PT003

After cooking darkening of potatoes

Adrian Dahlenburg
SA Research & Development Institute

Know-how for Horticulture™

PT003

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

The research contained in this report was funded by the Horticultural Research and Development.

Cover price: $20.00
HRDC ISBN 1 86423 588 8

Published and distributed by:
Horticultural Research & Development Corporation
Level 6
7 Merriwa Street
Gordon NSW 2072
Telephone: (02) 9418 2200
Fax: (02) 9418 1352
E-Mail: hrdc@hrdc.gov.au

HRDC
HORTICULTURAL
RESEARCH &
DEVELOPMENT
CORPORATION
Partnership in
horticulture

CONTENTS

1. SUMMARY

1.1 Technical Summary

1. Eighty potato crops predominantly from the Mt. Lofty Ranges region in SA were surveyed during one season with data collected on soil, petiole and tuber nutrient concentrations and correlated with tuber quality characteristics including after cooking darkening (ACD). Principle component analysis and graphical representations were then used to define the immediate experimental work program aimed at establishing true cause and effect relationships for ACD.

2. Eight field experiments were conducted to study the impact of fertiliser management strategy on the incidence of ACD. Key outcomes from these experiments include:
    - Increased rates of applied nitrogen were associated with the increased incidence and severity of ACD. However, the nitrogen status of the tubers is not well related to ACD incidence and it is proposed that it is probably indirectly related via the impact of nitrogen on crop growth factors.
    - There is a positive trend between rate of applied potash and reduction in ACD. Muriate of potash had a slightly greater effect than sulphate of potash at similar application rates however the impact of using the muriate form on other factors like specific gravity may be significant particularly if the irrigation water is saline. The timing of potash applications had no influence on the incidence of ACD.
    - The impact of phosphorus fertilisers on ACD was variable however, when nitrogen and potash applications were sufficient to maximise yield, increased rates of applied phosphorus decreased ACD. Reductions in tuber specific gravity were also recorded in relation to increasing rates of applied phosphorus. Our experiments showed no influence of either source of phosphorus or time of application on ACD.

3. From the grower survey and early field experiments a hypothesis on the relationship of tuber potassium and phosphorus concentrations and ACD was developed as follows:

NUTRIENT CONCENTRATION IN TUBER (%)		DEGREE OF ACD
POTASSIUM	PHOSPHORUS	
<2.4	<0.27	High
<2.4	>0.27	Medium/Low
>2.4	<0.27	Low (?)
>2.4	>0.27	Low

Experimental work in the second half of the program was principally designed to test and evaluate management and production techiniques which could influence the final tuber concentrations of potassium and phosphorus and hence influence ACD.

4. Foliar applications of growth regulators, chelating agents, nutrients and several other chemicals reported to possibly influence ACD, were applied in one experiment and none were found to have any influence on ACD.

5. Organic soil amendments including lime, dolomite, gypsum, chicken manure, base organic and blood and bone were used at 3 experimental sites at rates up to 16t/ha with no significant influence on ACD. Applications of lime at rates up to 30t/ha reduced the incidence and severity of ACD up to 60-65% however, these rates applied in the same season as the potato crop can lead to tuber scab formation.

6. Regional variations in ACD are significant with a high incidence for crops grown in the Mt. Lofty Ranges and Lower South East where the soil types are similar and low incidence for crops grown in the Northern Adelaide Plains and Upper South East.

7. Varietal variations in ACD are significant and more than a 50% reduction in ACD was achieved between the worst and best performing cultivars during variety evaluation trials at highly susceptible sites. Amoung the more common cultivars grown in SA, the following ranking in relation to susceptibility was proven on more than one occasion: Kennebec > Pontiac > Atlantic > Coliban.

8. For irrigated summer grown crops in SA the incidence of ACD is reduced for those crops planted later in the growing season. However, later planted crops also have a lower specific gravity.

9. The ACD of tubers increases during the growth cycle of the crop but is relatively stable at near to the maximum value in the last 30-40 days prior to haulm senescence.

10. Tubers in the 80-350gm size range had a slightly lower ACD than tubers in the greater than 350gm size range.

11. The severity of ACD in tubers is increased with storage for 3 and 6 months at 12°C.

1.2 Grower Recommendations

Our research has shown that there are no "quick-fix" answers to the ACD problem which occurs in cooked potatoes which have been grown in regions that are susceptible to this disorder. Significant reductions in the incidence and severity of the disorder can be obtained through modified fertiliser and management strategies. However, there are often complex interactions with other quality factors like specific gravity, crisp colour, size or yield and there has to be a compromise to achieve a reduction in ACD.

The following industry and grower recommendations can be made regarding the reduction of ACD.

1. Where ACD is likely to be a critical quality factor for the proposed end use of the tubers, consideration should be given to production only in those regions shown to be less susceptible to the problem ie. Northern Adelaide Plains and Upper South East.

