser was applied. MacLean *et al.* (1967) found that liming acid peat soils (Histosols) to pH_w above 4.1-4.3 did not increase yield. Hossner and Doll (1970) studied the effects of applied lime and Mg, and soil K concentrations on the yield of potatoes (cv. Sebago) grown in a loamy sand. In 2 experiments over 2 years the application of 6.7 t/ha of hydrated lime did not significantly increase tuber yield. Lee and MACDonald (1977) used pot experiments to study the growth and yield of the cvv. Netted Gem, Sebago, Katahdin and Green Mountain grown in loam soil (Ultisol) at pH_w 4.6, 5.3 and 5.7. In both experiments raising the pH of the soils from 4.6 to 5.3 or 4.6 to 4.9 significantly increased tuber yield. Raising the pH to 5.7 or 5.2 did not result in a further increase in yield. van

Lierop *et al.* (1982) reported on a pot experiment which studied the effects of liming on tuber (cv. Kennebec) yields. Eight sandy soils (Spodosols) typically used for potato production Quebec were used. The pH_w of the unlimed soils ranged from 4.6 to 5.0. The application of lime significantly increased (mean of 40%) tuber yield on 3 of the 8 soils. Increases in yield did not generally occur above pH 4.9. These studies show that liming can significantly affect tuber yield, therefore any study to assess the practical usefulness of liming to reduce Cd accumulation in tubers needs to determine tuber yield response as well.

This study reports a series of field and glasshouse experiments investigating the effect of applications of agricultural lime on **i)** soil pH and electrical conductivity (conductance); **ii)** Cd accumulation in tubers; and **iii)** tuber yield. We also present the coefficients of determination (r^2) for relationships between Cd concentrations in tubers and the concentrations of other nutrients in leaves and tubers.

MATERIALS AND METHODS

Glasshouse experiments

Six glasshouse experiments were carried out over a period of 2 years. Details of planting dates, cultivars used and harvest and leaf sampling dates are presented in Table 1.

The experimental design was a randomized block, with 2 replicates in experiments G1 and G2, 4 in G3 and G6, 5 in G5 and 6 in experiment G4.

The experimental procedure was as follows:

1) Soil, from the A horizon, was collected from sites in the Mt Lofty Ranges and South East of South Australia. Each soil was air dried and sieved to <5 mm before use. For each experiment 300 mm diameter, free draining pots and 15 kg of air dry soil were used.

2) The soil from each pot was spread on a plastic sheet to <10-20 mm in depth. Finely ground agricultural lime (100%, <0.25 mm) was broadcast over the soil and thoroughly mixed with the soil. The rates of applied lime were in the range 0-20 t/ha, calculated on the basis of the surface area of the pots.

Table 1. Experimental details

Experiment[A]	Soil	Plot size	Date lime	Date crop	Date	Date	Cultivar[C]
			Glasshouse	*experiments*			
G1	MLR		9.viii.91	10.ix.91	19.xi.91	10.ii.92	RB, Kenn
G2	LSE		23.viii.91	2.x.91	25.xi.91	3.ii.92	RB, Kenn
G3	MLR		5.xii.91	27.ii.92	6.iv.92	10.vi.92	RB, Atl,
G4	LSE		23.xii.91	24.ii.92	7.iv.94	14.vii.92	RB
G5	LSE		18.viii.92	15.ix.92	3.xi.92	8.ii.93	RB
G6	LSE		21.i.93	15.ii.92	23.iii.93	8.vi.93	RB, Atl
G7	MLR		21.i.93	15.ii.92	23.iii.93	8.vi.93	Atl
			Field	*experiments*			
F1	LSE	3 x 3.5 m	26.ix.91	19.x.91	3.xii.91	17.iii.92	RB
F2	LSE	3 x 3.5 m	9.x.91	28.x.91	13.xii.91	2.iii.92	Kenn
F3	MLR	3 x 3.5 m	10.x.91	30.x.91	17.xii.91	10.iii.92	Atl
F4	LSE	5 x 3.5 m	6.x.92	12.xi.92	17.xii.92	4.ii.93	Shepody
F5	LSE	5 x 3.5 m	7.x.92	n.a.	17.xii.92	8.vi.93	RB
F6	LSE	5 x 3 m	n.a.	n.a.	7.i.93	31.iii.93	Pont
F7	LSE	3.5 x 2 m	13.xi.92	n.a.	26.i.92	25.iii.93	Crystal
F8	MLR	3.5 x 2 m	26.x.92	n.a.	8.i.93	22.vi.93	Kenn
F9	MLR	6 x 1 m	n.a.	n.a.	8.i.93	16.vi.93	Rb, Atl

[A] G, Glasshouse experiments; F, Field experiments.
[B] MLR, Mount Lofty Ranges; LSE, Lower South East.
[C] RB, Russett Burbank; Kenn, Kennebec; Atl, Atlantic; Pont, Pontiac.
n.a., Not available.

3) The soil was replaced into the pot and wetted up. Soil moisture was maintained at field capacity (approximately -10 kPa) during the incubation period. Depending on the experiment, the incubation period was from 4-12 weeks and the pots were kept in a shed at room temperature.

4) Immediately prior to planting, the soil was again spread on a plastic sheet and a subsample was collected for chemical and physical analysis.

5) Nitrogen (N, as ammonium nitrate), phosphorus (P, as superphosphate) and potassium (K, as potassium sulfate) were broadcast at rates equivalent to 100-175 kg N/ha, 20-75 kg P/ha and 100-240 kg K/ha, depending on soil type and soil test values. The basal fertilisers were thoroughly mixed into the soil, after which approximately two thirds of the soil was replaced into the pot.

6) Tuber seed pieces (one per pot) were planted to a depth of 2-3 cm, after which the pots were placed in a glasshouse.

7) For each pot, the remaining soil was added when the plants were 20-25 cm tall to minimize the risk of tubers developing above the soil surface.

8) Depending on stage of growth, the plants were watered 1-6 times a week using either rain or tap water. For some soils, N and K were applied as side-dressings 2-3 times during the growth period to ensure these nutrients did not limit growth or yield response. During growth, each plant was supported by a trellis.

9) After haulm senescence, the contents of each pot were tipped onto a table and the tubers harvested. A soil sample was also collected for chemical analysis. After washing, the fresh weight of tubers was determined for each pot.

Field experiments

General site characteristics, including planting and harvest dates, cultivars used, plot dimensions and leaf sampling dates are presented in Table 1. Experiments F1-F8 were located in commercial plantings and experiment F9 at the Lenswood Centre, PI(SA). The experimental design was a randomized block with 3-4 replicates.

The field procedure was as follows:

1) After initial cultivations, plots were marked out and at some sites, soil samples to 0-15 and 16-30 cm depths, were collected from each plot. The number of rows per plot was 4 at sites F1-F6, 2 at sites F7-F8 and 1 at site F9.

2) Finely ground agricultural lime (100%, <0.25 mm) was spread by hand onto the plots at rates in the range 0-15 t/ha.

3) The lime was incorporated to a depth of 150-200 mm using a rotary hoe. The plots were then left undisturbed for 2-4 weeks, prior to planting.

4) After the incubation period, soil samples to 0-15 and 16-30 cm depths, were collected from each plot.

5) The tubers were mechanically planted.

6) N, at 50-150 kg N/ha, P at 50-100 kg P/ha and K, at 100-200 kg K/ha were applied either at planting or as side-dressings, depending on soil test data, soil type and cropping history.

7) Cultivation, pest and disease management and irrigation were carried out by the grower or by farm staff at the Lenswood Centre site. Crops were sprinkler irrigated, generally every 5-10 days depending on weather conditions, receiving approximately 20-30 mm water with each irrigation.

8) After haulm senescence, soil samples to 0-15 and 16-30 cm through the mound, were collected from each plot.

9) Tubers from 2 rows, 2 metres long, with the exception of site F9 (one row by three metres) were dug by hand and the total of fresh weight of tubers for each plot was recorded.

10) The tubers were placed into sacks and transported to the laboratory, were the were stored in open crates at 12°C for post harvest assessment and laboratory analysis.

Soil sampling

To characterise the soil at each site, 20 cores, 5 cm diameter, were collected to 0-15 and 16-30 cm depths from each experimental area. For the field work, the experimental plots were also sampled by collecting 6 cores, to 0-15 and 16-30 cm depths, from each plot at the times specified in Table 1. For each depth, the samples were bulked, thoroughly mixed and sub-sampled for analysis.

Leaf sampling

The index tissue sampled was the 5th leaf from the growing terminal. For the field experiments, 20-30 leaves were collected from each plot on the date specified in Table 1. On the basis of plant development, sampling occurred in the field when the length of the longest tubers was in the range 20-40 mm. For the glasshouse experiments, the number of leaves sampled ranged from 2-10, depending on the number of stems produced.

Chemical analysis of soils

All soil samples were air dried before being sieved (< 2 mm stainless steel mesh) prior to chemical analysis.

Soil pH and EC were measured in a water suspension of each soil using a soil:solution ratio of 1:5. Extractable-Cl was determined in a 1:5 soil:water extract using an automated ferricyanide method [APHA 1992]. Exchangeable cation concentrations were determined using the 1M NH_4Cl leaching procedure with an alcohol pre-wash to remove soluble salts [Rayment and Higginson 1992]. Total-C was measured using a LECO furnace [Rayment and Higginson 1992]. Bicarbonate-extractable P was determined according to the method of Colwell [Colwell 1963] and K was measured in the same extracts by flame atomic emission spectroscopy. Cadmium and Zn were extracted from soil using an EDTA-procedure [Clayton and Tiller 1979].

Chemical analysis of plant materials

Cadmium. Preparation of tubers and Cd analysis of tuber material was performed as outlined by McLaughlin et al. (1994). Subsamples (0.1 g) of the dried ground leaf materials from 2 glasshouse experiments (G5 and G6) were digested with concentrated nitric acid until the digest mixture was clear. The digest solution was diluted to 10 ml using 0.016M nitric acid. All samples were digested in duplicate with blanks and internal reference materials in each batch. Cadmium concentrations in the digest solutions were determined using an atomic absorption spectrophotometer with graphite furnace atomization and deuterium background correction. Orthophosphoric acid was used as a modifier.

All analytical procedures included two reference materials (rice flour from the National Institute for Environmental Studies, Japan and cabbage leaves from the Institute of Physics and Nuclear Techniques, Poland) having certified concentrations of Cd.

Cadmium concentrations in the tubers are reported on a fresh weight (f wt) basis and in the 5th leaf on a dry weight (d wt) basis.

Other elements. Concentrations of B, Ca, Cu, Fe, K, Mg, Mn, Na, P, S and Zn in the digest solutions was determined using Inductively-Coupled Plasma Atomic Emission Spectroscopy.

Statistical analysis

The effect of lime on soil pH and conductance, tuber yield and Cd concentrations in tubers was determined by analysis of variance. Coefficients of determination (r^2) were also determined for the relationships between N, P, K, Ca, Mg, Na, Cl, S, B, Cu, Zn, Mn and Fe concentrations in tubers and leaves and Cd concentrations in tubers.

RESULTS

Soil chemical and physical properties

Some chemical and physical properties of the soils from each experiment are given in Table 2.

All sites chosen had acid surface (0-15 cm) soils, with the pH values in the range 4.1-5.8 (Table 2). For the glasshouse experiments, the soil types ranged from sand (G3, G4 and G6) or loamy sand (G1 and G5) to sandy loam (G2 and G7). For the field experiments, the surface (0-15 cm) soils also ranged from sand (F1 and F5-F7) or loamy sand (F4, F8 and F9) to sandy loam (F2 and F3). The soils were siliceous sand/sandy loam over clay (Dy/Dr/Db) or siliceous sand (Uc) soils.

All except 2 of the soils chosen (G3 and G6) had organic-C values >1.5% in the surface (0-15 cm) layer indicating moderate to high fertility levels. Extractable P concentrations ranged from 7 to 65 mg/kg in the soils used for the glasshouse experiments and from 16 to 98 mg/kg in the surface (0-15 cm) soils of the field sites (Table 2). This range of values suggests widely different histories of application of P fertiliser between the sites.

Table 2. Selected chemical and physical properties of soils used in glasshouse and field experiments

Soil	Depth (cm)	pH_w	Org.-C (%)	Ext.-P (mg/kg)	Exch.-Ca cmol(+)/kg	C.E.C.	Sand (%)	Silt (%)	Clay (%)
				Glasshouse experiments					
G1		4.9	2.1	18.2	1.34	5.3	84	9	7
G2		4.7	2.3	65.1	3.98	7.3	86	1	13
G3		4.7	1.1	9.5	1.09	2.5	95	1	4
G4		4.9	2.2	19.4	1.34	5.9	90	2	8
G5		4.1	2.4	11.7	2.17	4.6	87	5	8
G6		4.7	1.4	7.1	0.51	3.4	93	1	6
G7		4.9	2.3	28.6	2.35	5.8	84	6	10
				Field experiments					
F1	0-15	5.3	2.0	18.0	3.36	5.0	96	3	1
	16-30	5.4	0.3	6.9	0.65	1.5	96	3	1
F2	0-15	5.8	2.4	18.2	5.28	10.4	79	10	11
	16-30	-	1.0	19.4	6.81	13.4	61	10	29
F3	0-15	4.7	2.0	43.7	3.53	8.9	74	12	14
	16-30	-	0.4	6.8	6.59	12.3	56	10	34
F4	0-15	5.0	1.9	66.0	2.50	5.8	87	8	5
	16-30	4.9	1.0	20.6	1.36	3.7	87	7	6
F5	0-15	4.8	1.8	16.1	1.32	4.5	91	5	4
	16-30	5.0	1.8	13.1	1.21	4.0	91	5	4
F6	0-15	5.3	2.2	33.8	2.17	6.1	91	5	4
	16-30	5.2	1.2	28.7	1.17	4.0	88	7	5
F7	0-15	5.5	2.2	11.1	1.97	5.3	90	5	5
	16-30	5.1	0.6	7.4	0.77	2.4	91	5	4
F8	0-15	5.3	2.1	68.4	2.04	4.8	88	8	4
	16-30	5.1	1.0	30.8	1.08	3.9	89	7	4
F9	0-15	5.4	2.0	97.7	9.01	8.6	81	7	12
	16-30	5.3	1.7	75.7	10.37	7.0	81	8	11

[A] G, Glasshouse experiments; F, Field experiments.

Soil pH

Main effects. The applications of lime significantly ($P<0.05$) increased soil pH in all experiments (Table 3). However, the rate of lime required to raise the pH by 1 to 2 units varied considerably between experiments. For example, increasing the rate of applied lime from nil to 5 t/ha, increased pH from 5.6 to 7.2 in experiment F1, in contrast, in experiment F6, pH increased from 5.2 to only 5.6.

Table 3. Main effects of lime, sampling time and depth on soil pH for field and glasshouse experiments

	Field experiments									Glasshouse experiments					
Rate	F1	F2	F3	F4	F5	F6	F7	F8	F9	G1	G2	G3	G4	G5	G6
							Lime (t/ha)								
0	5.6	5.6	4.8	5.0	4.7	5.2	5.5	5.2	5.4	4.8	5.1	4.8	4.8	4.4	4.3
0.5										5.0	4.8				
1	6.2	5.9	4.9							4.9	4.9				
1.5	6.2	5.9	5.0												
2	6.4	6.1	5.3								5.1				
2.5					5.2	5.5	5.8	5.9							5.5
3	6.2	6.1	5.6								5.3				
4		6.1	5.7								5.5				
5	7.2	6.5	5.8		5.5	5.6	6.2	6.3	6.6	6.1				6.2	6.2
6											5.8				
7.5				5.9			6.7	6.6				6.5			
10	7.3	6.6	6.2		5.9	5.9			6.8	6.6	6.4			7.1	6.8
15	7.7	7.0	6.8	6.2		5.9	6.9	7.2			7.1				
20													7.7	7.4	
l.s.d.	*0.4*	*0.4*	*0.2*	*0.2*	*0.2*	*0.1*	*0.3*	*0.2*	*0.1*	*0.2*	*0.3*	*0.1*	*0.1*	*0.1*	*0.1*
							Sampling time								
Plant.	6.4	6.2	5.3	5.5	5.5	5.6	6.1	6.2	6.3	5.6	5.4	5.6	6.2	6.2	5.9
Harv.	6.8	6.2	5.8	5.9	5.2	5.6	6.3	6.3	6.3	5.4	5.7	5.7	6.3	6.3	5.5
l.s.d.	*0.2*	*n.s.*	*0.1*	*0.1*	*0.2*	*n.s.*	*n.s.*	*0.1*	*n.s.*	*0.1*	*0.1*	*0.07*	*0.1*	*0.08*	*0.1*
							Soil depth (cm)								
0-15	6.8	6.2	5.8	6.1	5.7	6.1	6.6	6.4	6.4						
16-30	5.7	6.0	5.3	5.3	4.9	5.2	5.8	6.1	6.2						
l.s.d.	*0.2*	*n.s.*	*0.1*	*0.1*	*0.2*	*0.1*	*0.2*	*0.1*	*0.1*						

The pH values also varied between sampling times. For example, in experiments F1, F3, F4, F8 and G2-G5 pH determined at harvest was significantly ($P < 0.05$) higher, by 0.1-0.5 of a unit, compared with pH values measured at planting (Table 3). In experiments F5, G1 and G6, pH values significantly decreased by 0.2-0.4 units, during this period.

Soil depth also affected pH. In all except 1 field experiment (F2), pH was significantly ($P < 0.05$) lower at the 16-30 cm depth compared with the surface (0-15 cm) soil. (Table 3). This shows the limitation of the method of incorporation (i.e. rotary hoeing) used in the field experiments.

For glasshouse experiments G1, G2 and G6 there were significant ($P<0.05$) differences in soil pH, depending on which cultivar grew in the pots. However, the differences were small and of little practical significance. For example, in experiments G1 and G2 the soils from pots in which the cvv. Russet Burbank grew had a higher pH (5.6 and 5.8, respectively) compared with soils from pots in which the cv. Kennebec grew (5.4 and 5.4, respectively). In experiment G6, the soil from pots in which the cv. Atlantic grew had significantly ($P<0.05$) higher pH (5.8) compared with the soil from pots in which the cv. Russet Burbank had grown (5.6).