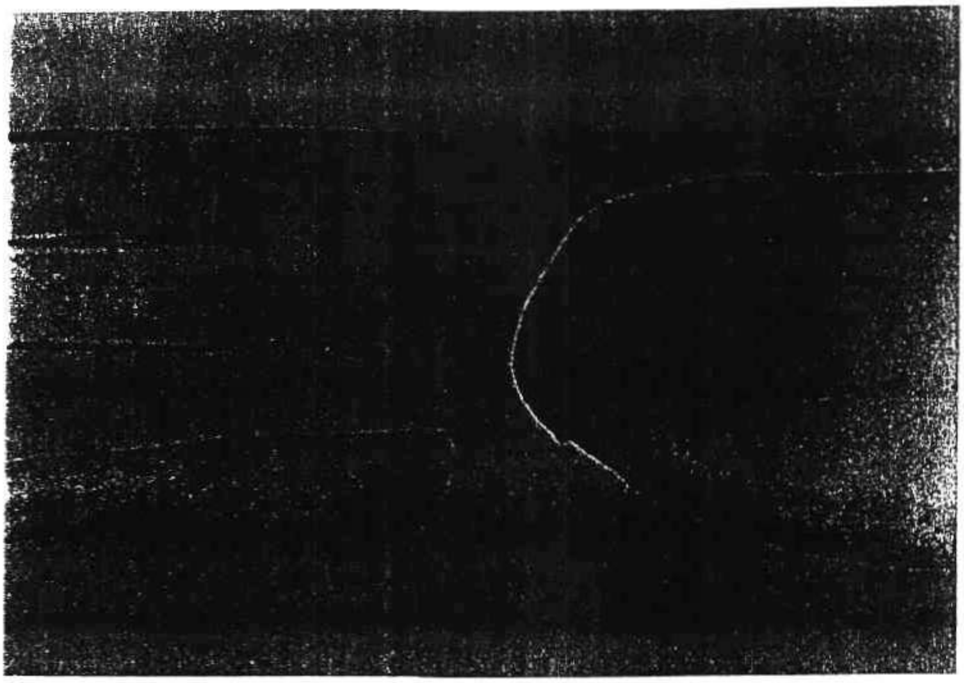
2. Varietal selection and breeding has the best potential for achieving reductions in ACD for tubers produced in susceptible regions. However, the industry has to decide on the relative importance of the disorder to the industry and adopt breeding and selection protocols which will lead to varieties less susceptible to ACD if considered to be of sufficient importance.

3. Reductions in ACD can be achieved in susceptible regions through a fertiliser strategy where nitrogen applications are reduced to a minimum or nil and potash and phosphorus fertiliser application rates are increased above that normally required. Soil analysis prior to planting is essential to determine the reductions and increases which may be suitable. If the soil organic C analysis is high and the potato crop is following several years or more of leguminous pasture it may be acceptable to apply no nitrogen. Tissue nutrient monitoring during the early stages of crop growth is highly recommended to ensure that the crop is not under nitrogen stress.

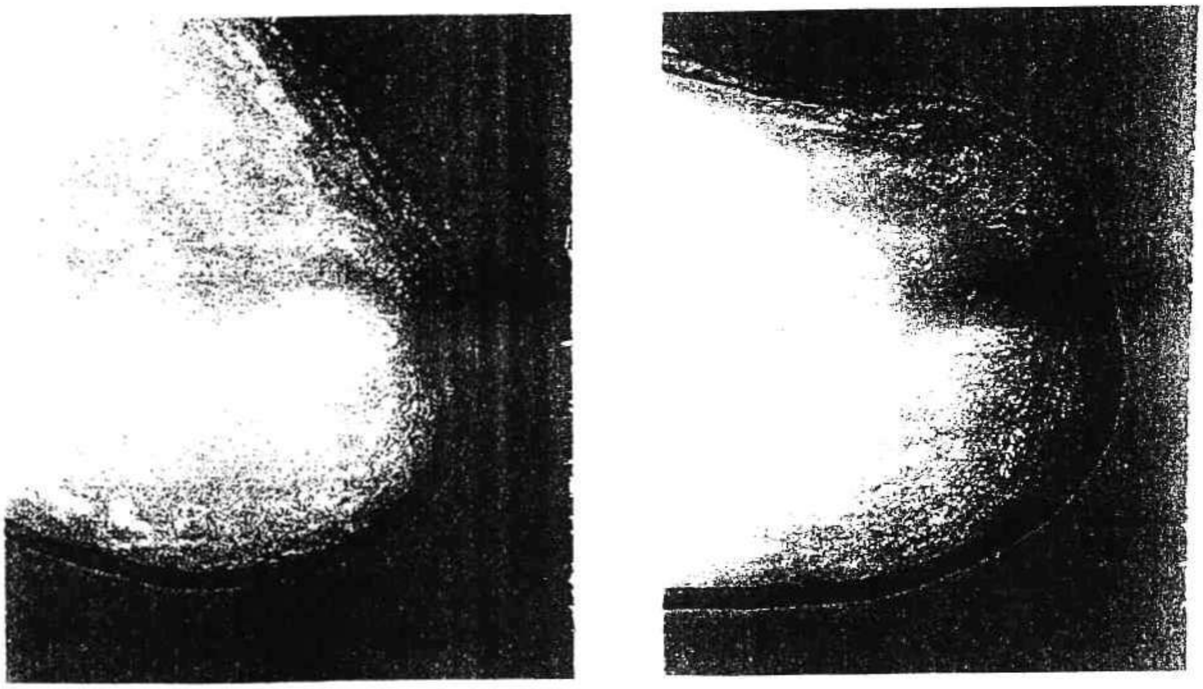
4. For summer grown irrigated crops in SA there is some reduction in ACD from later seasonal crop establishment ie. January planting vs October planting, but this practice also leads to a reduction in tuber specific gravity.

5. Storage of tubers at less than 15°C can increase the severity of ACD and fluctuating storage temperatures may further increase the problem.