Interactions. There were significant lime x sampling time interactions in experiments G1, G3, F1 and F3 ($P<0.05$), and G5 and G6 ($P<0.001$). The interactions were grouped into 3 categories, I) those experiments (e.g. G5, G6 and F1) in which there was a significant difference in pH between sampling times at nil or low rates of lime (eg. 1-3 t/ha) and not at the higher rates (eg. 5-15 t/ha). For example, in experiments G5 and F1, when nil lime was applied the pH of the soil at harvest (4.7 and 6.1, respectively) was significantly higher compared with planting (4.1 and 5.1, respectively). In contrast, at 15 or 20 t/ha lime the mean pH values were in the range 7.4-7.8. ii) those experiments (eg. G1 and F3) in which there was a significant difference in pH between sampling times at the higher rates of lime (eg. 10 or 15 t/ha) but not at the nil or low rates (eg. 1-3 t/ha). For example in experiment F3, for the nil lime treatment the pH at planting (4.7) and harvest (4.9) were similar. In contrast, when 15 t/ha of lime was applied the pH at planting (6.4) was significantly lower than the pH at harvest (7.2).

For the field experiments, there were significant lime x depth interactions in experiment F3 ($P<0.01$) and experiments F4-F6 ($P<0.001$). The interactions occurred because the differences in pH between the 0-15 and 16-30 cm depths depended on the rate of applied lime. For example, in experiment F6 at nil, 5 and 15 t/ha of applied lime the pH in the surface (0-15 cm) was 5.3, 6.0 and 6.8, respectively. In contrast at 16-30 cm the values were 5.1, 5.2 and 5.1, respectively. These data highlight the problem of effectively incorporating lime to depth in the field.

In experiments F9 ($P<0.05$), F4 ($P<0.01$), and F5 and F6 ($P<0.001$) there were significant sampling time x depth interactions. The interactions could be categorized as follows, I) the change in pH with depth was greater at harvest compared with planting (experiments F6 and F9). For example, in experiment F9 at planting the mean pH decreased from 6.3 at 0-15 cm to 6.2 at 16-30 cm, however, at harvest the decrease was from 6.5 to 6.1. ii) the change pH with depth varied with sampling time (eg. F4 and F5). For example, in experiment F5 the pH of the surface (0-15 cm) soil did not change between planting (5.7) and harvest (5.65), in contrast, at 16-30 cm the pH decreased from 5.2 to 4.7, respectively.

Conductance

Main effects. The application of lime significantly ($P<0.05$) increased conductance in experiments G1-G3 and F1-F7 (Table 4). However, the magnitude of the changes varied

between experiments. In experiment F9 conductance decreased with increasing rates of lime.

Table 4. Main effects of lime, sampling time and depth on soil conductance for field and glasshouse experiments

	Field experiments									Glasshouse experiments					
Rate	F1	F2	F3	F4	F5	F6	F7	F8	F9	G1	G2	G3	G4	G5	G6
							Lime (t/ha)								
0	0.14	0.44	0.39	0.12	0.19	0.13	0.37	0.43	0.8	0.14	0.38	0.43	0.51	0.41	0.40
0.5										0.15	0.48				
1	0.13	0.34	0.41							0.17	0.42				
1.5	0.15	0.54	0.46												
2	0.16	0.42	0.44								0.43				
2.5					0.20	0.13	0.54	0.38							0.40
3	0.20	0.48	0.40								0.45				
4		0.49	0.36								0.47				
5	0.15	0.40	0.46		0.21	0.14	0.41	0.39	0.4	0.23				0.39	0.40
6											0.54				
7.5				0.18			0.42	0.42				0.54			
10	0.27	0.62	0.60		0.23	0.16			0.5	0.27	0.54			0.44	0.4
15	0.23	0.54	0.52	0.20		0.19	0.49	0.45			0.57				
20													0.54	0.43	
l.s.d.	*0.08*	*0.17*	*0.14*	*0.05*	*0.04*	*0.03*	*0.07*	*n.s.*	*0.1*	0.06	0.08	0.05	n.s.	n.s.	n.s.
							Sampling time								
Plant.	0.11	0.27	0.23	0.21	0.08	0.08	0.23	0.16	0.6		0.68	0.52	0.48	0.41	0.40
Harv	0.25	0.68	0.67	0.13	0.33	0.22	0.66	0.67	0.5		0.28	0.46	0.57	0.42	0.50
l.s.d.	*0.04*	*0.08*	*0.07*	*0.04*	*0.03*	*0.02*	*0.05*	*0.06*	*n.s.*		*0.04*	*0.05*	*0.09*	*n.s.*	
							Soil depth (cm)								
0-15	0.25	0.68	0.67	0.25	0.25	0.22	0.56	0.50	0.5						
15-30	0.37	0.47	0.48	0.08	0.17	0.09	0.33	0.33	0.6						
l.s.d.	*0.05*	*0.10*	*0.07*	*0.04*	*0.03*	*0.02*	*0.05*	*0.06*	*0.1*						

The effect of sampling time on soil conductance was not consistent between experiments. For example, in experiments G2, G3 and F4 conductance significantly ($P<0.05$) decreased between planting and harvest (Table 4). In contrast, in experiments G5 and F9 the changes were not significant, while in all other experiments, conductance increased significantly ($P<0.05$) during this period. The increase may have been due to the accumulation of salts from the application of fertilisers and irrigation water.

Soil conductance was significantly higher in glasshouse soils at planting compared to field soils. This is presumably due to greater mineralisation of organic matter and minimal leaching of nutrient ions under glasshouse conditions.

Soil conductance also varied with soil depth. For example, in field experiments F1 and F9 conductance was significantly higher at 16-30 cm compared with 0-15 cm (Table 4). In all other experiments it was significantly ($P<0.05$) lower.

Interactions. Only in experiment F7 was there a significant ($P<0.001$) lime x sampling time interaction. At this site, changes in conductance due to the application of lime were greater at harvest than at planting. For example, increasing the rate of applied lime from nil to 2.5 t/ha increased conductance from 0.21 to 0.22 at planting, but from 0.52 to 0.86 at planting.

There were significant sampling time x depth interactions in experiments F9 ($P<0.05$), F4 and F8 ($P<0.01$), and F5 and F6 ($P<0.05$). The interactions occurred because at 0-15 cm there were larger and significant changes in conductance between planting and harvest, compared with the 16-30 cm depth. For example, in experiment F4, at 0-15 cm conductance decreased from 0.32 at planting to 0.18 at harvest. At 16-30 cm, the change was negligible, 0.09 to 0.08.

Tuber yield

The effect of current seasons lime applications on tuber yield was inconsistent. For example, the application of lime significantly ($P<0.05$) decreased (experiments F1, G3 and G5), increased (experiment G1) or increased and then decreased yield at the highest rate of lime (experiment F9) (Table 5). In all other experiments the effect of lime was not significant ($P>0.05$).

Table 5: Effect of rate of applied lime (t/ha) on the total fresh weight of tubers from field (t/ha) and glasshouse (g/plant) experiments

	Field experiments								*Glasshouse experiments*					
Rate	F1	F2	F3	F4	F5	F6	F7	F9	G1	G2	G3	G4	G5	G6
0	65.0	53.4	73.7	40.5	60.6	65.2	58.4	50.3	348.0	607.6	301.1	341.3	942.7	414.0
0.5									353.2	758.7				
1	62.1	58.7	68.4						437.0	607.8				
1.5	65.5	55.0	70.2											
2	57.8	58.6	70.7							751.1				499.3
2.5					68.2	59.9	57.6							
3	59.9	61.1	66.5							683.2				
4	59.4	60.7	67.1							673.3				
5	58.4	62.6	68.9		62.7	58.8	64.3	63.9	576.7				963.6	485.0
6										755.6				
7.5				40.3			61.8				220.3			
10	48.6	61.4	71.0		69.0	56.8		54.4	628.1	715.8			842.9	407.0
15	54.3	56.0	71.4	42.0		55.8	51.3			719.2				
20										502.1		306.2	813.2	
l.s.d.	*8.8*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*7.5*	*174.1*	*n.s.*	*54.7*	*n.s.*	*90.0*	*n.s.*

In experiments F9, G1, G3 and G4 the lime x cultivar interactions were not significant, indicating that in each experiment the response to lime was similar for the cultivars tested. In experiment G2 the interaction was significant ($P<0.001$). Increasing the rate of applied lime from nil to 20 t/ha decreased the yield of Kennebec from 1019 to 64 g/plant. In contrast, the yield of Russet Burbank increased from 196 to 939 g/plant.

Cadmium concentrations in tubers

In the field experiments, the application of lime, up to 15 t/ha, did not significantly reduce Cd in tubers (Table 6). Further, in experiments F5 and F6 it significantly ($P<0.05$) increased Cd concentrations. In contrast with the field experiments, the application of lime significantly reduced Cd concentrations in tubers in all except 1 glasshouse experiment (Table 6). In experiment G1, Cd concentrations decreased however, the effect was not significant due possibly to limited replication of treatments (Table 1).

Table 6. Effect of rate of applied lime (t/ha) on cadmium concentrations (mg/kg f wt) in tubers harvested from field experiments

Rate	F1	F3	F4	F5	F6	F7	F8	F9
0	0.033	0.042	0.073	0.027	0.075	0.135	0.182	0.015
0.5								
1	0.037	0.041						
1.5	0.035	0.047						
2	0.038	0.051						
2.5				0.032	0.097	0.155	0.185	
3	0.037	0.054						
4	0.039	0.050						
5				0.035	0.083	0.129	0.197	0.015
6	0.033	0.060						
7.5			0.084			0.152	0.209	
10	0.037	0.052		0.036	0.074			0.017
15	0.032	0.053	0.095		0.071	0.160	0.229	
20								
l.s.d.	*n.s.*	*n.s.*	*n.s.*	*0.005*	*n.s.*	*n.s.*	*0.026*	*n.s.*

Table 6. ctd. Effect of rate of applied lime (t/ha) on cadmium concentrations (mg/kg f wt) in tubers harvested from glasshouse experiments

Rate	G1	G2	G3	G4	G5	G6
0	0.106	0.048	0.102	0.215	0.044	0.032
0.5	0.080	0.061				
1	0.077	0.035				
1.5						
2		0.053				
2.5						0.031
3		0.044				
4		0.041				
5	0.071				0.029	0.027
6		0.029				
7.5			0.084			
10	0.069	0.031			0.021	0.024
15		0.025				
20				0.060	0.020	
l.s.d.	*n.s.*	*0.021*	*0.015*	*0.075*	*0.009*	0.005

There were significant lime x cv. interactions in experiments G3 ($P<0.001$) and G6 ($P<0.05$).

In experiment G3, Cd concentrations in tubers of the cv. Pontiac (0.138 mg/kg) were significantly higher compared with the cvv. Russet Burbank (0.078 mg/kg), Atlantic (0.080 mg/kg) and Desiree (0.076 mg/kg). Significant differences between cvv. also occurred in experiment G6, in which Cd concentrations in tubers of the cv. Atlantic (0.03 mg/kg) were higher than the cv. Russet Burbank. In field experiment F9, the differences in Cd concentration between the cvv. Russet Burbank (0.015 mg/kg) and Atlantic (0.016 mg/kg) were not significant.

Based on data for all experiments, the relationships between Cd concentrations in tubers and rate of applied lime (Figure 1a) and soil pH_w at harvest (Figure 1b) were poor. High Cd concentrations were associated with high soil conductance at harvest (Figure 1c).

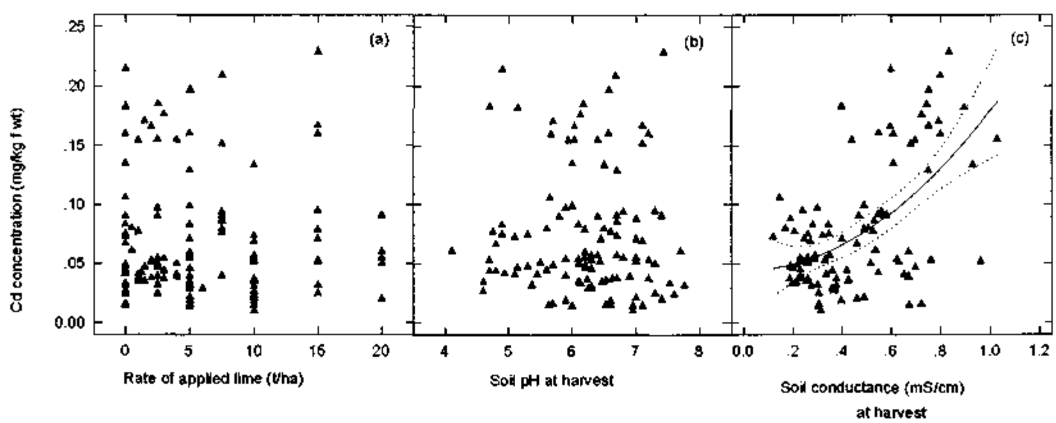

Figure 1. Relationships between (a) rate of applied lime, (b) soil pH_w and (c) conductance at harvest and Cd concentrations in tubers. Dotted lines indicate the 95% confidence limits.

Cadmium concentrations in 5th leaf

Data on the effect of applied lime on Cd concentrations in the 5th leaf were only collected in 2 experiments. In experiment G5, increasing the rate of applied lime from nil to 10 t/ha significantly decreased Cd concentrations from 2.52 to 0.78 mg/kg, d wt. Similarly, in experiment G6, Cd concentrations decreased from 1.23 to 0.75 mg/kg, d wt. In this experiment Cd concentrations in leaves of the cv. Atlantic (0.98 mg/kg, d wt) were significantly higher compared with the cv. Russet Burbank (0.88 mg/kg, d wt). The lime x cv. interaction was not significant.

Correlations between Cd concentrations in tubers and the concentrations of other elements in the tuber and fifth leaf

Regression analysis and visual inspection of the graphs showed that there were significant positive relationships between Ca (Figure 2), Mg, Na, Cl and Fe concentrations in 5th leaf, and K, Mg, Na, Cl and Zn concentrations in tubers and the concentration of Cd in tubers (Table 7). The relationship between Cu concentrations in the 5th leaf and Cd concentrations in tubers was negative. Except for Cl concentrations in tubers, the amount of variation in tuber Cd concentration accounted for by these relationships was low.

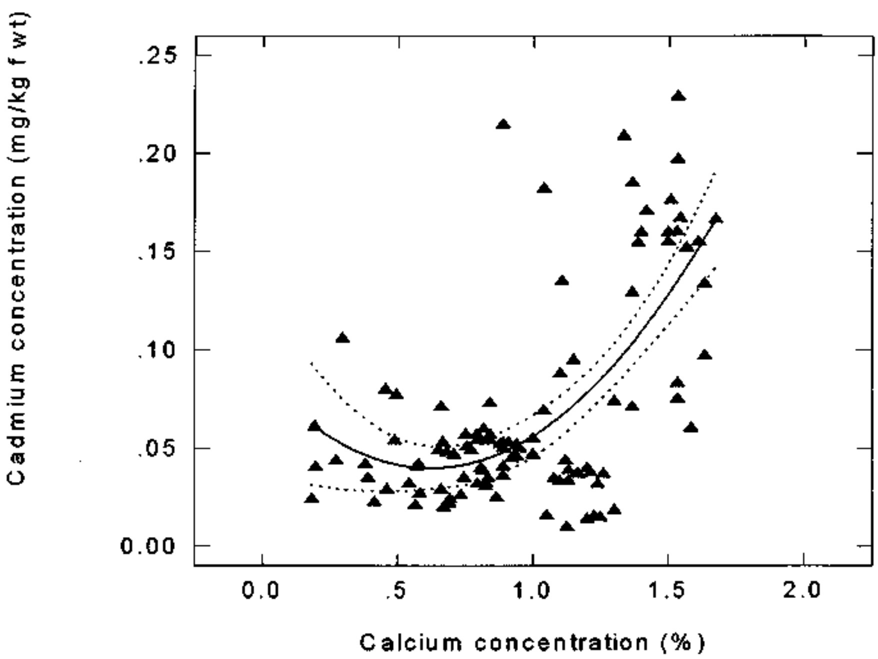

Figure 2. Relationship between Ca concentrations in 5th leaf and Cd concentrations in tubers.

Table 7. Coefficients of determination (r^2) for relationships between cadmium concentrations in tubers and other elements in 5th leaf and tubers

	5th leaf				Tuber			
Nutrient	r^2	F value	Probability	n	r^2	F value	Probability	n
N	0.02	1.7	n.s.	71	n.a.			
P	0.03	2	n.s.	75	0.02	1.2	n.s.	73
K	0.04	3.3	n.s.	75	0.13	10.9	<0.01	73
Ca	0.27	27.4	<0.001	75	0.003	0.2	n.s.	73
Mg	0.31	32.2	<0.001	75	0.18	16.1	<0.001	73
Na	0.24	23.6	<0.001	75	0.31	32.6	<0.001	73
Cl	0.33	33.6	<0.001	71	0.74	173.7	<0.001	63
S	0.05	3.6	n.s.	75	0.02	1.5	n.s.	73
B	0.002	0.1	n.s.	73	0.001	0.01	n.s.	73
Cu	0.21	19.6	<0.001	75	0.02	1.1	n.s.	73
Zn	0.003	0.2	n.s.	75	0.07	5	<0.05	73
Mn	0.01	0.09	n.s.	75	0.05	3.4	n.s.	73
Fe	0.06	4.4	<0.05	71	n.a.			

DISCUSSION

Most of the soils used in this study were light-textured and had pH values less than 6 prior to application of lime. These soils are typical of many potato-growing regions in southern Australia. Application of lime raised soil pH by one to three units depending on soil type and rate of lime application, with six of the 16 experiments having pH values above 7 at the highest application rates used.