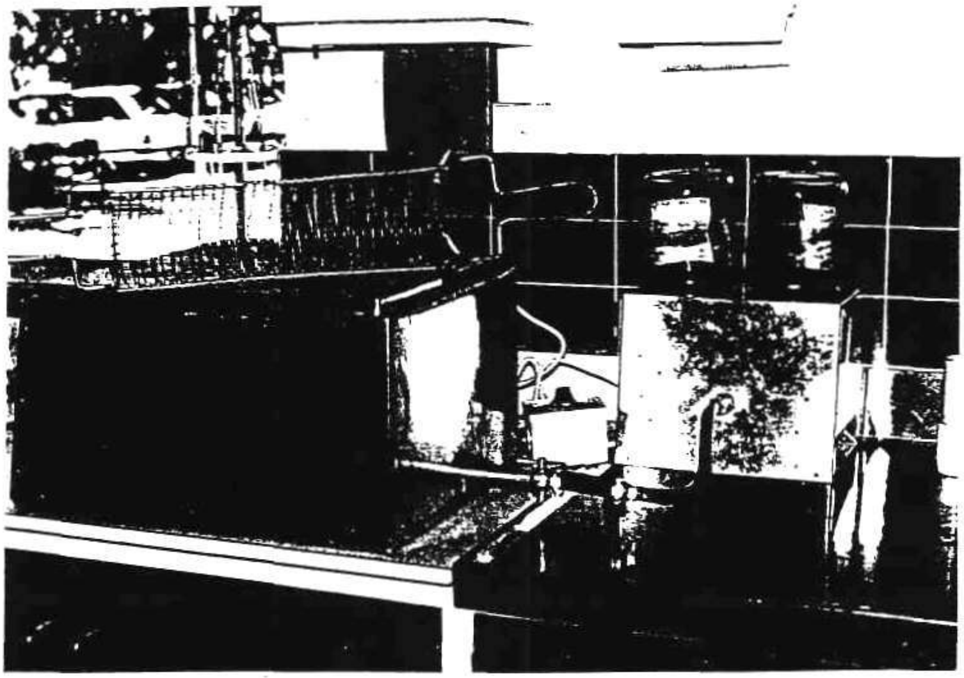
6. There is no quick or rapid pre-harvest test which can be used to predict whether a crop will be affected by ACD. Extractable soil potassium concentration and petiole manganese concentration could possibly be developed into a useful pre-harvest prediction system.



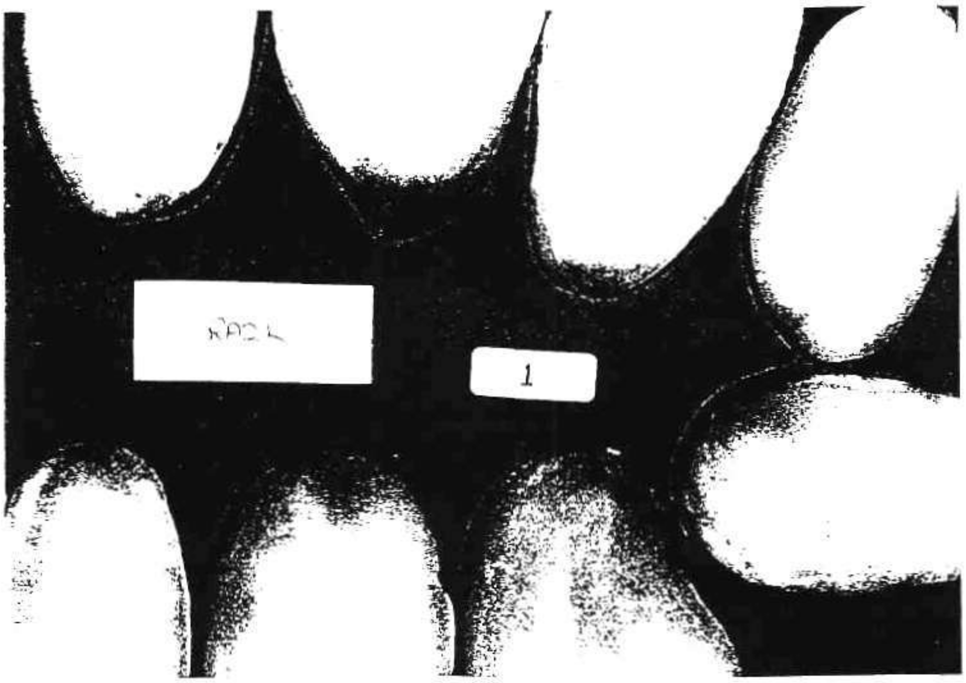
Severe ACD on steamed tuber slices and after par frying.



Tuber ACD indices: Left 100, Right 200.



Steaming apparatus used in the determination of ACD incidence and severity during this project.



Sample of steamed tubers showing ACD development after cooling.

2. INTRODUCTION

Potato growers and processors in S.A. have in recent years experienced a continuing problem of potatoes darkening after cooking. Most complaints have been received from the fast food industry where French fries and small roasts are partly prepared in advance and only finally cooked as required by customers. Darkening is most evident in this situation, but may also be encountered in the home. Consignments of tubers showing darkening may be rejected by processors. The darkening which occurred was identified as the problem commonly referred to as after-cooking darkening (ACD).