Liming generally increased the EC of soils, and while under field conditions soil EC values generally increased between planting and harvest, the EC values for soils in glasshouse trials generally decreased over the plant growth period. Presumably, the latter is due to the fact that plant uptake of nutrient elements and salts during growth reduces salt concentrations in soil, where good quality water is used to grow plants. In the field, use of poorer quality irrigation water led to salt build-up in most soils. Tuber yields were generally unaffected by liming.

Potatoes are generally regarded as being highly tolerant of acidic soil conditions, and our data supports this observation. In light-textured soils, application of lime may induce deficiencies of some trace elements in crops. From analysis of leaf samples collected during the early tuber growth period, there was no indication of deficiency for any macroor micronutrient, given current criteria for South Australian potato crops. A further concern with use of lime on soils used for potato production is the increased risk of infection of the crop with common scab [Huber 1990]. We observed no increased incidence of scab with liming at any site.

Concentrations of Cd in tubers grown under field conditions were either unaffected by liming or were increased compared to unlimed controls. By contrast, large reductions in concentrations of Cd in tubers were observed with experiments under glasshouse conditions. The reasons for these differential responses to lime are unknown. It has been known for some time that metal accumulation by crops under glasshouse conditions is markedly different to that in the field, even where the same soil and treatments are used. This has been attributed to differences in rooting habit and soil temperature and moisture conditions between the two environments. Under field conditions, where crops are irrigated rather than rain fed, differences in water quality between glasshouse and field environments may also lead to different metal concentrations in plants.

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APPENDIX 3

EFFECT OF LIME AND PHOSPHORUS ON THE GROWTH, YIELD AND N, P AND Cd CONCENTRATIONS IN POTATOES (*SOLANUM TUBEROSUM* L.)

INTRODUCTION

Potatoes are considered to be tolerant of acid soil conditions (Anonymous 1973; Sutherland 1979) and liming of soils used for potato growing is not commonly practiced because of the effect of decreasing acidity on the incidence of scab (Odland and Allbritten 1950; Doyle and MACLean 1960). However, in some potato growing regions of southern Australia, cadmium (Cd) residues often exceed the maximum permitted concentration (MPC) and management options which reduce Cd uptake need to be identified. Liming may be one such option (Page and Bingham 1973).

Phosphorus (P) is a major nutrient applied to potato crops. Depending on the soil type and residual P status, rates up to 150-250 kg P/ha may be applied (???). However, the application of P fertilisers has been identified as a major source of Cd taken up by plants (Tiller et al., 1994). Few studies have been published on the effect of increasing rates of superphosphate on Cd uptake by potatoes growing in siliceous sand/sandy loam over clay (Dy/Dr/Db) or siliceous sand (Uc) soils. Published studies on the effect of lime application on P availability and uptake by plants are contradictory (Haynes 1984; Sumner and Farina 1986). For potatoes, Bolton (1977) found that increasing rates of lime increased P concentrations in leaves especially if P fertiliser was omitted. At nil P, concentrations increased from 0.15-0.16 to 0.20-0.25% P. Lee and MACDonald (1977) reported that the application of dolomite significantly increased Ca (1.10 to 1.35%) and Mg (0.20 to 0.51%) concentrations but did not affect P (0.24-0.26%) concentrations.

In this paper we report on 3 field and 2 glasshouse experiments in which the effects of applying lime and P on the growth, yield, N and P concentrations in 5th leaf and Cd concentrations in tubers of the cvv. Russet Burbank, Pontiac and Crystal.

MATERIALS AND METHODS

Glasshouse experiments

Two glasshouse experiments were conducted during 1991/92 (G4) and 1992/93 (G5) at the Northfield Research Laboratories. Details of lime applications, planting, leaf sampling and harvest dates are presented in Table 1.

The experimental design was a randomized block, with 2 lime x 2 P treatments replicated 6 times in experiment G4, and 3 lime x 2 P treatments replicated 5 times in experiment G5. The cvv. grown were Russet Burbank, Pontiac and Crystal in experiments F5, F6 and F7, respectively in the field experiments, and Russet Burbank in the glasshouse experiments.

Table 1. Experimental details

Experiment	Plot size	Date of lime	Date crop	Date	Date of
		Glasshouse experiments			
G4	-	23.xii.91	24.ii.92	7.iv.92	14.vii.92
G5	-	18.viii.92	15.ix.92	3.xi.92	8.ii.93
		Field experiments			
F5	5 x 3.5 m	7.x.92	n.a.	17.xii.92	8.iv.93
F6	5 x 3 m	n.a.	n.a.	7.i.93	31.iii.92
F7	3.5 x 2 m	13.xi.92	n.a.	26.i.92	25.iii.93

The experimental procedure was as follows:

(I) Soil, from the A horizon, was collected from sites in the Mt Lofty Ranges (G4) and South East (G5) of South Australia. Each soil was air dried and sieved to <5 mm before use. To characterise the soil, a sub-sample was collected for chemical and physical analysis. For each experiment 300 mm diameter, free draining pots and 15 kg of air dry soil were used.

(ii) The soil from each pot was spread on a plastic sheet to <10-15 mm in depth. Depending on the treatment, finely ground agricultural lime (100%, <0.25 mm) was broadcast over the soil and then thoroughly mixed with the soil. The rates of lime were equivalent to 0 and 20 t/ha in experiment G4 and 0, 5 and 10 t/ha in experiment G5. The rates were calculated on the basis of the surface area of the soil in the pots.

(iii) The soil was placed back into the pot and 'wetted up'. Soil moisture was maintained at field capacity (approximately -10 kPa) during the incubation period. The moist incubation period was approximately 8 weeks in experiment G4 and 4 weeks in experiment G5 (Table 1). During this period the pots were kept in a shed at room temperature.

(iv) In both experiments the P treatment, equivalent to 75 kg P/ha as superphosphate, was incorporated into the soil 1 week before planting. At the same time, in experiment G4 N, equivalent to 50 kg N/ha as ammonium sulfate, and K, equivalent to 120 kg K/ha as potassium sulfate, were also applied to all pots. In experiment G5, N, equivalent to 50 kg N/ha as calcium nitrate, and K, equivalent to 100 kg K/ha as potassium sulfate were applied to all pots. The rates of N and K applied depended on soil type and soil test values. The basal fertilisers were thoroughly mixed into the soil, after which approximately two thirds of the soil was replaced into the pot.

(v) Immediately prior to planting, a subsample of soil was collected from each pot for chemical analysis.

(vi) Tuber seed pieces (one per pot) were planted and covered with 2-3 cm of soil, after which the pots were placed in a glasshouse.

(vii) For each pot, the remaining soil was added when the plants were 25-30 cm tall to minimize the risk of tubers developing above the soil surface.

(ix) Depending on stage of growth, the plants were watered 1-6 times a week using either rain or tap water. In experiment G4, 2 side-dressings of N, each equivalent to 50 kg N/ha, were applied on the 13th and 26th of March 1992. In experiment G5, side-dressings of K, equivalent to 37.5 kg K/ha, were applied on the 8th and 20th of October. Three side-dressings of N, equivalent to 37.5, 50 and 37.5 kg N/ha were also applied on the 8th and 20th October and the 20th November, respectively. The side-dressings were applied to ensure these nutrients did not limit growth or yield response. During growth, each plant was supported by a trellis.

(x) After haulm senescence, the contents of each pot were tipped onto a table and the tubers harvested. A soil sample was also collected for chemical analysis. After washing, the fresh weight of tubers was determined for each pot.

Field experiments

Three field experiments, located in commercial plantings, were conducted during 1992/93 in the lower (sites F5 and F6) and upper (site F7) South East of South Australia. Lime application, leaf sampling and harvest dates are presented in Table 1.

The experimental design was a randomized block. There were 2 lime x 3 P rates in experiment F5, and 5 lime x 2 P rates in experiments F6 and F7. The treatments were replicated 3 times in experiments F5 and F7, and 4 times in experiment F6.

The field procedure was as follows:

(I) After initial cultivations, soil samples were collected across the experimental area for chemical and physical analysis to characterise the soil at each site. Plots were then marked out.

(ii) Finely ground agricultural lime (100%, <0.25 mm) was spread by hand over the plots at rates in the range 0-15 t/ha..

(iii) The lime was incorporated to a depth of 150-200 mm using a rotary hoe. The plots were then left undisturbed for 2-4 weeks, prior to planting.

(iv) After the incubation period, soil samples to 0-15 and 16-30 cm depths, were collected by sampling through the mounds of each plot.

(v) The tubers were mechanically planted.

(vi) Before banking, the P treatments were applied, either broadcast (experiments F5 and F6) or banded along the rows (experiment F7) and incorporated into the soil. In experiments F5 and F6, N at 150 kg N/ha as ammonium nitrate and K, at 200 kg K/ha as potassium sulfate, were also applied. In experiment F7, The N and K rates applied were 50 kg N/ha and 100 Kg K/ha, respectively. The growers applied further rates of N, K and trace element sprays to the plantings, including the experimental plots, during the growing season. The rates applied depended on soil type, cropping history and soil test data.

(vii) Cultivation, pest and disease management and irrigation were carried out by the grower. Crops were sprinkler irrigated, generally every 5-10 days depending on weather conditions, receiving approximately 20-30 mm water with each irrigation.

(viii) After haulm senescence, soil samples to 0-15 and 16-30 cm through the mound, were collected from each plot.

(ix) Tubers from 2 rows, 2 metres long and located in the centre of the plot, were dug by hand and the total of fresh weight of tubers for each plot was recorded.

(x) The tubers were placed into sacks and transported to the laboratory, were the were stored in open crates at 12°C for post harvest assessment and laboratory analysis.

Soil sampling

To characterise the soil at each site, 20 cores, 5 cm diameter, were collected to 0-15 and 16-30 cm depths from each experimental area, after the initial soil preparation. For the field work, the experimental plots were also sampled immediately before planting and harvest by collecting 6 cores, to 0-15 and 16-30 cm depths, from each plot at the times specified in Table 1. For each depth, the samples were bulked, thoroughly mixed and sub-sampled for analysis.

Leaf sampling

The index tissue sampled was the 5th leaf from the growing terminal. For the field experiments, 20-30 leaves were collected from each plot on the date specified in Table 1. On the basis of plant development, sampling occurred in the field when the length of the longest tubers was in the range 20-40 mm. For the glasshouse experiments, the number of leaves sampled ranged from 2-10, depending on the number of stems per plant.

Chemical analysis of soils

All soil samples were air dried before being sieved (< 2 mm stainless steel mesh) prior to chemical analysis.

Soil pH and EC were measured in a water suspension of each soil using a soil:solution ratio of 1:5. Extractable-Cl was determined in a 1:5 soil:water extract using an automated ferricyanide method [APHA 1992]. Exchangeable cation concentrations were determined using the 1M NH_4Cl leaching procedure with an alcohol pre-wash to remove soluble salts [Rayment and Higginson 1992]. Total-C was measured using a LECO furnace [Rayment and Higginson 1992]. Bicarbonate-extractable P was determined according to the method of Colwell [Colwell 1963] and K was measured in the same extracts by flame atomic emission spectroscopy. Cadmium and Zn were extracted from soil using an EDTA-procedure [Clayton and Tiller 1979].

Chemical analysis of plant materials

Cadmium. Preparation of tubers and Cd analysis of tuber material was performed as outlined by McLaughlin et al. (1994). Subsamples (0.1 g) of the dried ground leaf materials from 2 glasshouse experiments (G5 and G6) were digested with concentrated nitric acid until the digest mixture was clear. The digest solution was diluted to 10 ml using 0.016M nitric acid. All samples were digested in duplicate with blanks and internal reference materials in each batch. Cadmium concentrations in the digest solutions were determined using an atomic absorption spectrophotometer with graphite furnace atomisation and deuterium background correction. Orthophosphoric acid was used as a modifier.

All analytical procedures included two reference materials (rice flour from the National Institute for Environmental Studies, Japan and cabbage leaves from the Institute of Physics and Nuclear Techniques, Poland) having certified concentrations of Cd.

Cadmium concentrations in the tubers are reported on a fresh weight (f wt) basis and in the 5th leaf on a dry weight (d wt) basis.

Other elements. Concentrations of B, Ca, Cu, Fe, K, Mg, Mn, Na, P, S and Zn in the digest solutions was determined using Inductively-Coupled Plasma Atomic Emission Spectroscopy.

Statistical analysis

The effects of rate of applied lime and P on soil pH and conductance, tuber yield, plant height, number of tubers and stems per plant, dry matter leaf, stem and leaf+stem yields, and elemental concentrations in 5th leaf and tubers were determined by analysis of variance.

RESULTS AND DISCUSSION

Soil chemical and physical properties

Selected chemical and physical properties of the soil used in each experiment are presented in Table 2.

Table 2. Selected chemical and physical properties of the field and glasshouse soils

	Soil depth (cm)	pH_w	Total carbon (%)	Ext.-P (mg/kg)	C.E.C.	Sand (%)	Silt (%)	Clay (%)
Glasshouse experiments								
G4		4.9	2.2	19	5.9	90	2	8
G5		4.1	2.4	12	4.6	87	5	8
Field experiments								
F5	0-15	4.8	1.8	16	4.5	91	5	4
	16-30	5.0	1.8	13	4.0	91	5	4
F6	0-15	5.3	2.2	34	6.1	91	5	4
	16-30	5.2	1.2	29	4.0	88	7	5
F7	0-15	5.5	2.2	11	5.3	90	5	5
	16-30	5.1	0.6	7	2.4	91	5	4

All sites chosen had acid surface (0-15 cm) soils, with the pH values in the range 4.1-5.5 (Table 2). For the glasshouse experiments, the soil types ranged from sand (G4) to a loamy sand (G5). For the field experiments, the surface (0-15 cm) soils were a sand. All the soils chosen had organic-C values >1.5% in the surface (0-15 cm) layer indicating moderate to high fertility levels. Extractable P concentrations ranged from 12 to 19 mg/kg in the soils used for the glasshouse experiments and from 11 to 34 mg/kg in the surface (0-15 cm) soils of the field sites (Table 2). This range of values suggests different histories of application of P fertiliser between the sites.

Soil pH

Main effects. The applications of lime significantly ($P<0.05$) increased soil pH in all experiments (Table 3). The application of P as superphosphate was only significant ($P<0.05$) in experiment G5, however, the effect was small and of little practical importance.

Interactions. The lime x P interaction was not significant at any site (data not presented).

Table 3. Main effects of lime (t/ha) and P (kg/ha) as superphosphate, on pH determined at harvest for glasshouse and field (0-15 cm) soils

	Glasshouse experiments			*Field experiments*	
Rate	G4	G5	F5	F6	F7
		Lime			
0	4.5	4.7		5.4	5.9
2.5				5.8	6.3
5		6.0	5.9	6.1	6.8
7.5					7.1
10		7.0	6.5	6.6	
15				6.9	7.3
20	7.6				
l.s.d. (P=0.05)	*0.4*	*0.3*	*0.3*	*0.2*	*0.5*
		Phosphorus			
0	6.0	5.8	6.3	6.2	6.7
50			6.0		
75	6.1	6.1			
100			6.3	6.1	6.6
l.s.d. (P=0.05)	*n.s.*	*0.2*	*n.s.*	*n.s.*	*n.s.*

Conductance

Main effects. The effects of increasing rates of applied lime and P on soil conductance measured at harvest were inconsistent. For example, in experiments G5, F6 and F7 increasing the rate of applied lime from nil to 10 or 15 t/ha significantly (P<0.05) increased soil conductance (Table 4). Further, in experiment G5 the application of P significantly decreased conductance, and in experiment F5 conductance increased up to the highest rate of P. Although the effects were statistically significant the changes were small and of little practical significance. At all other sites the effects were not significant.

Interactions. There were significant lime x P interactions in experiments G4 and F7. In experiment G4, at nil P, increasing the rate of applied lime from nil to 20 t/ha increased conductance from 0.67 to 0.94 mS/cm. In contrast, when P was applied at rate equivalent to 75 kg P/ha, conductance decreased from 0.74 to 0.69 mS/cm. In experiment F7, at nil P the maximum conductance occurred at 3 t/ha of lime, compared with 15 t/ha when 100 kg P/ha was applied.

Table 4. Main effects of rate of applied lime (t/ha) and P kg/ha) as superphosphate, on soil conductance determined at harvest for glasshouse and field (0-15 cm) soils

	Glasshouse experiments			*Field experiments*	
Rate	G4	G5	F5	F6	F7
		Lime			
0	0.71	0.39		0.29	0.62
2.5				0.32	0.91
5		0.40	0.39	0.30	0.69
7.5					0.71
10		0.51	0.39	0.34	
15				0.40	0.95
20	0.81				
l.s.d. (P=0.05)	*n.s.*	*0.1*	*n.s.*	*0.07*	*0.15*
		Phosphorus			
0	0.80	0.48	0.35	0.32	0.77
50			0.38		
75	0.72	0.39			
100			0.43	0.34	0.77
l.s.d. (P=0.05)	*n.s.*	*0.09*	*0.07*	*n.s.*	*n.s.*

Tuber yield

The application of 10-20 t/ha lime significantly ($P<0.05$) decreased tuber yield in experiments G4, F6 and F7 (Table 5). In contrast the application of P significantly increased yield in all except 1 (experiment F6) experiment. For loamy sand to sandy clay loams, Maier *et al.* (1989) grouped sites with extractable P concentrations in the surface (0-15 cm) soil: < 30 mg/kg deficient; 30-40 mg/kg marginal; and >40 mg/kg adequate. The main effects for these experiments (Table 5) are consistent with this classification.

The lime x P interactions were not significant at any site.