After cooking darkening has been extensively investigated and reviewed by researchers in the U.K. and U.S.A. over the last 50 years. These studies showed that the prediction of ACD was not simple and the relationships between ACD and rate and types of fertilizer used, harvest date, storage and other crop management factors were not consistent. However, the chemical reactions involved in ACD have been established. ACD is due to the formation of a dark coloured complex of ferric ions and chlorogenic acid. Oxidation is necessary for the formation of the dark pigment, probably by the oxidation of a colourless ferrous compound to the corresponding dark coloured ferric compound. As well as chlorogenic acid, citric acid content of the tuber has been reported to affect the degree of darkening.

Crop management factors, particularly fertilizer strategy, have been reported to affect the incidence of ACD. High N to K ratios in tubers have been positively correlated with the degree of ACD. Data obtained from the 1986/87 soil and plant nutrient surveys of irrigated potato crops in S.A., suggested that plants high in N and low in K, and therefore have a low K/N ratio, were more likely to produce tubers with a high degree of ACD. Climatic conditions have also been related to ACD, with a greater degree likely in cool-wet seasons. Storage conditions can have a significant influence on the concentration of chlorogenic acid in the tuber and may therefore affect the degree of ACD.

During the 1986/87 season, the degree of ACD was such that some growers had extreme difficulty in selling their tubers to either processors for chip manufacture or on the fresh market. This prompted the local industry to seek assistance in eliminating or reducing the degree of ACD, and they were prepared to financially support a research program for this purpose.

In view of the limited local knowledge regarding the incidence of ACD a survey was conducted in the Mt. Lofty Ranges to provide data on the incidence and possible 'causes' of ACD, and to provide directions for future research. At the same time, experiments to determine the importance of NPK interactions and their effects on potato yield and quality, were conducted. It was decided to test tubers from these experiments for the degree of ACD to provide additional information on the relationships between ACD and crop nutrition.

From the survey data, interaction experiment and scientific literature a hypotheses was developed regarding tuber potash and phosphorus concentrations and the incidence of ACD.

Tubers from 5 variety evaluation experiments during the 1989/90 and 1990/91 seasons were also assessed for ACD. In the same two seasons, 5 experiments were undertaken to further investigate our developed hypothesis in regard to the potash and potassium concentrations in tubers and test practical methods of altering that composition to achieve a lower incidence of ACD. In the same experiment a range of organic soil amendments were tested.

During the 1989/90 and following two seasons, extensive crop monitoring was undertaken as part of this project and for a potato crisp quality improvement project. Samples collected during the monitoring were assessed for ACD as well as other quality factors and provided new or additional data on the incidence of ACD in relation to tuber size, planting time, tuber maturity, in ground storage and regional variations.

This report presents the result of all work undertaken on ACD from the industry survey in the 1987/88 season through to pot and field experiments in 1992 investigating the impact of the amelioration of low pH soils on potato yield and quality. The project researchers have a continuing committment to the assessment of ACD in potato experiments to ensure that any new management strategies developed will not significantly increase darkening or may be useful in reducing darkening.

3. WORK SUMMARY AND METHODS

3.1 Sequence of Events

Data collection and experimental work for the Potato ACD project commenced with an industry survey in the 1987/88 season and continued through to 1992. Table 1 summarizes the 9 experiments and developments involved with this project including references to the relevant results and discussion sections of this report.

Table 1 - Experments and data collection events for the potato ACD project.

ACTION	RESULTS REF.
Industry survey (88 sites, 149 crops)	1, 6
Storage of survey samples (89 samples)	10
NPK interaction trial (Site 1, Pages Flat)	2
NPK Interaction Trials (Sites 2,3, Mt Barker& Mundulla)	2
Development of tuber composition hypothesis	-
P & K sidedressings (Site 4, Mt Barker)	2
Variety Assessment Trials (NAP, MLR & LSE)	6
Foliar spray application trial (Mt Barker)	3
Crop Monitoring - ACD Project	5 - 9
Crop Monitoring - Crisp Quality Project & ACD Project	5 - 9
P & K Sidedressing/Organic Soil Amendment Trials (Sites 5,6,7)	2, 4
Variety assessment trials (NAP & LSE)	6

3.2 Tuber Compostion Hypothesis

In mid 1989, after the compilation and analysis of the survey data and ACD assessment of tubers from the NPK Interaction trials a hypothesis was developed in regard to tuber potash and phosphorus concentrations and their relationship to the incidence of ACD. The hypothesis is summarized in Table 2.

The hypothesis was developed from the considerations of the earlier results of overseas researchers, the principle component analysis of the survey results and further confirmed by the results of the NPK interaction trial at Site 1 (Figures 1 and 2).

Table 2 - Hypothesis on the relationship between the ACD of potatoes and potassium and phosphorus concentrations in the tuber.

CONCENTRATION IN TUBER (%)		DEGREE OF ACD
POTASSIUM	PHOSPHORUS	
<2.4	<0.27	High
<2.4	>0.27	Medium/Low
>2.4	<0.27	Low (?)
>2.4	>0.27	Low

Much of the experimental work from this point was developed to further substantiate this hypothesis and investigate effective means by which the nutrient composition of tubers could be altered through commercially viable crop management practices. The hypothesis was also tested against samples collected during crop monitoring work from 1989 to 1991.

Figure 1 - Relationship between tuber potassium concentration and ACD for the cv. Atlantic (Site 1).

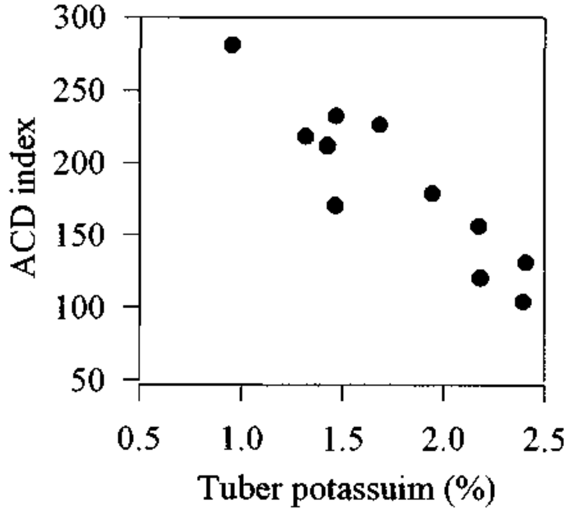
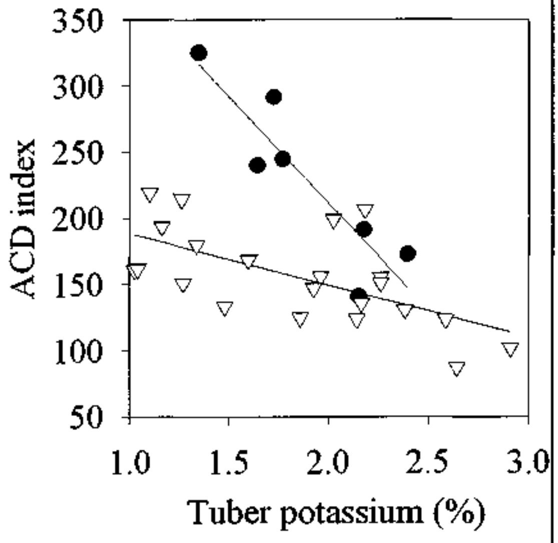


Figure 2 - Relationship between tuber potassium concentration and ACD for the cv. Kennebec separated for tuber phosphorus concentrations > 0.27% (∇) and < 0.27% (●) (Site 1).



3.3 Methods

The experimental methods used for the survey and experimental and crop monitoring work of the project are summarised in the sections below.

3.3.1 ACD Assessment

Wherever possible for ACD assessment a maximum of 16 tubers from the crop sample were washed and allowed to drain. Each tuber was then cut in half by cutting through the stolon scar and bud-end of the tuber. A 10mm slice was cut from one half for ACD assessment. The tuber slices were steamed for 15 minutes and after cooling for up to 6 hours were visually rated on a scale of 1 (no ACD) to 5 (severe ACD) (Table 3). From these ratings an ACD index was calculated for each sample using the formula:

$$\text{ACD Index} = 100 \times \text{average severity value} \times \frac{\text{number of tubers with score} > 1}{\text{total number of tubers asessed}}$$

Tubers with ACD index values less than 130 were considered acceptable, 130 - 200 borderline and greater than 200 unacceptable.

Table 3 - Potato tuber darkening zones in relation to ACD score.

ACD SCORE	DEGREE OF DISCOLOURATION INTENSITY		
	BLACK ZONE	**BLACK TO LIGHT GREY ZONE**	**ZONE OF NO DISCOLOURATION**
1	0	0	Full tuber
2	0	0-5 mm deep	> 5 mm deep
3	< 5 mm deep	5-10 mm deep	> 10 mm deep
4	< 10 mm deep	10-25 mm deep	>25 mm deep or < 50% tuber area
5	10 mm deep	10 mm deep to> 50% tuber area	< 50% tuber area

3.3.2 Industry Survey

3.3.2.1 Soil analysis.

During July to September, surface (0-15cm) soil samples were collected from 80 potato crop paddocks representing 33 different growers. Sites were selected in the Mt. Lofty Ranges (67 paddocks) from Echunga to Mt. Pleasant, 8 paddocks in the Mundulla region and 5 in the Lower Murray (Bow Hill) district. Soil samples were air-dried and analysed for pH, total soluble salts, bicarbonate-extractable phosphorus and potassium, DTPA extractable copper, zinc, manganese and iron, total nitrogen, organic carbon and phosphorus sorption. The surface soils were also characterised for soil particle size by determination of the percent sand, silt and clay.

3.3.2.2 Petiole sampling and analysis.

Tissue samples (petioles of the youngest fully expanded leaves, P-YFEL) were collected from the crops when the length of the largest tubers was 5-10mm. A total of 149 crops, comprising 11 varieties, were sampled (Table 4). Petiole samples were dried in a forced draught oven at 60-70°C, ground to < 1mm and analysed for total Kjeldahl nitrogen, nitrate nitrogen, phosphorus, potassium, chloride, sodium, aluminium, boron, calcium, copper, iron, magnesium, manganese, sulphur and zinc.

3.3.2.3 Harvesting.

Where possible tubers were harvested after the tops had fully senesced. From each crop, a sample of 30-35 kg of tubers was collected and transported to the Northfield Research Laboratories for assessment and storage. Samples not tested immediately, were stored at 12 ± 0.5°C for a maximum of 15 days prior to assessment. Mean storage time prior to assessment was 6 days.