Table 5. Main effects of rate of applied lime (t/ha) and P (kg P/ha) on the total fresh weight of tubers from field (t/ha) and glasshouse (g/plant) experiments

	Glasshouse experiments		*Field experiments*		
Rate	G4	G5	F5	F6	F7
		Lime			
0	293.8	536.7		65.2	56.0
2.5				58.8	54.0
5		591.5	60.0	59.9	56.4
7.5					58.5
10		506.4	61.4	56.8	
15				55.8	46.3
20	230.1				
l.s.d. (P=0.05)	*46.0*	*n.s.*	*n.s.*	*7.7*	*7.0*
		Phosphorus			
0	200.7	182.0	54.5	57.7	49.8
50			61.8		
75	323.3	907.7			
100			65.8	60.9	58.7
l.s.d. (P=0.05)	*46.0*	*83.5*	*10.7*	*n.s.*	*4.4*

Number of tubers and stems per plant

The application of lime significantly decreased the number of set tubers per plant in experiments G5, F6 and F7 (Table 6).

Table 6. Main effects of rate of applied lime (t/ha) and P (kg P/ha) on the total number of tubers per plant in field and glasshouse experiments

	Glasshouse experiments		*Field experiments*		
Rate	G4	G5	F5	F6	F7
		Lime			
0	18	18		10	13
2.5				9	11
5		13	14	8	11
7.5					12
10		9	14	8	
15				8	11
20	19				
l.s.d. (P=0.05)	*n.s.*	*4*	*n.s.*	*1*	*1.5*
		Phosphorus			
0	13	8	15	8	11
50			14		
75	24	19			
100			14	9	12
l.s.d. (P=0.05)	*4*	*3*	*n.s.*	*n.s.*	*0.9*

There was a significant ($P<0.001$) interaction between lime x P in experiment G5. In this experiment when no P was applied the application of lime did not affect the number of tubers set per plant. However, at 75 kg P/ha, increasing the rate of lime from nil to 10 t/ha significantly decreased the number of tubers/plant from 31 to 10.

The application of lime or P did not significantly affect the number of stems per plant in experiments G4, F5 and F6. The mean number of stems at the optimum P rate was 11, 4 and 5 in experiments G4, F6 and F7, respectively. In experiment G5, the effect of applied lime was not significant, however, increasing the rate of applied P from nil to 75 kg P/ha increased the number of stems from 2 to 3 ($P<0.05$). There was no significant lime x P interaction in any experiment.

Plant height and dry matter production

Main effects. The application of lime did not significantly affect plant height, or dry matter leaf, stem and leaf+stem yields (data not presented). In experiment G5, increasing the rate of lime from nil to 5 t/ha decreased the total stem dry weight from 12.3 to 8.8 g/plant ($P<0.05$). The effect was not significant in experiment G4.

In contrast with the effect of lime, the application of P significantly increased leaf, stem and total tops dry matter yields and plant height in both glasshouse experiments (Table 6). These growth responses are consistent with the tuber yield responses which occurred when fertiliser P was applied to these P deficient soils.

Table 6. Main effects of P on leaf, stem and total top dry matter yields (g/plant) and plant height (cm) for glasshouse experiments G4 and G5

Rate (kg/ha)	*Leaf*		*Stem*		*Tops*		*Height*	
	G4	G5	G4	G5	G4	G5	G4	G5
0	9.7	12.0	4.2	3.6	13.9	15.6	605	733
75	12.5	37.8	5.8	16.7	18.4	54.5	813	1279
l.s.d. (P=0.05)	*1.8*	*6.1*	*1.0*	*2.4*	*2.3*	*7.5*	*85*	*128*

Total-N and phosphorus concentrations in the 5th leaf

Nitrogen. The effect of applied lime on total-N concentrations in the 5th leaf was not significant in any experiment (data not presented). In contrast, the application of P significantly increased total-N concentrations in experiments G4, F5 and F7 (Table 7). The importance of the synergistic interaction between P and N for the interpretation of plant test data have been discussed by Maier *et al.* (1994).

The lime x P interactions were not significant at any site.

Table 7. Main effects of phosphorus on the concentrations of total-N and P in the 5th leaf

Rate	*Glasshouse experiments*		*Field experiments*		
(kg/ha)	G4	G5	F5	F6	F7
		Total-N (%)			
0	5.5	n.a.	5.6	6.4	5.2
50			6.9		
75	6.1	n.a.			
100			6.2	6.2	5.5
l.s.d. (P=0.05)	*0.3*		*0.3*	*n.s.*	*0.2*
		Phosphorus (%)			
0	0.23	0.33	0.34	0.52	0.23
50			0.49		
75	0.53	0.74			
100			0.51	0.47	0.38
l.s.d. (P=0.05)	*0.07*	*0.08*	*0.05*	*n.s.*	*0.03*

Phosphorus. Increasing rates of lime significantly (P<0.05) decreased P concentrations in the 5th leaf in experiments G4 and F7. In experiment G4, increasing the rate of applied lime from nil to 20 t/ha decreased P concentrations from 0.41 to 0.34%, respectively. In field experiment F7, P concentrations decreased from 0.35 to 0.28% when the rate of applied lime increased from nil to 20 t/ha. In the experiments where the effects were not significant, mean P concentrations were in the range 0.49-0.58%, G4; 0.44-0.46%, F5; and 0.46-0.52%, F6.

The application of P significantly increased P concentrations in the 5th leaf in all except 1 (experiment F6) experiment (Table 7).

Cadmium concentrations in tubers

In the field experiments, the application of lime, up to 15 t/ha, did not significantly reduce Cd in tubers (Table 8). In contrast with the field experiments, the application of lime significantly reduced Cd concentrations in tubers in both glasshouse experiments.

Table 8. Main effects of rate of lime (t/ha) and phosphorus (kg/ha) on cadmium concentrations (mg/kg fwt) in tubers

	Glasshouse experiments		*Field experiments*		
Rate	G4	G5	F5	F6	F7
			Lime		
0	0.159	0.053		0.073	0.108
2.5				0.082	0.132
5		0.023	0.033	0.078	0.129
7.5					0.140
10		0.018	0.034	0.074	
15				0.067	0.142
20	0.045				
l.s.d. (P=0.05)	*0.033*	*0.018*	*n.s.*	*n.s.*	*n.s.*
			Phosphorus		
0	0.068	0.028	0.032	0.072	0.115
50			0.033		
75	0.136	0.035			
100			0.035	0.078	0.146
l.s.d. (P=0.05)	*0.033*	*n.s.*	*n.s.*	*n.s.*	*0.016*

The application of P, as superphosphate, significantly increased Cd concentrations in tubers in experiments G4 and F7 (Table 8). In the other experiments, even though the effects were not statistically significant, the trend was positive in all experiments.

The lime x P interaction was significant ($P<0.05$) in experiment G4.

In an earlier study we also found that increasing rates of P, as superphosphate, significantly increased Cd concentrations in tubers at 2 out of 3 sites (Table 9; N. A. Maier unpublished data).

Table 9. Further data on the effect of increasing rates of applied P, as superphosphate, on cadmium concentrations (mg/kg fwt) in tubers

Rate	Site		
(kg/ha)	1	2	3
0	0.072	0.117	0.176
80	0.073	0.132	0.218
160	0.070	0.137	0.249
320		0.145	
l.s.d. (P=0.05)	*n.s.*	*0.012*	*0.026*

Effect of Cd concentration in superphosphate

In 1 glasshouse experiment (experiment G6) we compared the effect on Cd concentrations in tubers of using superphosphate low in Cd. The rate of P applied was equivalent to 75 kg P/ha. The application of low Cd superphosphate significantly decreased the Cd concentration in tubers (Table 9).

Table 9. Effect of applying superphosphate containing different amounts of Cd on the concentration of Cd in tubers

Cd concentration (mg Cd/kg	Lime (t/ha) 5	10
4	0.019	0.014
28	0.030	0.021
l.s.d. (P=0.05)	*0.003*	

GENERAL DISCUSSION

The lack of any effect of lime on tuber Cd concentrations under field conditions confirms results from earlier experiments (Appendix 2). Cadmium concentrations in tubers were significantly reduced by application of lime under glasshouse conditions.

The effect of P fertilizer was inconsistent, with 3 out of 6 field trials and 1 out of 2 glasshouse experiments indicating a significant effect. It is interesting to note that the soils where application of P had a significant effect on Cd uptake by tubers were the soils having high Cd concentrations initially (i.e. without P). In glasshouse experiments, Williams and David (1977) noted that adding P to a soil increases Cd uptake through a stimulation of root proliferation in the zone into which P is added. Sparrow et al. (1993) compared Cd uptake by potatoes fertilised with both low- and high-Cd DAP in field trials and found little differences in Cd uptake between the two sources, with Cd concentration in tubers being related to the rate of P applied, rather than the rate of Cd applied. These data support the early results of Williams and David and are in agreement with the data presented here

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APPENDIX 4

EFFECT OF LIME AND NITROGEN SOURCE ON THE YIELD, GROWTH, LEAF NUTRIENT COMPOSITION AND CADMIUM CONCENTRATIONS IN POTATOES (*SOLANUM TUBEROSUM* L.)

INTRODUCTION

Nitrogen (N) is a major nutrient applied to potato crops. Depending on the soil type and residual N fertility, acidifying N fertilisers (eg. ammonium sulfate, ammonium nitrate and urea) may be applied at rates up to 300 kg N/ha (Williams and Maier 1985). Studies with other crops have shown that application of these fertilisers resulted in significant decreases in pH (Spiers 1978; Errebhi and Wilcox 1990; Schwamberger and Sims 1991). The increased soil acidity may in turn affect nutrient uptake and therefore plant chemical composition, productivity and quality. Because of the high rates of NH_4-N fertilisers applied to potatoes, which are often growing in strongly acid (pH_w <5.5) soils, we compared the effects of ammonium sulfate, ammonium nitrate, urea and calcium nitrate on the growth, yield of leaf chemical composition of the potato cvv. Russet Burbank and Atlantic.

Increased soil acidity has also been reported to increase cadmium (Cd) uptake (Page and Bingham, 1973). However, we are not aware of any published studies on the effect of N source, particularly the use acidifying N fertilisers, on the accumulation of Cd in potato tubers.

Published studies on the effects of liming on Cd uptake under field conditions are contradictory (Tiller et al. 1994). Anderson and Siman (1991) have reported that the application of lime significantly reduced Cd uptake by wheat on some sites but had no effect on others. To provide further information on the effect of liming on Cd uptake by potato tubers and to determine the effect of N sources on Cd uptake at different soil pH levels, varying rates of lime were included in the experiments.

In this study we used pot experiments because we were able to I) achieve very thorough incorporation of the lime into the soil; ii) lime the whole rooting volume of the plant; and iii) ensure an effective period of moist incubation. With field experiments, lime is usually spread by hand and incorporated using a rotary hoe, which therefore limits incorporation to 15-20 cm.

MATERIALS AND METHODS

Glasshouse experiments

Three glasshouse experiments were conducted during 1991/92 (G4), 1992/93 (G5) and 1993 (G6) at the Northfield Research Laboratories. Details of lime applications, planting, leaf sampling and harvest dates are presented in Table 1.

The experimental design was a randomized block. The treatments were, 2 lime rates x 2 N sources in experiment G4, 2 lime rates x 4 N sources in experiment G5 and 3 lime rates x 4 N sources in experiment G6. The treatments were replicate 6, 5 and 4 times in experiments G4, G5 and G6, respectively. The N sources were calcium nitrate (15.5% N), ammonium nitrate (34% N), urea (46% N) and ammonium sulfate (21% N). In experiment G4, only calcium nitrate and ammonium sulfate were used. The cvv. grown were Russet Burbank in experiments G4 and G5, and Atlantic in experiment G6.

Table 1. Lime application, planting, leaf sampling and harvest dates

Experiment	Lime applied	Tubers planted	Leaves sampled	Harvest
G4	23.xii.91	24.ii.92	7.iv.92	14.vii.92
G5	18.viii.92	15.ix.92	3.xi.92	8.ii.93
G6	21.i.93	15.ii.93	23.iii.93	8.vi.93

The experimental procedure was as follows:

(I) Soil, from the A horizon, was collected from sites in the Mt Lofty Ranges (G4) and South East (G5 and G6) of South Australia. Each soil was air dried and sieved to <5 mm before use. To characterise the soil, a sub-sample was collected for chemical and physical analysis. For each experiment 300 mm diameter, free draining pots and 15 kg of air dry soil were used.

(ii) Soil from each pot was spread on a plastic sheet to <10-15 mm in depth. Depending on the treatment, finely ground agricultural lime (100%, <0.25 mm) was broadcast over the soil and then thoroughly mixed with the soil. The rates of lime were equivalent to 0 and 20 t/ha in experiment G4; 5 and 10 t/ha in experiment G5 and 0, 5 and 10 t/ha in experiment G6. The rates were calculated on the basis of the surface area of the soil in the pots.

(iii) The soil was placed back into the pot and 'wetted up'. Soil moisture was maintained at field capacity (approximately -10 kPa) during the incubation period. The moist incubation period was approximately 8 weeks in experiment G4 and 4 weeks in experiments G5 and G6 (Table 1). During this period the pots were kept in a shed at room temperature.

(iv) 'Basal' nutrients were applied to the soil and these included: N, equivalent to 50 kg N/ha using each N source; K, equivalent to 120 (experiment G4) or 100 kg K/ha (experiments G5 and G6) as potassium sulfate; and P, equivalent to 75 kg P/ha as superphosphate. The nutrients were applied approximately 1 week before planting in experiments G4 and G5, and at the same time as the lime in experiment G6. The K and P were applied to ensure these nutrients were not deficient. The 'basal' fertilisers were thoroughly mixed into the soil, after which approximately two thirds of the soil was placed back into the pot.

(v) Immediately prior to planting, a subsample of soil was collected from each pot for chemical analysis.

(vi) Tuber seed pieces (one per pot) were planted and covered with 2-3 cm of soil, after which the pots were placed in a glasshouse.

(vii) For each pot, the remaining soil was added when the plants were 25-30 cm tall to minimize the risk of tubers developing above the soil surface.

(ix) Depending on stage of growth, the plants were watered 1-7 times a week using either rain or tap water. In experiment G4, 2 side-dressings of N, each equivalent to 50 kg N/ha, were applied on the 13th and 26th of March 1992. In experiments G5 and G6, 3 side-dressings of N, equivalent to 37.5, 50 and 37.5 kg N/ha and 2 side-dressings of K, equivalent to 37.5 kg K/ha were applied. The side-dressings were applied approximately 3 (plants 10-15 cm tall), 6 (plants 20-40 cm tall) and 9 weeks after planting. The side-dressings were applied to ensure these nutrients did not limit growth or yield response. During growth, each plant was supported by a trellis.

(x) After haulm senescence, the contents of each pot were tipped onto a table and the tubers harvested. A soil sample was also collected for chemical analysis. After washing, the fresh weight of tubers was determined for each pot.

Soil sampling

Soil samples were collected from each pot immediately prior to planting and at harvest for chemical analysis.

Leaf sampling

The index tissue sampled was the 5th leaf from the growing terminal. The leaves were sampled 5-6 weeks after planting (Table 1). On the basis of plant development, sampling occurred at tuber initiation or early tuber set. The number of leaves sampled ranged from 2-10, depending on the number of stems per plant.

Chemical analysis of soils

All soil samples were air dried before being sieved (< 2 mm stainless steel mesh) prior to chemical analysis.

Soil pH and EC were measured in a water suspension of each soil using a soil:solution ratio of 1:5. Exchangeable cation concentrations were determined using the 1M NH_4Cl leaching procedure with an alcohol pre-wash to remove soluble salts [Rayment and Higginson 1992]. Total-C was measured using a LECO furnace [Rayment and Higginson 1992]. Bicarbonate-extractable P was determined according to the method of Colwell [Colwell 1963].

Chemical analysis of plant materials

Cadmium. Preparation of tubers and Cd analysis of tuber material was performed as outlined by McLaughlin et al. (1994). Subsamples (0.1 g) of the dried ground leaf materials from 2 glasshouse experiments (G5 and G6) were digested with concentrated nitric acid until the digest mixture was clear. The digest solution was diluted to 10 ml using 0.016M nitric each batch. Cadmium concentrations in the digest solutions were determined using an atomic absorption spectrophotometer with graphite furnace atomisation and deuterium background correction. Orthophosphoric acid was used as a modifier.

All analytical procedures included two reference materials (rice flour from the National Institute for Environmental Studies, Japan and cabbage leaves from the Institute of Physics and Nuclear Techniques, Poland) having certified concentrations of Cd.

Cadmium concentrations in the tubers are reported on a fresh weight (f wt) basis and in the 5th leaf on a dry weight (d wt) basis.

Other elements. Concentrations of B, Ca, Cu, Fe, K, Mg, Mn, Na, P, S and Zn in the digest solutions was determined using Inductively-Coupled Plasma Atomic Emission Spectroscopy.

Statistical analysis

The effects of rate of applied lime and N source on soil pH and conductance, tuber yield, plant height, dry matter stem, leaf and stem+leaf yields, and elemental concentrations in 5th leaf and tubers were determined by analysis of variance.

RESULTS AND DISCUSSION

Soil chemical and physical properties

Selected chemical and physical properties of the soil used in each experiment are presented in Table 2. All soils chosen were strongly acid, with the pH values in the range 4.1-4.9 (Table 2). In all experiments the soil type used was a sand. The soils had total-C values in the range 1.4-2.4%, indicating a range of fertility levels. Extractable P concentrations were low and ranged from 7 to 19 mg/kg.

Table 2. Selected chemical and physical properties of the soils

Experiment	pH_w	Total carbon (%)	Extractable-P (mg/kg)	C.E.C	Sand (%)	Silt (%)	Clay (%)
G4	4.9	2.2	19	5.9	90	2	8
G5	4.1	2.4	12	4.6	87	5	8
G6	4.7	1.4	7	3.4	93	1	6

Soil pH

Main effects. The application of lime significantly ($P<0.05$) increased soil pH in all experiments (Table 3). In experiments G5 and G6, there were also significant differences in pH between the different N sources. The application of ammonium sulfate resulted in the lowest pH (Table 3). Soil pH was significantly lower at harvest compared with planting in experiments G5 and G6.