3.3.2.4 Tuber assessment and analysis.

From each crop a 4-5 kg subsample of tubers was used to determine specific gravity (weight in air, weight in water method). Tubers were sampled and assessed for ACD as outlined in section 3.3.1. A 1mm slice was cut from the other half of each tuber for crisp color determination and then a 1 cc (approx) cube of tissue (including skin) was cut from the stem end for nutrient analysis. Tissue cubes were dried at 60-70°C in a forced draught oven, ground and analysed for total Kjeldahl nitrogen, phosphorus, potassium and chloride.

Table 4 - Summary of potato crops sampled and stored for the industry ACD survey.

VARIETY	HARVESTED	STORED
Kennebec	85	66
Coliban	24	-
Denali	5	5
Pontiac	13	-
Atlantic	11	11
Desiree	3	3
Snowchip	2	2
Norchip	2	2
Exton	3	-
Katahdin	1	-
Sebago	1	1
TOTAL	149	89

3.3.2.5 Storage.

After 2 weeks curing at 12 ± 0.5°C and fogging with CIPC sprout inhibitor, tuber samples from 89 crops, covering 7 varieties (Table 4), were divided into 2 equal lots. Half the samples were stored in a coldroom at 12 ± 0.5°C and the other half were stored in an uninsulated shed in the Mt Lofty Ranges to simulate grower storage conditions. After 3 and 6 months, subsamples were removed from each storage regime and tested for SG, crisp colour and ACD using the same methods as described above.

3.3.3 NPK Interaction Experiments

Eight experiments were conducted from 1987 to 1991 to investigate the importance of interactions in the effects of N, P and K on yield, quality and storage life of tubers of the cvv. Kennebec and Atlantic. The sites, and rates of nutrients applied are shown in Table 5 and the fertiliser application strategies for each site are summarized in Table 6. Petiole samples (P-YFEL) were collected at the same stage of crop growth as used in the ACD crop survey.

Crops were harvested after complete haulm senescence with complete plots machine harvested at sites 1-3, 5 and 7 and two metres of row hand harvested from each plot at sites 4 and 6. After harvest, the tubers were weighed and size graded and 15-20 kg samples were retained from each plot for post harvest assessments as described above (section 2.3.2.4). All tubers were stored at 12 ± 0.5°C at the Northfield Research Laboratories.

Table 5 - Details of experimental sites and rate of applied nutrients

SITE	LOCATION	VARIETY	P RATES	N RATES	K RATES	HARVEST AMOUNT
1	Pages Flat	Kennebec	50, 100	0, 45, 90, 180, 360	0, 240, 480	Full Plot
		Atlantic	50	0, 90, 180, 360	0, 240, 480	
2	Mt. Barker	Kennebec	50, 100	0, 45, 90, 180, 360	0, 240, 480	Full Plot
		Atlantic	50	0, 90, 180, 360	0, 240, 480	
3	Mundulla	Kennebec	50, 100	0, 45, 90, 180, 360	0, 240	Full Plot
		Atlantic	50, 100	0, 45, 90, 180, 360	0, 240	
4	Mt. Barker	Kennebec	0, 50, 100, 200	0, 120	0, 120, 240, 480, 960	2m of Row
5	Woodside	Kennebec	0, 80, 160	0	0, 240, 480	Full Plot
6	Yundi	Kennebec	0, 80, 160, 320	60	0, 120, 240, 480	2m of Row
7	Forreston	Kennebec	0, 80, 160	0	0, 240, 480	Full Plot

Table 6 - Nutrient application strategies used on experimental plantings.

NUTRIENT	PLANTING[A]	SIDEDRESSING[AB]		
		1	2	3
Site 1				
N	0.33	0.33	0	0.33
P	0.5	0.5	0	0
K	0.5	0.5	0	0
Site 2				
N	0.33	0.33	0.3	0
P	1	0	0	0
K	0.5	0.5	0	0
Site 3				
N	0.33	0	0.33	0.33
P	1	0	0	0
K	0.5	0	0.5	0
Site 4				
N	0	0	1	0
P	0	1	0	0
K	0	0.5	0.5	0
Site 5				
N	0	0	0	0
P	0.5	0.5	0	0
K	0.5	0.5	0	0
Site 6				
N	0	0.5	0.5	0
P	0	0.5	0.5	0
K	0	0.5	0.5	0
Site 7				
N	0	0	0	0
P	0.5	0.5	0	0
K	0.5	0.5	0	0

[A] Proportion of the total applied either at planting or as sidedressings.

[B] Fertiliser was placed as a double band along the row at 3 growth stages: 1, plants up to 15 cm tall; 2, `hookstage' to length of longest tuber of 15 mm; 3, length of longest tuber 20-35 mm.

3.3.4 Foliar Sprays

A range of chemical foliar sprays were applied at the rates shown in Table 7 to a Kennebec crop at Mt. Barker on 20/12/89, 3/1/90, and 16/1/90. Three replicates were used for each treatment and applied to plots of two rows 6m wide x 2m long. Barrier rows were left between each pair of treatment rows. At the first spray application the plants were approximately at the tuber hook stage of development and the last application was when the average tuber length was 80mm. Sprays were applied by hand using pressurised hand sprayers to the point of run off.

After haulm senescence, two metres of row from each plot was harvested by hand and post harvest assessments made as described above (section 2.3.2.4).

Table 7 - After cooking darkening, specific gravity and crisp color data for tubers harvested from crops treated with foliar sprays at various application rates.