Table 3. Main effects of lime (t/ha), N source and sampling time on soil pH and conductance (mS/cm)

Variable	pH G4	pH G5	pH G6	Conductance G4	Conductance G5	Conductance G6
		Lime				
0	4.8		4.4	0.57		0.41
5		5.8	5.9		0.41	0.48
10		7.0	6.7		0.46	0.51
20	7.6			0.61		
l.s.d.(P=0.05)	*0.2*	*0.1*	*0.1*	*n.s.*	*n.s.*	*0.05*
		N source				
Calcium nitrate	6.2	6.7	5.8	0.52	0.42	0.48
Ammonium nitrate		6.5	5.9		0.38	0.41
Urea		6.6	5.7		0.37	0.44
Ammonium sulfate	6.1	5.9	5.3	0.66	0.57	0.55
l.s.d.(P=0.05)	*n.s.*	*0.1*	*0.1*	*0.06*	*0.07*	*0.05*
		Sampling time				
Planting	6.2	6.7	5.9	0.54	0.37	0.40
Harvest	6.2	6.1	5.5	0.64	0.50	0.54
l.s.d.(P=0.05)	*n.s.*	*0.1*	*0.1*	*0.06*	*0.05*	*0.04*

Interactions. In experiments G5 and G6, there were significant first and second order interactions between the factors studied. To show the effects, data for the lime x N source x sampling time interaction, which was significant in experiments G5 ($P<0.01$) and G6 ($P<0.001$), are presented in Table 4. The application of urea significantly increased pH at planting, when nil (experiment G6) or 5 t/ha (experiment G5) lime was applied. In contrast at harvest, ammonium sulfate resulted in lower pH values compared with the other N sources, when increasing rates of lime were applied (Table 4).

Our results show that, depending on sampling time, differences in pH of up to 1.8 units occurred between the N sources. Other studies (eg. Schwamberger and Sims 1991) have also reported large decreases in pH due to the use of NH_4 fertilisers, the magnitude depending on N source, soil buffering capacity with regard to soil acidity and rate of N fertilisation.

Table 4. Effect of applied lime, N source and sampling time (planting and harvest) on pH

Lime (t/ha)	N source	Experiment G5 Planting	Experiment G5 Harvest	Experiment G6 Planting	Experiment G6 Harvest
0	Calcium nitrate			4.6	4.4
	Ammonium nitrate			4.7	3.9
	Urea			5.2	4.1
	Ammonium sulfate			4.6	4.0
5	Calcium nitrate	6.1	6.3	6.1	6.1
	Ammonium nitrate	6.2	5.6	6.6	6.3
	Urea	6.5	5.6	5.9	5.5
	Ammonium sulfate	6.0	4.5	5.9	4.8
10	Calcium nitrate	7.2	7.0	6.8	6.9
	Ammonium nitrate	7.3	6.9	6.9	6.9
	Urea	7.5	6.7	6.7	6.6
	Ammonium sulfate	7.2	6.1	6.6	6.0
	l.s.d. (P=0.05)	*0.2*		*0.2*	

Conductance

Main effects. Soil conductance was significantly ($P<0.05$) affected by all the variables studied (Table 3). For example, increasing rates of applied lime increased conductance in experiment G6; the application of ammonium sulfate increased conductance compared with the other N sources in all experiments; and conductance was consistently higher at harvest compared with planting.

Interactions. There were significant first and higher order interactions between variables in there effects on conductance. Specifically: I) lime x sampling time ($P<0.05$) in experiment G4. The application of lime increased conductance from 0.47 to 0.60 mS/cm when measured at planting. However, at harvest, the difference was not significant, 0.66 and 0.62 mS/cm, respectively; ii) N source x sampling time ($P<0.01$) in experiment G5. With ammonium sulfate as the N source, conductance at harvest (0.72 mS/cm) was significantly higher compared with planting (0.42 mS/cm) For the other N sources the differences were not significant (data not presented); and iii) In experiment G6, the lime x N source x sampling time interaction was significant ($P<0.001$) and the data are presented in Table 5.

Table 5. Effect of applied lime, N source and sampling time on conductance (mS/cm)

Data are for experiment G6

Lime (t/ha)	N source	Sampling time Planting	Harvest
0	Calcium nitrate	0.39	0.59
	Ammonium nitrate	0.28	0.54
	Urea	0.31	0.48
	Ammonium sulfate	0.44	0.30
5	Calcium nitrate	0.40	0.53
	Ammonium nitrate	0.34	0.49
	Urea	0.39	0.51
	Ammonium sulfate	0.51	0.71
10	Calcium nitrate	0.46	0.52
	Ammonium nitrate	0.41	0.42
	Urea	0.41	0.53
	Ammonium sulfate	0.49	0.89
	l.s.d. (P=0.05)	*0.13*	

At nil lime and using ammonium sulfate, conductance decreased significantly between planting and harvest. With increasing rates of lime, the effect was reversed and conductance increased from planting to harvest (Table 5). With the other N sources, conductance increased between planting and harvest when no lime was applied, and with increasing rates of lime the differences between sampling times became less.

Tuber yield

In experiments G5 and G6, the main effects and the lime x N source interactions were significant ($P<0.001$) (Table 6). Liming and N source did not significantly affect yield in experiment G4. When Calcium nitrate was the N source, liming decreased tuber yields. In contrast, with ammonium sulfate, yield increased (Table 6).

Table 6. Effects of lime and N source on the total fresh weight (g/plant) of tubers

Lime (t/ha)	Nitrogen source Calcium nitrate	Ammonium	Urea	Ammonium
		Experiment G4		
0	339.0			326.1
20	306.2			340.6
		n.s.		
		Experiment G5		
5	946.0	970.0	1052.0	879.9
10	823.5	966.5	860.6	983.7
		l.s.d. (P=0.05) = 87.6		
		Experiment G6		
0	486.4	465.0	486.6	172.3
5	444.8	505.1	525.8	526.7
10	387.5	405.9	453.7	538.6
		l.s.d. (P=0.05) = 78.9		

Number of tubers and stems per plant

Main effects. The application of lime and the use of different N sources did not significantly affect tuber or stem number (Table 7).

Table 7. Main effects of applied lime and N source on the number of tubers and stems per plant

	Tubers			Stems		
Variable	G4	G5	G6	G4	G5	G6
		Lime				
0	19		10	11		5
5		16	11		3	5
10		16	9		3	6
0	20			11		
l.s.d.(P=0.05)	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*
		N source				
Calcium nitrate	20	14	11	10	3	6
Ammonium nitrate		19	10		3	5
Urea		15	10		3	6
Ammonium sulfate	19	17	10	11	3	6
l.s.d.(P=0.05)	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*

Plant height and dry matter production

The application of lime significantly ($P<0.05$) increased the weight of leaves (experiments G5 and G6), and stems (all experiments) harvested (Table 7). In experiments G4 and G6, plant height also increased in response to applied lime.

Table 8. Main effects of lime on the weight (g/plant d wt) of leaves and stems produced, and plant height (cm)

Lime (t/ha)	Leaf G4	Leaf G5	Leaf G6	Stem G4	Stem G5	Stem G6	Height G4	Height G5	Height G6
0	12.2		17.4	5.0		6.9	68.9		91.5
5		35.8	20.2		17.0	9.5		131.4	102.1
10		39.0	22.2		14.9	9.6		128.6	101.7
20	12.1			6.3			87.1		
l.s.d.(P=0.05)	*n.s.*	*3.1*	*1.2*	*1.2*	*1.9*	*0.7*	*12.0*	*n.s.*	*4.4*

In experiments G4 and G5, N source did not significantly affect the yield of leaves, stems or plant height (data not presented). In contrast, in experiment G6, the effect of N source and the lime x N source interaction were significant ($P<0.01$) for all these variables. Data for this experiment are presented in Table 9.

Table 9. Effect of applied lime and N source on weight (g/plant d wt) of leaves and stems and plant height (cm)

Data are for experiment G6

Lime (t/ha)	Nitrogen source: Calcium nitrate	Ammonium	Urea	Ammonium
		Leaves		
0	19.6	17.7	19.1	13.4
5	20.3	20.3	20.5	19.8
10	21.8	21.3	22.9	22.8
		l.s.d. (P=0.05) = 2.3		
		Stems		
0	8.4	8.1	7.3	3.6
5	10.0	9.4	9.2	9.3
10	9.5	10.4	9.6	9.1
		l.s.d. (P=0.05) = 1.4		
		Height		
0	98.3	106.8	96.0	65.0
5	103.8	102.0	104.5	98.3
10	101.5	104.0	102.0	99.3
		l.s.d. (P=0.05) = 8.8		

Consistent with the effect on tuber yield, when no lime was applied the weight of leaves and stems, and plant height were significantly lower when ammonium sulfate was used. At 5 or 10 t/ha lime, the differences were not significant ($P<0.05$).

Chemical composition of 5th leaf

Many studies have reported significant effects of N source on plant nutrient composition. For example, Spiers (1978) reported that N, P, Ca, Mg, Mn and Fe concentrations were highest in leaves of blueberry plants fertilised with ammonium sulfate. Concentrations of Al, Zn, B, Cu and K were not affected by N source. Schwamberger and Sims (1991) working with tobacco, found that NH_4^+ increased plant P concentrations compared with NO_3^-. Leidi *et al.* (1992) reported decreased K uptake by peanut and cotton fertilised with NH_4-N.

Phosphorus. In experiment G4, increasing the rate of applied lime from nil to 20 t/ha significantly decreased P concentrations from 0.61 to 0.51%. In the other experiments the effect of lime was not significant and mean P concentrations ranged from 0.73-0.78 and 0.73-0.77% in experiments G5 and G6, respectively. The effect of N source was significant in experiments G5 and G6. For example, in experiment G5 the use of calcium nitrate (0.69%) resulted in significantly lower P concentrations compared with ammonium sulfate (0.81%). In experiment G6, the use of calcium nitrate (0.72%) and ammonium sulfate (0.71%) resulted in lower P concentrations compared with the other N sources (0.77 or 0.80%). The lime x N source interactions were not significant at any site.

Potassium. The application of lime significantly decreased K concentrations in experiments G4 and G6 (Table 10). The use of ammonium sulfate resulted in significantly lower K concentrations compared with calcium nitrate and ammonium nitrate (Table 10). In experiment G6 there was a significant ($P< 0.01$) lime x N source interaction. With ammonium sulfate and urea K concentrations decreased with increasing rates of applied lime. For example, using ammonium sulfate, K concentrations at 0, 5 and 10 t/ha lime were 6.0, 5.1 and 4.4%, respectively.

Calcium. Increasing rates of applied lime significantly increased Ca concentrations in the 5th leaf in all experiments (Table 10). The use of calcium nitrate also increased Ca concentrations compared with the other N sources (Table 10). The lime x N source interaction was significant ($P<0.05$) in experiment G5. At 5 t/ha lime the difference in Ca concentration between urea and ammonium sulfate was not significant (0.22 vs 0.18%). In contrast, at 10 t/ha lime, the difference was significant (0.42 vs 0.27%).

Table 10. Main effects of lime (t/ha) and N source on the concentrations of K, Ca, Mg, S, B, Mn and Cd in the 5th leaf

	G4	G5	G6	G4	G5	G6	G4	G5	G6
	Potassium			Calcium			Magnesium		
				Lime					
0	6.4		5.5	0.52		0.25	0.38		0.30
5		4.9	4.9		0.28	0.72		0.25	0.38
10		5.1	5.0		0.43	0.76		0.29	0.37
20	5.1			1.34			0.41		
l.s.d. (P=0.05)	*0.6*	*n.s.*	*0.3*	*0.23*	*0.03*	*0.08*	*n.s.*	*0.01*	*0.04*
				N source					
Calcium nitrate	5.9	5.4	5.1	1.22	0.51	0.73	0.46	0.33	0.39
Ammonium nitrate		5.1	5.1		0.36	0.57		0.27	0.35
Urea		4.9	5.0		0.32	0.52		0.25	0.31
Ammonium sulfate	5.5	4.6	5.2	0.64	0.22	0.49	0.32	0.23	0.34
l.s.d. (P=0.05)	*n.s.*	*0.4*	*n.s.*	*0.23*	*0.04*	*0.10*	*0.04*	*0.01*	*0.04*
	Boron			Manganese			Cadmium		
				Lime					
0	n.a.		23	110		63	n.a.		1.32
5		25	19		25	66		0.77	0.91
10		21	14		48	50		0.67	0.84
20	n.a.			58			n.a.		
l.s.d. (P=0.05)		*2*	*4*	*11*	*3*	*5*		*n.s.*	*0.18*
				N source					
Calcium nitrate	n.a.	22	14	95	39	64	n.a.	0.81	1.17
Ammonium nitrate		23	13		38	58		0.84	1.10
Urea		23	23		34	58		0.64	0.87
Ammonium sulfate	n.a.	24	23	73	34	59	n.a.	0.61	1.04
l.s.d. (P=0.05)		*n.s.*	*4*	*11*	*4*	*n.s.*		*0.17*	*0.18*

Magnesium. The increase in Mg concentration due to the application of lime was significant in 2 of the 3 experiments (Table 10). The use of calcium nitrate resulted in the highest Mg concentrations in all experiments (Table 10). The lime x N source interaction was significant ($P<0.05$) in experiment G5. The increase in Mg concentration was greater for ammonium nitrate and urea compared with calcium nitrate and ammonium sulfate. For example, increasing the rate of applied lime from 5 to 10 t/ha increased Mg concentrations from 0.32 to 0.34% when calcium nitrate was used, and from 0.22 to 0.28% with urea.

Sulfur. In experiments G4 and G5 the application of lime significantly decreased S concentrations in the 5th leaf (Table 10). Sulfur concentrations also varied with N source, however, the effects were not consistent between sites. For example, in experiment G4, S concentrations were higher when calcium nitrate was used as the N source compared with ammonium sulfate. In experiment G6, S concentrations were significantly lower when calcium nitrate was the N source. The lime x N source interaction was significant (*P*<0.001) in experiment G6. At nil lime, the use of urea and ammonium sulfate resulted in higher S concentrations (0.72 and 1.15%, respectively) compared with ammonium nitrate (0.54%) and calcium nitrate (0.52%). At 5 and 10 t/ha lime, the differences in Mg concentration between the N sources were not significant (*P*>0.05).

Table 10 Effect of lime and N source on S concentrations in 5th leaf

Variable	G4	G5	G6
		Sulfur	
Lime			
0	0.72		0.73
5		0.46	0.49
10		0.47	0.51
20	0.50		
l.s.d. (P=0.05)	*0.17*	*n.s.*	*0.07*
N source			
Calcium nitrate	0.70	0.49	0.49
Ammonium nitrate		0.46	0.51
Urea		0.45	0.58
Ammonium sulfate	0.52	0.47	0.73
l.s.d. (P=0.05)	*0.17*	*0.03*	*0.08*

Boron. The application of lime significantly decreased B concentrations in the 2 experiments in which they were determined (Table 10). In experiment G6, B concentrations were significantly lower when calcium nitrate and ammonium nitrate were used as N sources (Table 10). The lime x N source interaction was not significant in any experiment.

Copper. In experiment G6, increasing the rate of applied lime from nil to 10 t/ha decreased (*P*<0.05) Cu concentrations from 10.5 to 7.7 mg/kg. The effect of N source on Cu concentrations was not significant in any experiment. The mean Cu concentrations were in the range 13-16 and 8-11 mg/kg in experiments G4 and G5, respectively.

Zinc. In experiment G6, increasing the rate of applied lime from nil to 10 t/ha decreased (*P*<0.05) Zn concentrations from 66 to 54 mg/kg. The effect of N source and the lime x N source interaction were not significant in experiments G5 and G6. The mean Zn concentrations were in the range 65-78 and 85-39 mg/kg in experiments G5 and G6, respectively. The lime x N source interaction was significant (*P*<0.05) in experiment G4. At nil lime, the use of ammonium sulfate resulted in significantly higher Zn concentrations

(101 mg/kg) compared with calcium nitrate (70 mg/kg). At 20 t/ha lime, the difference in concentrations was not significant (63 vs 77 mg/kg).

Manganese. The effect of rate of applied lime on Mn concentrations was not consistent between experiments. In experiments G4 an G6 the application of lime decreased Mn concentrations, in contrast, in experiment G5 Mn concentrations increased (Table 10).

The use of ammonium sulfate (experiment G4) and urea and ammonium sulfate (experiment G5) resulted in lower Mn concentrations compared with the other N sources (Table 10).

The lime x N source interaction was significant in experiment G6 ($P<0.001$) (Table 11). With calcium nitrate and ammonium nitrate, Mn concentrations decreased with increasing rates of applied lime. In contrast with ammonium sulfate and urea, Mn concentrations increased and then decreased at the highest rate of lime (Table 11).

Table 11. Effects of lime and N source Mn concentrations (mg/kg) in 5th leaf
Data are from experiment G6

Lime (t/ha)	Nitrogen source Ammonium	Calcium nitrate	Urea	Ammonium
0	64	86	53	50
5	53	63	72	76
10	59	44	48	51
	l.s.d. (P=0.05) = 10			

Cadmium. The decrease in Cd concentrations was significant in 1 of the 2 experiments in which it was determined (Table 10). The use of urea in experiment G6, and urea or ammonium sulfate in experiment G5 resulted in lower Cd concentrations in the 5th leaf compared with the other N sources (Table 10). In experiment G6, the lime x N source interaction was significant ($P<0.05$). For the different N sources, the Cd concentrations at nil and 10 t/ha of lime were: ammonium nitrate, 1.32 and 0.85 mg/kg; calcium nitrate, 1.62 and 0.85 mg/kg; urea, 0.88 and 0.83 mg/kg; and ammonium sulfate, 1.46 and 0.83 mg/kg. These data show that when no lime was applied, the use of urea resulted in significantly lower Cd concentrations compared with the other N sources.

Cadmium concentrations in tubers

The application of lime significantly decreased Cd concentrations in tubers in all experiments (Table 12). The lime x N source interaction was significant in experiments G4 ($P<0.01$) and G5 ($P<0.001$). The use of calcium nitrate resulted in significantly higher Cd

Table 12. Effect of applied lime and N source on the concentration of cadmium (mg/kg f wt)in tubers

Lime (t/ha)	Nitrogen source Calcium nitrate	Ammonium	Urea	Ammonium
		Experiment 4		
0	0.211			0.151
20	0.060			0.103
		l.s.d. (P=0.05) = 0.046		
		Experiment 5		
5	0.029	0.029	0.023	0.021
10	0.021	0.019	0.026	0.021
		l.s.d. (P=0.05) = 0.004		
		Experiment 6		
0	0.056	0.041	0.035	0.038
5	0.036	0.032	0.028	0.028
10	0.027	0.026	0.025	0.026
		l.s.d. (P=0.05) = 0.010		

Cd concentrations in tubers compared with ammonium sulfate. However, the differences were not significant when 10 or 20 t/ha lime were applied.

GENERAL DISCUSSION

As found in previous experiments (Appendices 2 and 3) application of lime reduced tuber Cd concentrations in plants grown under glasshouse conditions.

The N sources did not affect Cd as expected given their potential to acidify soil. Ammonium sulfate is the most acidifying N source and yet did not produce tubers with the highest Cd concentrations. Eriksson (1989) found that ammonium sulfate increased Cd uptake by rapeseed plants compared to calcium nitrate or ammonium nitrate. Willaert and Verloo (1992) also found ammonium sulfate enhanced Cd uptake by spinach plants. In contrast, we found that addition of calcium nitrate as the N source resulted in plants with the highest tuber Cd concentrations. It is possible that Ca added in this fertilizer enhanced Cd uptake through displacement of Cd from soil surfaces, although this needs confirmation. This hypothesis is also consistent with the observation that lime may sometimes increase tuber Cd concentrations (Appendix 2).

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APPENDIX 5

EFFECT OF LIME, CHLORIDE CONCENTRATION IN IRRIGATION WATER AND SOIL TYPE ON THE YIELD, GROWTH, LEAF NUTRIENT COMPOSITION AND CADMIUM CONCENTRATIONS IN POTATOES (*SOLANUM TUBEROSUM* L.)

INTRODUCTION

In previous experiments (Appendix 2) it was found that cadmium (Cd) concentrations in tubers over a range of sites was correlated to electrical conductivity (EC) of the soil at harvest. Combined with a relationship between chloride (Cl) and Cd in tubers, this suggests that soil salinity is the dominant factor controlling Cd concentrations in potato tubers in South Australia. This hypothesis is also in agreement with the results of McLaughlin et al. (1994) who found Cl concentrations in soil were closely related to Cd concentrations in potato tubers.

is often recommended to reduce uptake of Cd by crops. However, previous experiments indicated that liming under field conditions had little effect on Cd concentrations potato tubers (Appendix 2). Under glasshouse conditions, liming was generally found to be effective in reducing Cd uptake by potatoes. However, where Cl is mobilising Cd in soil (McLaughlin et al. 1994) lime may be ineffective in reducing tuber Cd concentrations. This hypothesis may explain the lack of any effect of lime under field conditions in South Australia (Appendix 2). The aim of this experiment therefore was to determine the interaction between lime application and irrigation water salinity on Cd uptake by potatoes.

MATERIALS AND METHODS

Experimental procedures, planting and harvest dates and chemical analyses were similar to those reported in Appendix 2. The cv. used was Atlantic.

Sodium chloride solutions. Irrigation water of varying salinity was prepared by adding reagent grade NaCl to rainwater. Treatment concentrations (mg l^{-1}) of Cl were 21 (treatment 0), 600 (treatment 1) and 1200 (treatment 2).

Soils. Two soils were used in this experiment. Soil 1 was a sand (S), and was obtained from the lower South East (G6, Appendix 2). Soil 2 was a loamy sand (LS), and was obtained from the site used for field experiment F8 in the Mt. Lofty Ranges (Appendix 2).

Source of K. Data are also presented from experiment G5, and field experiments conducted during 1990/91, on the effect of K_2SO_4 and KCl on Cd uptake by potato tubers.

Lime. Two treatments were imposed: Unlimed and limed with lime applied at a rate equivalent to 5 t ha^{-1}.

RESULTS AND DISCUSSION

Soil pH and conductance

Liming significantly increased soil pH in both soils. Irrigation water Cl concentration had no consistent effect on soil pH.

Surprisingly, soil EC was not consistently increased by Cl treatments. Only the unlimed loamy sand soil showed any significant increase in EC with increasing Cl concentrations in the irrigation water.

Table 1. Effect of lime, chloride concentration in irrigation water and soil type (S, sand; LS, loamy sand) on soil pH and conductance determined at planting and harvest

Lime	Cl	pH				Conductance			
		Planting		Harvest		Planting		Harvest	
(t/ha)	(?)	S	LS	S	LS	S	LS	S	LS
0	0	4.7	4.9	4.0	4.4	0.28	0.39	0.54	0.55
	1	4.5	4.9	4.3	4.7	0.39	0.39	0.62	0.58
	2	4.5	5.0	4.5	4.6	0.39	0.39	0.50	0.85
5	0	6.6	6.0	6.3	5.6	0.34	0.41	0.49	0.60
	1	6.4	5.9	6.7	5.8	0.42	0.48	0.43	0.63
	2	6.3	5.9	6.3	5.9	0.39	0.40	0.59	0.70
l.s.d. (P=0.05)		*0.2*				*0.15*			

Yield and growth responses

Liming significantly increased tuber yield but had no effect on number of tubers per plant, number of stems per plant or plant height. Increasing Cl concentrations significantly reduced the tuber yield but increased the number of tubers per plant.

Table 2. Effect of lime, chloride concentration in the irrigation water and soil type (S, sand; LS, loamy sand) on tuber yield, number of tubers and stems per plant and plant height

Variable	Yield (g/plant)	Number of tubers/plant	Number of stems/plant	Height (cm)
		Lime (t/ha)		
0	358.8	12.4	5.4	89.9
5	423.9	12.6	5.3	97.2
l.s.d. (P=0.05)	*37.1*	*n.s.*	*n.s.*	*5.6*
		Chloride concentration		
0	422.3	10.6	4.8	92.9
1	403.8	14.0	5.9	92.8
2	347.9	12.8	5.4	94.9
l.s.d. (P=0.05)	*45.4*	*2.6*	*n.s.*	*n.s.*
		Soil		
S	446.4	14.1	5.8	99.2
LS	336.3	10.8	4.9	87.9
l.s.d. (P=0.05)	*37.1*	*2.1*	*0.8*	*5.6*

Dry matter production

Liming significantly increased leave dry matter production. Chloride had no consistent effect on plant dry matter production.

Table 3. Effect of lime, chloride concentration in the irrigation water and soil type (S, sand; LS, loamy sand) on leaf, stem and leaf+stem dry matter yields (g/plant d wt)

Variable	Leaves	Stems	Leaves+stems
	Lime (t/ha)		
0	17.2	8.0	25.2
5	18.7	8.8	27.4
l.s.d. (P=0.05)	*1.3*	*n.s.*	*2.0*
	Chloride concentration		
0	17.3	7.9	25.2
1	19.1	8.9	28.1
2	17.4	8.4	25.8
l.s.d. (P=0.05)	*1.6*	*n.s.*	*2.5*
	Soil		
S	19.9	9.3	29.2
LS	16.0	7.5	23.5
l.s.d. (P=0.05)	*1.3*	*1.0*	*2.0*

Tuber quality

Liming marginally increased tuber dry matter content. Chloride had no significant effect on tuber dry matter content.

Table 4. Effect of lime, chloride concentration in the irrigation water and soil type on tuber dry matter content, after-cooking darkening, hollow heart and internal browning

Variable	Dry weight	After-cooking	Hollow heart	Internal
		Lime (t/ha)		
0	22.6	89	2.1	22.7
5	23.5	93	2.4	24.2
l.s.d. (P=0.05)	*0.8*	*n.a.*	*n.a.*	*n.a.*
		Chloride concentration		
0	23.3	36	0.0	3.1
1	23.1	84	3.1	8.7
2	22.8	153	3.6	58.6
l.s.d. (P=0.05)	*n.s.*	*n.a.*	*n.a.*	*n.a.*
		Soil		
S	22.7	91	4.5	26.9
LS	23.3	91	0.0	20.0
l.s.d. (P=0.05)	*n.s.*	*n.a.*	*n.a.*	*n.a.*

Leaf chemical composition

Leaf Cd concentrations were significantly decreased by lime and significantly increased by Cl. The magnitude of the Cl effect (+60%) was large compared to the lime effect (-14%).

Liming significantly decreased leaf concentrations of P, K, S, B, Cu, Zn and Mn, while concentrations of Ca and Mg were increased, the former by 140%. Of the trace elements, Mn was the element whose concentrations were most affected by liming.

Increasing concentrations of Cl in irrigation water increased leaf concentrations of P, B, Cu, Zn and Mn, although the magnitude of the effects were small.

Table 5. Effect of lime, chloride concentration in the irrigation water and soil type (S, sand; LS, loamy sand) on the concentration (d wt basis) of selected elements in the 5th leaf

Variable	Cd (mg/kg)	P (%)	K (%)	Ca (%)	Mg (%)	S (%)	B	Cu	Zn	Mn
							(mg/kg)			
Lime (t/ha)										
0	1.87	0.66	5.30	0.35	0.44	0.53	30	14	62	219
5	1.60	0.61	4.92	0.85	0.49	0.47	23	10	42	63
l.s.d. (P=0.05)	0.22	0.04	0.23	0.08	0.04	0.02	2	1	5	27
Chloride concentration										
0	1.29	0.61	5.05	0.55	0.43	0.50	22	11	49	121
1	1.85	0.62	5.06	0.64	0.50	0.50	28	12	51	156
2	2.07	0.67	5.22	0.60	0.46	0.50	28	13	57	145
l.s.d. (P=0.05)	*0.27*	*0.04*	*n.s.*	*n.s.*	*0.04*	*n.s.*	*2*	*1*	*6*	*33*
Soil										
S	1.51	0.81	5.06	0.58	0.38	0.51	21	10	56	67
LS	1.97	0.46	5.16	0.62	0.54	0.49	32	14	49	215
l.s.d. (P=0.05)	*0.22*	*0.04*	*n.s.*	*n.s.*	*0.04*	*0.02*	*2*	*1*	*5*	*27*

Tuber chemical composition

Liming significantly increased tuber Cd concentrations in the loamy sand soil and decreased tuber Cd concentrations in the sandy soil. Chloride significantly increased tuber Cd concentrations in both soils, even after liming.

Liming decreased concentrations of S, Cu, Zn and Mn in tubers and increased concentrations of Ca and Mg. Chloride increased concentrations of P, K, Cu and Zn but decreased concentrations of Ca and Mg.

There were significant relationships between Cl concentrations in leaves and Cd concentrations in tubers and between Cl and Cd concentrations in tubers (Figure 1).

Table 6. Effect of lime, chloride concentration in the irrigation water and soil type (S, sand; LS, loamy sand) on the concentration of selected elements in tubers

Variable	Cd (mg/kg f	P (%)	K (%)	Ca (mg/kg)	Mg	S (%)	Cu (mg/kg)	Zn	Mn
				Lime (t/ha)					
0	0.050	0.29	2.28	157	916	0.20	4.8	37	7.9
5	0.052	0.28	2.31	221	1049	0.19	4.1	30	6.2
l.s.d. (P=0.05)	*n.s.*	*n.s.*	*n.s.*	*29*	*48*	*0.008*	*0.3*	*4*	*0.6*
				Chloride concentration					
0	0.036	0.27	2.10	208	1070	0.21	3.9	30	7.3
1	0.052	0.29	2.33	194	947	0.19	4.8	36	6.7
2	0.065	0.30	2.45	166	931	0.19	4.5	35	7.2
l.s.d. (P=0.05)	*0.007*	*0.01*	*0.10*	*35*	*59*	*0.01*	*0.4*	*4*	*n.s.*
				Soil					
S	0.048	0.37	2.14	141	870	0.19	2.6	36	6.3
LS	0.054	0.20	2.45	237	1095	0.20	6.3	31	7.8
l.s.d. (P=0.05)	*0.005*	*0.01*	*0.08*	*29*	*48*	*0.008*	*0.3*	*4*	*0.6*

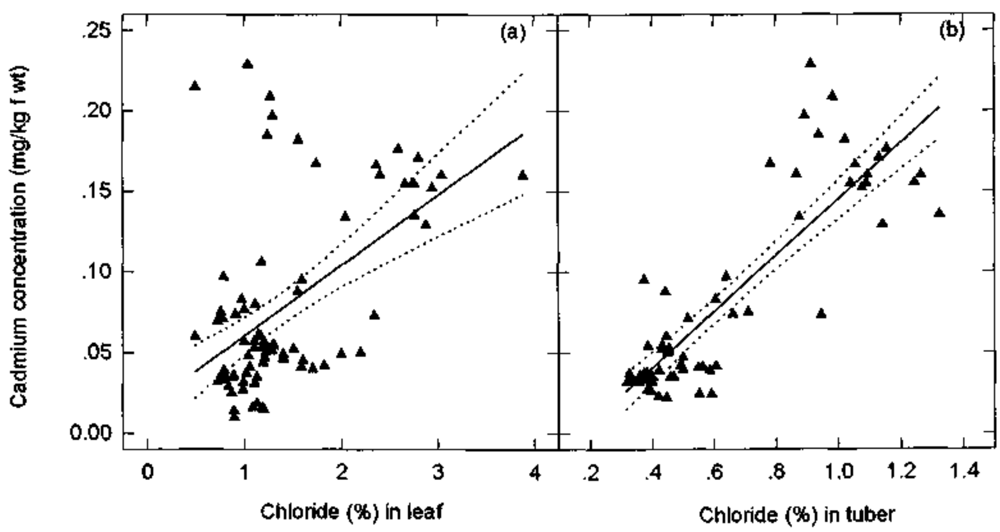

Figure 1. Relationships between chloride concentrations in (a) leaves and (b) tubers and cadmium concentrations in tubers

Effect of K source

Significant increases in Cd concentrations in tubers were observed where KCl was the source of K added compared to K_2SO_4, particularly where high rates of K were applied.

DISCUSSION

The results from this study confirm that Cl has a major effect on mobilising Cd in soil and rendering more Cd available for uptake by plants. This effect was observed even in limed soils. There was a close relationship between Cd and Cl in tubers which confirmed this effect. These data support the conclusions of McLaughlin et al. (1994) that Cl salinity plays a dominant role in the control of Cd uptake by potatoes.

The effect on tuber Cd concentrations of switching K fertilizers from the sulfate to the chloride form also supports the above hypothesis. This effect has also been noted by Sparrow et al. (1994), although it should be noted that the magnitude of the "K effect" is often not large and is only manifest at very high rates of K application and where irrigation water quality is good (McLaughlin et al. 1995). Furthermore, significant cost penalties are involved in a switch from KCl to K_2SO_4 so that risks to growers are high compared to the small and uncertain benefits which could accrue from such a practice.

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APPENDIX 6

FURTHER STUDIES INTO THE EFFECT OF ANIONS ADDED TO IRRIGATION WATER, LIME AND SOIL TYPE ON THE GROWTH, YIELD AND CADMIUM CONCENTRATIONS IN POTATOES (*SOLANUM TUBEROSUM* L.)

INTRODUCTION

Previous experiments indicated that Cl in irrigation water plays a major role in mobilising Cd in soil and increasing plant uptake (Appendix 5). Irrigation waters in South Australia vary in quality, with salinity being contributed by both Cl and sulfate (SO_4) in the water. Furthermore, the waters may contain significant concentrations of bicarbonate (HCO_3) which could affect soil pH and potentially Cd availability. The south-east of South Australia is an area subject to dryland salinisation and groundwaters in some areas have high salt concentrations. This area is also a major area for production of irrigated potatoes in South Australia. In a survey of water quality data for over 750 bores in the south-east of South Australia (SA Dept. Mines and Energy, pers, comm.), irrigation water pH values ranged from 6.7 to 8.4, Cl concentrations ranged from 61 to over 5000 mg l^{-1} , SO_4 concentrations from 1 to over 6000 mg l^{-1} and HCO_3 concentrations from 165 to 1000 mg l^{-1}. Waters used for irrigation of potatoes may be saline, with concentrations of Cl, SO_4 and HCO_3 up to 1200, 1000 and 800 mg l^{-1}. Sulfate also has the potential to mobilize Cd in soil and increase plant availability of this element, although Bingham et al. (1986) have suggested that SO_4 has little effect on plant availability.

The aim of this study was to investigate if SO_4 or HCO_3 in irrigation waters have any beneficial or detrimental impact on tuber Cd concentrations.

MATERIALS AND METHODS

Experimental details. The experimental procedure was similar to that used in experiment G6, and details of soil preparation, planting, leaf sampling and harvesting are presents in Appendix 2. The experiment was conducted during September 1993 to January 1994. The cv. grown was Atlantic. Each pot received a basal application of NPK equivalent to, 50 kg N/ha (as ammonium nitrate); 100 kg P/ha (as single superphosphate; 30-35 mg Cd/kg superphosphate); and 100 kg K/ha (as potassium sulfate). Plants received side-dressings of N and K as described in previous glasshouse experiments.

Anions/solutions. Irrigation waters were prepared with the following concentrations of anions, based on data from irrigation bores as described above;

Rainwater	unamended
Rainwater +Cl	1200 mg l^{-1}
Rainwater +SO_4	400 mg l^{-1}
Rainwater +HCO_3	750 mg l^{-1}

Soils. Two soils were used in this experiment. Soil 1 was a sand (S), and was obtained from the lower South East. Soil 2 was a krasnozem and was obtained from the Ballarat region of Victoria.

Lime treatments. Soils were either unlimed or were limed at a rate equivalent to 10 t ha^{-1}.

RESULTS AND DISCUSSION

Soil pH and conductance

Soil pH was markedly increased by lime, although Soil 2 was less affected (better buffered) than Soil 1.. Addition of HCO_3 in irrigation water also increased soil pH, due to the alkaline nature of this anion. Soil EC values were increased by Cl but generally unaffected by HCO_3 ion. Sulfate however, increased EC in Soil 2, but the effect was not significant in Soil 1.