ACD FOLIAR SPRAY TRIAL				
SPRAY MATERIAL	RATE	ACD	S.G.	CRISP
Nil	-	235	1.0721	74
Cycocel	2ml	233	1.0699	61
Cycocel	10ml	210	1.0703	78
Cycocel	2ml*	229	1.0702	78
Na-EDTA	10gm	243	1.0707	125
Na-EDTA	10gm*	256	1.0675	68
Na-Citrate	20gm	247	1.0725	72
Na-Citrate	50gm	220	1.0697	80
Citric acid	20gm	221	1.0711	91
Citric acid	50gm	233	1.0716	71
Mangasol	3ml	216	1.0684	58
Mangasol	5ml	237	1.0705	87
K-nitrate	20gm	243	1.0712	65
K-nitrate	50gm	239	1.0715	105
L-chloride	20gm	263	1.0733	98
K-chloride	50gm	202	1.0730	75
Bravo	1ml	258	1.0723	86
Bravo	5ml	241	1.0708	95
Na-metabisul	20gm	237	1.0724	81
Na-metabisul	50gm	220	1.0682	53
LSD (P=0.05)		NS	NS	NS
* Soil drench				

3.3.5 Organic Soil Amendments

At the experimental sites 5-7 a range of organic soil amendments (lime, gypsum, dolomite, chicken manure, base organic and blood and bone) were applied and the rates and application strategies are summarized in Table 8. At sites 5 and 7, the soil ammendment treatments were applied at planting and as single side dressings, when the plants were approximately 150mm high. At site 6, all treatments were applied as side dressings to a growers established crop when the plants were approximately 150mm tall. All side dressing treatments were lightly incorporated into the soil and applied prior to banking to ensure incorporation into the mound of the growing plant. Crops were harvested and postharvest assessments made as described above (section 2.3.2.4).

Table 8 - After cooking darkening scores for tubers harvested for crops grown with organic soil amendments at sites 5 to 7.

SOIL AMENDMENT		ACD INDEX		
TYPE & RATE (t/ha)	**APPLICATION**	**SITE 5**	**SITE 6**	**SITE 7**
Control		256	295	144
Lime				
1	Banded	260	-	190
2	Banded	291	-	186
3	Banded	275	-	155
3	1/2 Plants & 1/2 SD	270	-	172
3	All SD	254	277	180
3	Incorporated	250	-	169
6	All SD	-	257	-
Dolomite				
1	Banded	260	-	187
2	Banded	271	-	196
3	All SD	-	301	-
6	All SD	-	287	-
Gypsum				
1	Banded	269	-	139
2	Banded	256	-	165
3	All SD	-	262	-
6	All SD	-	255	-
LSD (5%)		*NS*	*22.5*	*NS*
Chicken Manure				
1	Banded	265	-	143
2	Banded	287	-	165
8	All SD	-	310	-
16	All SD	-	273	-
Base Organic				
1	Banded	266	-	169
2	Banded	285	-	180
8	All SD	-	298	-
16	All SD	-	301	-
Blood & Bone				
1	Banded	264	-	172
2	Banded	275	-	149
8	All SD	-	298	-
16	All SD	-	296	-
LSD(5%)		*NS*	*NS*	*NS*

3.3.6 Variety Evaluation Trials

Tubers from three variety evaluation trials in 1989/90 in the Lower South East, Mt Lofty Ranges and Northern Adelaide Plains and 2 sites in 1990/91 in the Lower South East and Northern Aderlaide Plains were assessed for ACD. All crops were grown on growers properties, managed in the same way as the growers commercial crops at that site and harvested at full haulm senescence. Tubers were cooked and scored for ACD as outlined above (section 2.3.2.4).

3.3.7 Crop Monitoring

Through the crop monitoring program, potato crops from various regions of the state were closely monitored from the time of soil preparation through to harvest. Throughout the growing period of the crop, plants and tubers were sampled at 10-14 day intervals and data collected on a wide range of parameters to measure top growth, tuber development and tuber quality. Soil samples were taken for nutrient analysis prior to planting and petiole tissue samples collected and analysed at approximately four different growth stages for selected crops.

At plant samplings where at least some of the tubers were greater than 20mm in diameter, cooking test for crisps colour and ACD were conducted. Only selected information of relevance to ACD from this program is reported here. This program provided valuable information about the incidence of ACD in relation to growing region, planting time, tuber size and crop maturity.

4. RESULTS AND DISCUSSION

4.1 Industry Survey

4.1.1 Data Summary

Means, standard errors and ranges for all parameters measured during the industry survey are summarized in Table 9. For the cvv. Coliban and Kennebec, data for each parameter were plotted against ACD indices determined immediately after harvest. Based on these relationships the following parameters were selected for principal component analysis, specific gravity, petiole Kjeldahl nitrogen, petiole chloride, petiole calcium, petiole manganese, soil organic carbon, soil pH, extractable soil potassium and harvest date. Data for Mundulla and the Mt. Lofty Ranges were analysed separately for the cv. Kennebec.

Tuber data, namely Kjeldahl nitrogen, potassium, phosphorus, chloride, iron and manganese, were analysed separately. For the cv. Kennebec, analyses were performed on the Mt. Lofty Ranges data alone and on the combined data for Mt. Lofty Ranges and Mundulla regions.

Table 9 - Means, standard errors and ranges for all data collected from crops in the ACD survey.