Table 1. Effect of anions added to irrigation water, lime and soil type on soil pH and conductance determined at harvest

Lime		pH		Conductance (mS/cm)	
Lime	Anion added	Soil	Soil 2	Soil 1	Soil 2
0	Rain water	4.4	4.8	0.13	0.21
	Rain water+Cl	4.7	4.9	0.39	1.45
	Rain water+SO_4	4.5	4.9	0.21	0.56
	Rain water+HCO_3	6.0	5.5	0.18	0.35
10	Rain water	7.0	6.2	0.19	0.23
	Rain water+Cl	7.2	6.2	0.62	1.31
	Rain water+SO_4	7.1	6.1	0.31	0.57
	Rain water+HCO_3	8.5	6.7	0.24	0.43
	l.s.d. (P=0.05)	0.3		0.13	

Yield and growth responses

Addition of lime significantly increased tuber yield, leave dry weight and plant height .

Both Cl and HCO_3 anions in irrigation water adversely affected tuber yield.

Table 2. Effect of anions added to irrigation water, lime and soil type on tuber yield, number of tubers and stems per plant and plant height, and dry matter production

Variable	Tubers (g/plant)	Number of stems/plant	Height (cm)	Leaves	Stems (g/plant d wt)	Leaves+stems
			Lime (t/ha)			
0	447.5	10	1004	22.6	15.1	37.7
10	575.6	11	1088	29.8	14.3	44.1
l.s.d. (P=0.05)	*66.2*	*n.s.*	*34*	*1.3*	*n.s.*	*2.7*
			Anion			
Rain water	614.7	10	1054	25.0	12.6	37.6
Rain water+Cl	396.7	10	1061	29.9	16.4	46.3
Rain water+SO_4	569.1	12	1083	25.0	14.9	39.9
Rain water+HCO_3	465.9	11	1074	24.8	15.0	39.8
l.s.d. (P=0.05)	*93.6*	*n.s.*	*n.s.*	*1.8*	*n.s.*	*n.s.*
			Soil			
Soil 1	292.3	11	1057	25.7	14.6	40.3
Soil 2	730.9	10	1079	26.7	14.8	41.5
l.s.d. (P=0.05)	*66.2*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*

Cadmium concentration in tubers

Cadmium concentrations in tubers were increased by Cl in irrigation water for both soils, and in both unlimed and limed treatments. Sulfate and HCO_3 also increased tuber Cd concentrations in soil 1, but only where the soil was unlimed.

Table 3. Effect of anions added to irrigation water, lime and soil type on the concentration of cadmium in tubers

Lime (t/ha)	N source	Cadmium (mg/kg f Soil 1	Soil 2
0	Rain water	0.047	0.026
	Rain water+Cl	0.266	0.082
	Rain water+SO_4	0.087	0.025
	Rain water+HCO_3	0.086	0.021
10	Rain water	0.045	0.011
	Rain water+Cl	0.090	0.067
	Rain water+SO_4	0.041	0.013
	Rain water+HCO_3	0.048	0.014
	l.s.d. (P=0.05)	*0.024*	

DISCUSSION

The data confirm results from earlier experiments (Appendices 2 and 5) and McLaughlin et al. (1994) which show that Cl is the major factor mobilising Cd in soils and increasing its availability to plants.

The impact of SO_4 was not consistent, with only an increase noted in the unlimed treatment of Soil 1. Sulfate had no effect in Soil 2 or in both soils when limed. Bingham et al (1986) also found that SO_4 had no impact on Cd uptake by Swiss Chard, although the soil used in their experiments had been dosed with added Cd.

Bicarbonate had no effect on tuber Cd concentrations in Soil 2, but increased tuber Cd concentrations in Soil 1 when no lime was applied. This was surprising given the fact that soil pH in this treatment increased from 4.4 to 6.0 due to HCO_3 in the irrigation water. Availability of Cd is usually decreased by increases in soil pH.

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APPENDIX 7

EFFECT OF CURRENT SEASONS GYPSUM AND LIME APPLICATIONS ON THE YIELD, QUALITY, LEAF CHEMICAL COMPOSITION AND CADMIUM CONCENTRATIONS IN POTATOES (*SOLANUM TUBEROSUM* L.)

INTRODUCTION

Potatoes are often grown on moderately-strongly acid sands, which may be low in exchangeable calcium (Ca). Previous studies have shown the importance of Ca concentrations in tubers to reduce the incidence/severity of tuber disorders such as internal brown spot, after-cooking darkening and Erwinia soft rot.

We are not aware of any studies published on the effect of applied gypsum on Cd accumulation in tubers. High rates of gypsum are often applied to heavier textured soils as a 'conditioner' to improve structure.

In this paper we report on the effects of lime and gypsum, broadcast and rotary hoed into the soil before planting, on soil pH and conductance, and potato growth, yield, quality and chemical composition.

MATERIALS AND METHODS

Experimental details. All experiments were located in commercial crops in the Mt. Lofty Ranges and upper south East of SA. Details concerning experiments F4, F7 and F8 have been given in earlier papers in this report. Experiments F10 and F11 were conducted during 1993/94. In all experiments the gypsum and lime were applied at a rate of 5 t/ha. Nitrogen, K and P were applied in the basal fertiliser to ensure these nutrients were not limiting yield and growth responses. The treatments were replicated 3 times.

Field operations, assessment of yield and quality, chemical analyses and statistical analysis of the data, were similar to those reported in previous papers in the report (eg. Appendices 1 and 2).

Soils. The soils were sand-loamy sands.

RESULTS AND DISCUSSION

Soil pH

In 4 of the 5 experiments the application of lime significantly increased pH (Table 1). In experiments F4 and F7, gypsum significantly decreased pH. Carter and Cutcliffe (1990) also reported that the application of 4.3 t/ha gypsum reduced pH of loamy sand-sandy loam Orthic Podzols. They suggest because of the effect on pH, gypsum should be applied in small

Table 1. Effect of gypsum and lime, soil depth and sampling time on soil pH
Data are from field experiments F4, F7, F8, F10 and F11

Variable	Experiment				
	F4	F7	F8	F10	F11
Lime and gypsum					
Control	5.0	5.5	5.2	5.7	5.6
Lime	5.9	6.2	6.3	5.9	5.9
Gypsum	4.6	4.9	5.0	5.5	5.4
l.s.d. (P=0.05)	*0.1*	*0.3*	*0.3*	*n.s.*	*0.2*
Soil depth (cm)					
0-15	5.4	5.8	5.6	5.7	5.7
16-30	5.0	5.2	5.4	5.7	5.5
l.s.d. (P=0.05)	*0.1*	*0.2*	*0.2*	*n.s.*	*0.1*
Sampling time					
Planting	5.1	5.4	5.5	5.5	5.4
Harvest	5.3	5.6	5.5	5.8	5.8
l.s.d. (P=0.05)	*0.1*	*0.2*	*n.s.*	*n.s.*	*0.1*

amounts or in mixtures with lime. The effects of soil depth and sampling time are consistent with those reported in earlier papers (see Appendix 2).

Soil conductance

The application of gypsum increased conductance of the soils (Table 2).

Table 2. Effect of gypsum and lime, soil depth and sampling time on soil conductance (mS/cm)

Data are from field experiments F4, F7, F8, F10 and F11

	Experiment				
Variable	F4	F7	F8	F10	F11
	Lime and gypsum				
Control	0.12	0.37	0.43	0.44	0.18
Lime	0.18	0.41	0.39	0.40	0.18
Gypsum	0.39	0.72	0.52	0.51	0.32
l.s.d. (P=0.05)	*0.06*	*0.08*	*0.12*	*n.s.*	*0.04*
	Soil depth (cm)				
0-15	0.36	0.67	0.57	0.52	0.25
16-30	0.11	0.33	0.32	0.38	0.20
l.s.d. (P=0.05)	*0.05*	*0.06*	*0.10*	*0.12*	*0.03*
	Sampling time				
Planting	0.27	0.31	0.21	0.39	0.26
Harvest	0.20	0.69	0.68	0.51	0.19
l.s.d. (P=0.05)	*0.05*	*0.06*	*0.10*	*n.s.*	*0.03*

Yield and quality

The effects of gypsum and lime on yield and quality factors was small and of little practical significance (Table 3). The application of gypsum increased after-cooking darkening compared with liming in 1 experiment (F4), and liming significantly reduced medulla CCI in the same experiment.

Table 3. Effect of gypsum and lime on total tuber yield and after-cooking darkening index, of tubers

Data are from field experiments F4, F7, F8, F10 and F11

	Yield (t/ha)				After- cooking darkening			
Variable	F4	F7	F10	F11	F4	F7	F10	F11
Control	40.5	56.0	39.2	36.4	112	19	86	n.a.
Lime	40.3	56.4	33.9	38.3	89	21	85	n.a.
Gypsum	38.8	54.2	34.9	36.9	162	18	103	n.a.
l.s.d. (P=0.05)	*n.s.*	*n.s.*	*n.s.*	*n.s.*	72	*n.s.*	*n.s.*	

Table 3 ctd. Effect of gypsum and lime on medulla crisp colour index (CCI) and dry matter content (%) of tubers

Data are from field experiments F4, F7, F8, F10 and F11

	Medulla CCI				% Dry matter		
Variable	F4	F7	F10	F11	F4	F7	F8
Control	93	215	60	4	19.5	14.9	18.0
Lime	28	167	168	31	19.7	14.8	18.2
Gypsum	83	168	85	0	20.5	14.4	19.5
l.s.d. (P=0.05)	62	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*

Leaf and tuber chemical composition

The effects of applied lime and gypsum on leaf and tuber chemical composition were variable. Nutrients for which significant effects occurred are presented in Table 4.

5th leaf. Liming significantly increased Ca, and to a lesser extent Mg concentrations, and decreased B and Mn concentrations in leaves sampled at early tuber set (Table 4). In contrast, gypsum did not affect nutrient levels, although there was a tendency for higher Mn concentrations in leaves sampled from plants in the gypsum plots. Carter and Cutcliffe (1990) also found that the application of up to 4.3 t/ha gypsum only increased the Ca content of Brussels sprout leaves in 1 out of 6 experiments. Applying gypsum also increased K and S concentrations, and did not affect N, P and Mg concentrations.

Tuber. The effects of incorporating 5 t/ha lime or gypsum on tuber nutrient content were small and not consistent between sites. The application of gypsum in creased Ca concentrations in tubers in 2 experiments. Liming or the application of gypsum were ineffective in reducing Cd accumulation in tubers. In fact in 1 experiment, gypsum significantly increased Cd concentrations (Table 4).

Table 4. Effect of gypsum and lime on the concentration of selected elements in 5th leaf and tubers

Data are from field experiments F4, F7, F8, F10 and F11

	Leaf				Tuber				
Variable	F4	F7	F8	F11	F4	F7	F8	F10	F11
					Calcium				
	(% d wt)				(mg/kg d wt)				
Control	0.84	1.11	1.04	0.92	127	252	202	162	151
Lime	1.10	1.37	1.53	0.94	199	240	283	209	167
Gypsum	0.87	0.94	1.08	0.93	172	274	211	176	218
l.s.d. (P=0.05)	*0.16*	*0.42*	*0.35*	*n.s.*	*29*	*n.s.*	*n.s.*	*n.s.*	*51*
					Magnesium				
	(% d wt)				(mg/kg d wt)				
Control	0.42	0.62	0.55	0.64	767	1112	1189	1149	895
Lime	0.40	0.73	0.57	0.61	881	1106	1086	1158	899
Gypsum	0.38	0.67	0.57	0.59	764	1123	1149	1126	995
l.s.d. (P=0.05)	*0.02*	*0.10*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*93*
					Cadmium (mg/kg f wt)				
Control	n.a.	n.a.	n.a.	n.a.	0.07	0.13	0.18	0.091	0.045
Lime					0.09	0.13	0.20	0.099	0.046
Gypsum					0.09	0.13	0.20	0.103	0.059
l.s.d. (P=0.05)					*n.s.*	*n.s.*	*n.s.*	*n.s.*	*0.012*
					Boron (mg/kg d wt)				
Control	25	35	20	28	6	4	5	7	7
Lime	20	34	13	25	5	5	5	8	6
Gypsum	26	38	22	27	6	5	2	7	7
l.s.d. (P=0.05)	*2*	*n.s.*	*6*	*3*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*
					Manganese (mg/kg d wt)				
Control	193	130	243	108	6	8	9	5	5
Lime	123	89	45	72	6	7	6	6	5
Gypsum	218	160	323	153	6	8	8	6	6
l.s.d. (P=0.05)	*37*	*50*	*179*	*49*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*0.7*

REFERENCES

Carter, M. R., and Cutcliffe, J. A. (1990). Effects of gypsum on growth and mineral content of Brussels sprouts, and soil properties of Orthic Podzols. *Fertilizer Research* **24,** 77-84.

APPENDIX 8

COMPARISON OF THE EFFECT OF ZEOLITE AND LIME ON THE YIELD, GROWTH, LEAF CHEMICAL COMPOSITION AND CADMIUM CONCENTRATIONS IN POTATOES (*SOLANUM TUBEROSUM* L.)

INTRODUCTION

be used to minimize Cd uptake by potato crops. Constraints to the use of zeolite may be the high cost of the material, but if only small additions are required to significantly reduce Cd uptake, the material could be commercially useful.

The aim of this experiment therefore was to determine if zeolite could be used to reduce Cd uptake by potato tubers.

MATERIALS AND METHODS

Experimental details. Zeolite treatments were included in glasshouse experiments G5 and G6. Soil preparation, planting, assessment of yield and quality, chemical analyses and statistical analysis of the data, were similar to those reported in earlier papers in the report (eg. Appendices 1 and 2).

The **soils** were sand (G4) and loamy sand (G5).

RESULTS AND DISCUSSION

Soil pH and conductance

Lime significantly increased soil pH as found previously (Appendices 2-7). Zeolite had no effect on soil pH at low rates of application, but increased soil pH when used at high application rates Table 1).

Zeolite had no consistent effect on soil EC values (Table 1).

Table 1. Effect of zeolite and lime on soil pH and conductance

	Rate		pH		Conductance (mS/cm)	
Factor	(t/ha)	(g/pot)	Planting	Harvest	Planting	Harvest
			Experiment G6			
	0	0	4.5	4.2	0.41	0.43
Lime	2.5	15.4	5.8	4.9	0.37	0.55
	5.0	30.8	6.3	5.6	0.35	0.62
Zeolite	2.5	15.4	4.6	4.1	0.37	0.53
	5	30.8	4.7	4.0	0.30	0.66
l.s.d. (P=0.05)			*0.3*	*0.3*	*n.s.*	*0.12*
			Experiment G5			
	0	0	4.1	4.7	0.46	0.37
Lime	10	61.6	7.2	7.0	0.39	0.53
	20	123.2	7.5	7.4	0.43	0.44
Zeolite	-	500	5.3	5.6	0.50	0.38
l.s.d. (P=0.05)			*0.2*	*0.2*	*n.s.*	*n.s.*

Yield and growth responses

There was little impact of either lime or zeolite on plant dry matter production or tuber yields. The number of tubers per plant was significantly reduced by both lime and zeolite (Table 2).

Table 2. Effect of zeolite and lime on tuber yield, number of tubers and stems per plant, plant height and leaf and stem dry matter yields

Variable	Rate (t/ha)	Rate (g/pot)	Tubers (g/plant)	Number tubers/plant	Number stems/plant	Height (cm)	Leaves (g/plant d wt)	Stems (g/plant d wt)
				Experiment G6				
	0	0	363.0	14	8	99.5	21.1	7.6
Lime	2.5	15.4	441.0	18	7	113.3	19.4	10.8
	5	30.8	464.9	16	10	111.5	20.9	10.9
Zeolite	2.5	15.4	419.7	15	8	108.3	19.4	8.5
	5	30.8	473.3	14	7	107.5	19.5	8.2
l.s.d. (P=0.05)			*n.s.*	*n.s.*	*1.5*	*n.s.*	*n.s.*	*n.s.*
				Experiment G5				
	0	0	950.8	30	3	1290	41.2	21.9
Lime	10	61.6	856.9	10	2	1278	39.5	14.1
	20	123.2	813.8	11	3	1320	38.3	12.6
Zeolite	-	500	910.5	16	2	1303	41.0	16.8
l.s.d. (P=0.05)			*90.3*	*7*	*n.s.*	*n.s.*	*n.s.*	*5.1*

Chemical composition of 5th leaf

The application of calcitic lime significantly decreased P, S and Mn concentrations, and increased Ca and Mg concentrations (Table 3). The effect of zeolite was inconsistent.

Leaf Cd concentrations were significantly reduced by both lime and zeolite.

Table 3. Effect of zeolite and lime on the concentration of elements in the 5th leaf

Factor	Rate (t/ha)	Rate (g/pot	P (%)	K (%)	Ca (%)	Mg (%)	S (%)	Cu (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	Cd (mg/kg d
					Experiment G6						
	0	0	0.82	4.75	0.18	0.23	0.48	9	65	53	1.15
Lime	2.5	15.4	0.85	4.83	0.47	0.31	0.44	7	47	58	0.87
	5	30.8	0.74	4.51	0.69	0.35	0.43	6	44	52	0.77
Zeolite	2.5	15.4	0.90	4.93	0.20	0.24	0.47	9	59	62	0.88
	5	30.8	0.89	5.08	0.20	0.26	0.45	9	56	61	0.85
l.s.d. (P=0.05)			*0.01*	*n.s.*	*0.11*	*0.04*	*0.03*	*n.s.*	*10*	*n.s.*	*0.20*
					Experiment G5						
	0	0	0.84	4.88	0.27	0.28	0.47	8.4	93	95	2.52
Lime	10	61.6	0.66	5.55	0.56	0.34	0.52	7.5	78	50	0.78
	20	123.2	0.59	5.21	0.67	0.35	0.46	5.2	63	49	0.78
Zeolite	-	500	0.76	4.74	0.44	0.38	0.44	23.5	60	79	0.59
l.s.d. (P=0.05)			*0.14*	*0.64*	*0.05*	*0.03*	*0.06*	*2.6*	*20*	*8*	*0.25*

Chemical composition of tubers

Cadmium concentrations in tubers were decreased by application of both lime and zeolite. The magnitude of the reduction was similar for both materials.

Table 3. Effect of zeolite and lime on the concentration of elements in tubers

Factor	Rate (t/ha)	Rate (g/pot)	K (%)	Ca (mg/kg)	Mg (mg/kg)	S (%)	Cu (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	Cd (mg/kg f
					Experiment G6					
	0	0	1.97	273	931	0.23	2.3	37	9	0.024
Lime	2.5	15.4	2.07	476	1123	0.19	1.8	32	10	0.024
	5	30.8	2.21	595	1235	0.20	1.8	26	10	0.022
Zeolite	2.5	15.4	1.96	303	958	0.22	1.6	37	9	0.020
	5	30.8	1.98	316	974	0.23	1.7	38	10	0.020
l.s.d. (P=0.05)			*0.14*	*133*	*76*	*0.03*	*0.7*	*10*	*n.s.*	*0.003*
					Experiment G5					
	0	0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.043
Lime	10	61.6								0.021
	20	123.2								0.021
Zeolite	-	500								0.026
l.s.d. (P=0.05)										*0.003*

DISCUSSION

In these experiments the use of zeolites showed no advantages over lime in terms of reducing tuber Cd concentrations. Given the extra cost involved in use of zeolite there appear to offer few advantages over lime. Only one type of zeolite was tested in these experiments and it may be worthwhile screening other zeolites for their potential to reduce Cd availability to plants.

APPENDIX 9

EFFECT OF DEPTH OF INCORPORATION OF LIME ON SOIL pH AND CONDUCTANCE, AND CADMIUM CONCENTRATIONS IN POTATO (*SOLANUM TUBEROSUM* L.) TUBERS

INTRODUCTION

We have found that in glasshouse pot experiments, liming was highly effective in reducing Cd concentrations in tubers (Appendices 2-6 and 8). In field experiments, the application of lime did not have a significant effect, or in a few experiments Cd concentrations significantly increased.

Factors which may account for the ineffectiveness of liming reported in our and published studies include:

i) Inadequate incorporation/mixing - In field experiments, lime was broadcast by hand and 'rotary hoed in'. If the soil is moist this may lead to 'caking' of the lime, and therefore the lime is not thoroughly/evenly mixed into the soil. In the glasshouse work, the soil was dried before mixing and incorporation.

ii) Inadequate depth of incorporation - Conventional rotary hoes are only effective to 15-20 cm. Therefore much of the potato plants root zone is not affected by liming. In the pot experiments the whole root volume was limed.

iii) Inadequate incubation/time - In both field and glasshouse experiments incubation time was 'short' (3-8 weeks). In the pot experiments, the soils were kept moist (field capacity) during the incubation period. In the field experiments, there was no control over soil moisture levels during incubation. Some soils may have been to dry. The period of incubation may not be a major factor because in the pot work some short incubation periods (3-4 weeks) were used, however liming was still effective.

We therefore conducted a field and pot experiment to determine the effect of placement of lime/depth of incorporation on Cd concentrations in tubers. In the field experiment, the effect applying P (at 15-30 cm) on Cd uptake was also investigated.

MATERIALS AND METHODS

Field experiment. During 1993/94 an experiment located in a commercial crop, was conducted in the lower South East, using the cv. Russet Burbank. Rates of lime up to 10 t/ha were incorporated by rotary hoeing, into the following depths: 0-15, 0-15+15-30 and 15-30 cm. To place the lime at 15-30 cm, a grader was used to remove the surface 0-15 cm soil. After the subsurface treatments had been applied and incorporated, the surface soil replaced and the treatments for the 0-15 cm soil were applied. Half of each plot also received an application of 100 kg P/ha at the same time the lime was applied to the 15-30 cm layer. The experimental design was a randomized block and treatments were replicated 3 times.

Field operations, assessment of yield and quality, chemical analyses and statistical analysis of the data, were similar to those reported in previous papers in the report (eg. Appendices 1 and 2).

Glasshouse experiment. In experiment G7, a rate of lime equivalent to 10 t/ha was incorporated either I) throughout the soil; ii) into the soil placed in the bottom half of the pot; and iii) into the soil placed into the top half of the pot. Other experimental details are presented in previous papers (eg. Appendix 2). The cv. grown was Atlantic.

RESULTS AND DISCUSSION

Soil pH and conductance

Depending on the depth the calcitic lime was applied to, pH significantly increased by 1-2 units, in both field (Table 1) and glasshouse (Table 2) experiments.

Table 1. Effect of depth of incorporation and rate of lime on pH and conductance

Soil samples were collected on 6/4/94 and data are for site F12

Depth of incorporation (cm) 0-15	15-30	pH 0-15	pH 15-30	EC (mS/cm) 0-15	EC (mS/cm) 15-30
Rate applied (t/ha)					
0	0	5.7	5.3	0.22	0.15
2.5	0	6.1	5.4	0.29	0.21
5	0	6.4	5.4	0.35	0.28
10	0	7.0	5.6	0.26	0.11
2.5	2.5	6.3	5.6	0.29	0.14
5	5	6.7	5.6	0.35	0.16
10	10	7.3	6.5	0.26	0.19
0	2.5	6.2	5.6	0.22	0.11
0	5	6.3	5.5	0.23	0.17
0	10	6.3	5.8	0.26	0.14
l.s.d. (P=0.05)		0.5		0.10	

Table 2. Effect of depth of incorporation of lime on pH and conductance of soil sampled from the top and bottom halves of pots at harvest

Data are for experiment G7

Rate (t/ha)	Incorporation	pH Top half	pH Bottom half	Conductance (mS/cm) Top half	Conductance (mS/cm) Bottom half
0	-	4.6	4.3	0.11	0.15
10	Throughout	7.0	7.2	0.11	0.26
10	Bottom half	4.7	6.8	0.07	0.25
10	Top half	.6.7	4.4	0.10	0.26
l.s.d. (P=0.05)		*0.2*	*0.3*	*n.s.*	*n.s.*

Cadmium concentrations in tubers

There was no significant effect of liming the subsoil in the **field experiment**, with lime either having no effect or increasing tuber Cd concentrations Table 3)

Table 3. Effect of depth of incorporation and rate of lime and phosphorus application on cadmium concentration in tubers

Depth of incorporation		P applied (kg/ha)	
0-15	15-30		
Rate applied (t/ha)		0	100
0	0	0.042	0.049
2.5	0	0.046	0.054
5	0	0.062	0.057
10	0	0.051	0.055
2.5	2.5	0.047	0.057
5	5	0.056	0.057
10	10	0.055	0.050
0	2.5	0.043	0.049
0	5	0.056	0.055
0	10	0.049	0.053
l.s.d. (P=0.05)		*0.012*	*n.s.*

Data from the **pot experiment** were similar where lime also resulted in increases in tuber Cd concentrations, when only the top or bottom half of the soil volume or rot zone was limed. The only likely explanation for this effect is the displacement of Cd from soil surfaces by Ca, thus leading to enhanced Cd uptake by the crop.

Table 4. Effect of depth of incorporation of lime on cadmium concentration in tubers

Data are for experiment G7

Rate (t/ha)	Incorporation	Cadmium (mg/kg f wt)
0	-	0.045
10	Throughout	0.045
10	Bottom half	0.069
10	Top half	0.083
l.s.d. (P=0.05)		*0.024*

APPENDIX 10

EFFECTS OF SULFUR AND LIME ON SOIL pH, CONDUCTANCE, YIELD AND CADMIUM CONCENTRATIONS IN POTATOES (*SOLANUM TUBEROSUM* L.)

INTRODUCTION

In 1993/94 the final 2 field experiments were conducted to determine the usefulness of liming in reducing Cd uptake by potato tubers. In all experiments, S treatments were included to determine the effect of increasing soil acidity on yield and Cd concentrations in tubers.

The plots used in experiment F9 in 1992/93 were again planted with potatoes in 1993/94. This provided information on the effect of a longer (incubation) period between lime/S applications and determining yield, growth and nutrient uptake responses.

MATERIALS AND METHODS

Field operations, assessment of yield and quality, chemical analyses and statistical analysis of the data, were similar to those reported in previous papers in the report (eg. Appendices 1 and 2).

RESULTS AND DISCUSSION

Soil pH and conductance

The application of calcitic lime significantly increased pH at planting and harvest (Tables 1 and 2). In contrast, the application of S, significantly decreased pH in experiment F9 (Table 1).

Table 1. Effect of soil depth, and lime and sulfur applied in winter 1992, on pH determined at planting and harvest of two successive potato crops at site F9

Variable	Rate (t/ha)	1993 Planting	1993 Harvest	1994 Planting	1994 harvest
		Lime and sulfur			
	0	5.2	5.3	5.6	5.6
Lime	5	6.3	6.5	6.1	6.4
	10	6.6	6.6	6.9	6.9
Sulfur	1.25	4.2	4.8	5.1	5.0
	2.5	4.0	4.3	4.8	4.5
l.s.d. (P=0.05)		*0.4*	*0.5*	*0.5*	*0.5*
		Depth			
0-15		5.3	5.7	5.8	5.9
16-30		5.2	5.3	5.6	5.5
l.s.d. (P=0.05)		*n.s.*	*0.3*	*n.s.*	*0.3*

Table 2. Effect lime and sulfur on pH and conductance of the surface (0-15 cm) soil sampled at harvest at sites F10 and F11

Variable	Rate (t/ha)	pH F10	pH F11	Conductance F10	Conductance F11
	0	5.8	5.9	0.57	0.23
Lime	2.5	6.4	6.2	0.47	0.20
	5	6.0	6.3	0.49	0.19
	7.5	6.8	5.9	0.56	0.23
	15	6.2	7.0	0.49	0.24
	20	7.4	6.8	0.58	0.23
Sulfur	1.25	5.6	5.8	0.65	0.25
	2.5	5.3	5.9	0.55	0.22
l.s.d. (P=0.05)		*0.7*	*0.5*	*n.s.*	*n.s.*

Yield and quality

The application of calcitic lime or elemental sulfur did not significantly affect tuber yield in experiments F10 and F11 (Table 3). Data for other experiments are presented in Appendix 2. Overall, and consistent with earlier field experiments the effects of liming were inconsistent between sites.

Table 3. Effect lime and sulfur on yield at sites F10 and F11

Variable	Rate (t/ha)	Yield F10	Yield F11	No. F10
	0	39.2	36.4	13
Lime	2.5	31.9	34.6	10
	5	33.9	38.3	8
	7.5	32.4	35.9	10
	15	32.6	34.9	9
	20	32.2	28.6	9
Sulfur	1.25	37.1	46.4	11
	2.5	38.9	36.4	10
l.s.d. (P=0.05)		*n.s.*	*n.s.*	3

Cadmium concentrations in tubers

Lime decreased tuber Cd concentrations in both cultivars in 1993 but the effect was absent in 1994; in fact lime increased tuber Cd concentrations. Sulfur increased tuber Cd concentrations in both cultivars in both years. At sites F10 and F11, both lime and sulfur had no effect on tuber Cd concentrations.

Table 4. Effect of lime and sulfur applied in winter 1992 on cadmium concentrations in tubers of the cvv. Atlantic and Russet Burbank harvested in 1993 and 1994 in experiment F9

Variable	Rate (t/ha)	1993 Atlantic	1993 Russet	1994 Atlantic	1994 Russet
	0	0.020	0.021	0.014	0.016
Lime	5	0.016	0.017	0.014	0.019
	10	0.019	0.016	0.015	0.024
Sulfur	1.25	0.030	0.023	0.020	0.028
	2.5	0.036	0.022	0.021	0.029
		l.s.d. (P=0.05)=0.01			

Table 5. Effect lime and sulfur on cadmium concentrations (mg/kg f wt) in tubers from experiments F10 and F11

Variable	Rate (t/ha)	Site F10	Site F11
	0	0.091	0.045
Lime	2.5	0.091	0.047
	5	0.099	0.046
	7.5	0.094	0.054
	15	0.079	0.052
	20	0.091	0.055
Sulfur	1.25	0.087	0.047
	2.5	0.088	0.057
l.s.d. (P=0.05)		*n.s.*	*n.s.*

These data further show the complex and variable effects of applying calcitic lime on Cd accumulation in potato tubers.

APPENDIX 11

RELATIONSHIP BETWEEN pH DETERMINED USING WATER AND $CaCL_2$

Introduction

During 1991/92 and 1992/93 soil pH was determined using both water (1:5 soil:water) and 0.01M $CaCl_2$. For information the relationships between the 2 methods are presented below.

Table 1. Equations and coefficients of determination (r^2) for linear relationships between pH determined using water (X) and calcium chloride (Y)

Experiment	Equation	r^2	F val.	Signif.	n	Y^A (at X=6)
			Field experiments			
F1	Y=0.92X-0.16	0.960	1641.0	P<0.001	71	5.4
F2	Y=1.00X-0.57	0.873	536.1	P<0.001	80	5.4
F3	Y=1.01X-0.59	0.980	4034.0	P<0.001	81	5.5
F4	Y=1.00X-0.64	0.933	858.2	P<0.001	64	5.4
F5	Y=0.99X-0.60	0.929	1240.0	P<0.001	96	5.3
F6	Y=1.13X-1.44	0.962	1939.0	P<0.001	79	5.3
F7	Y=1.08X-0.97	0.980	2283.0	P<0.001	60	5.5
F8	Y=0.99X-0.41	0.960	1721.0	P<0.001	72	5.5
F9	Y=0.91X+0.16	0.977	3289.0	P<0.001	80	5.6
			Glasshouse experiments			
G1	Y=0.96X-0.40	0.956	807.7	P<0.001	39	5.4
G2	Y=1.00X-0.62	0.888	548.6	P<0.001	71	5.4
G3	Y=1.05X-0.82	0.980	2934.0	P<0.001	61	5.5
G4	Y=0.98X-0.42	0.995	4404.0	P<0.001	23	5.5
G5	Y=0.96X-0.24	0.980	2012.0	P<0.001	33	5.5

[A], Calculated using the equation.

In all cases the 2 methods were highly correlated (Table 1; Figure 1). A pH_{Ca} was 0.4-0.7 of a unit less than pH_w.

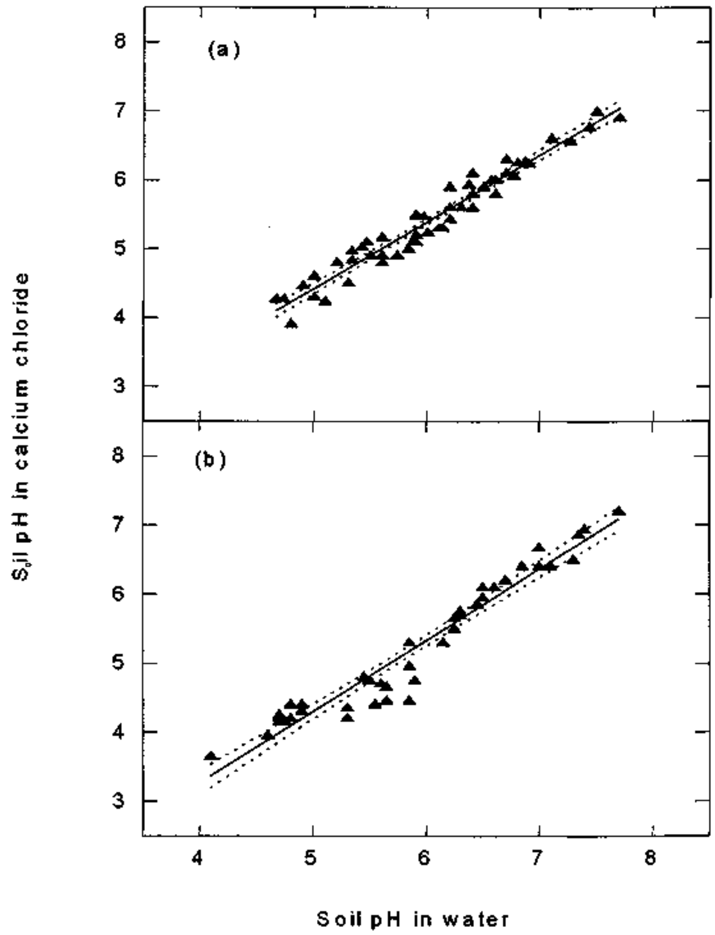

Figure 1. Examples of the relationships between pH determined using water (pH_w) and calcium chloride (pH_{Ca}).

APPENDIX 12

VARIABILITY IN SOIL pH

Introduction

For a given method of measurement, pH, as with many other chemical properties, varies with depth, spatially and time (eg. seasons). An understanding of this variation is important, particularly for reliable soil testing and comparison of data. As part of this study, some information on variability was collected and is presented for information.

Depth. For the field experiments we sampled the 0-15 and 15-30 cm depths and after liming 1.1 unit difference in pH occurred (Appendix 2).

Temporal. On our lime plots, differences of up to 0.5 of a unit occurred between planting and harvest.

Spatial. We sampled (transect) 5 apparently uniform paddocks in the Mt. Lofty Ranges and the mean, range and coefficients of variation (CV%)are presented in Table 1.

Table 1. Mean, range and CV (%) for pH_w in apparently uniform potato paddocks

	Paddock				
Statistic	1	2	3	4	5
Mean	5.8	5.4	5.8	5.7	6.0
Range	5.4-6.3	5.2-5.7	5.4-6.4	5.5-5.9	5.5-6.4
CV (%)	5.7	12.3	4.3	2.4	8.3

The data show that 0.4-1.0 unit differences can occur even in apparently uniform potato paddocks. The CV(%) were higher than reported in other studies, for example, 1.2-5.1% (Dolling *et al.* 1990) and 1.4-4.6% (Bowman 1991).

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Bowman, R. A. (1991). Spatial variability of selected carbon, nitrogen, and phosphorus parameters on acid and calcareous rangeland soils. *Communications in Soil Science and Plant Analysis* **22**, 205-12.

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