VARIABLE	NO. SAMPLES	UNIT	MEAN	S.E.	RANGE
A) Soil data					
pH	106		5.77	0.04	4.8 - 7.0
Total soluable solids	106	%	0.03	0.003	0.01 - 0.14
Total soil nitrogen	93	%	0.16	0.005	0.08 - 0.39
Organic carbon	106	%	1.92	0.05	1.0 - 4.55
Extractable phosphorus	106	mg/kg	55.75	3.94	4.0 - 250
Extractable potassium	106	mg/kg	187.97	12.22	35.0 - 750
DTPA - Zinc (Zn)	106	mg/kg	1.53	0.09	0.37 - 5.20
DTPA - Copper (Cu)	106	mg/kg	0.76	0.09	0.16 - 9.40
DTPA - Iron (Fe)	106	mg/kg	88.78	2.46	26.0 - 122.0
DTPA - Manganese (Mn)	106	mg/kg	13.94	0.70	0.82 - 32.0
B) Petiole data					
Total Kjeldahl N (TKN)	106	%	3.12	0.03	2.32 - 4.08
Nitrate nitrogen(NO_3-N)	106	%	2.81	0.03	2.0 - 3.6
Phosphorus (P)	106	%	0.50	0.01	0.31 - 0.71
Potassium (K)	106	%	12.48	0.11	9.30 - 14.61
Calcium (Ca)	106	%	0.77	0.187	0.29 - 1.60
Magnesium (Mg)	106	%	0.68	0.019	0.32 - 1.50
Sulphur (S)	106	%	0.29	0.003	0.22 - 0.36
Sodium (Na)	79	%	0.20	0.04	0.04 - 2.84
Chloride (Cl)	106	%	2.22	0.08	0.08 - 5.62
Aluminium (Al)	106	mg/kg	393.84	33.95	72 - 2200
Boron (B)	106	mg/kg	27.27	0.25	21 - 33
Copper (Cu)	106	mg/kg	7.12	0.21	2.3 - 13.0
Iron (Fe)	106	mg/kg	359.34	24.92	110 - 1700
Manganese (Mn)	106	mg/kg	104.5	6.65	10 - 390
Zinc (Zn)	106	mg/kg	95.42	2.07	54 - 180
C) Tuber Data					
Total Kjeldahl N (TKN)	127	%	1.71	0.024	1.15 - 2.48
Phosphorus (P)	127	%	0.19	0.003	0.12 - 0.31
Potassium (K)	127	%	2.00	0.03	1.08 - 2.72
Chloride (Cl)	127	%	0.86	0.02	0.21 - 1.82
Iron (Fe)	126	mg/kg	35.15	1.52	6.6 - 91.0
Manganese (Mn)	126	mg/kg	13.87	0.43	7.1 - 32.0

4.1.2 Soil and Petiole Correlations with ACD

Principal component analysis loadings for the cv. Coliban (Table 10) suggest that ACD is high when:

* soil pH is low
* soil potassium is low
* petiole Kjeldahl nitrogen is high
* petiole chloride is high
* harvest date is late

For crops of the cv. Kennebec grown in the Mt. Lofty Ranges, principal component analysis loadings (Table 10) suggest that ACD is high when:

* soil organic carbon is low
* soil pH is low
* soil potassium is low
* petiole manganese is high.

Table 10 - Principle component analysis loadings for the effects of soil and petiole parameters on ACD for the cvv. Kennebec and Coliban.

VARIABLE	COLIBAN	KENNEBEC	
		MUNDULLA	MT. LOFTY RANGES
ACD	0.3809	0.6152	0.4247
Specific gravity	0.2038	0.4362	0.0067
Petiole nitrogen	0.3541	0.4463	0.2414
Petiole chloride	0.3403	0.4463	0.1417
Petiole calcium	-0.2393	-0.3772	-0.1428
Petiole manganese	0.3153	-0.0739	0.3792
Soil organic carbon	-0.0234	0.0985	-0.4131
Soil pH	-0.4040	-0.1330	-0.4089
Soil extractable potassium	-0.3590	0.1909	0.4023
Harvest date	0.3506	na	0.2743

Figures 3 - 8 show typical relationships between soil pH, soil extractable potassium and petiole manganese and ACD index for the survey data.

Because the number of Kennebec crops sampled from the Mundulla region were small, the principal component analysis results may be unreliable. Loadings (Table 10) suggest that ACD is high when:

* petiole Kjeldahl nitrogen is high
* specific gravity is high
* petiole calcium is low.

Figure 3 - Relationship between petiole total Kjeldahl nitrogen and ACD for the cv. Coliban (Mt. Lofty Ranges)

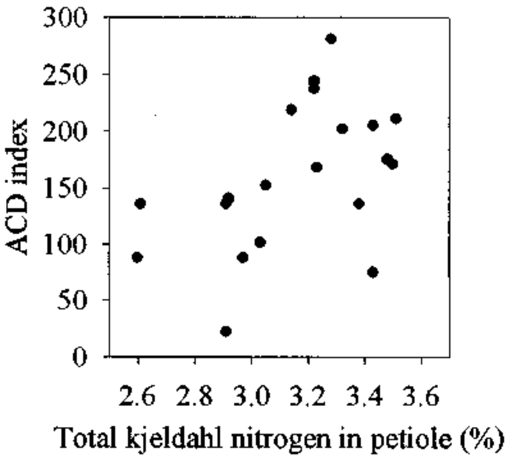


Figure 4 - Relationship between petiole chloride and ACD for the cv. Coliban (Mt. Lofty Ranges)

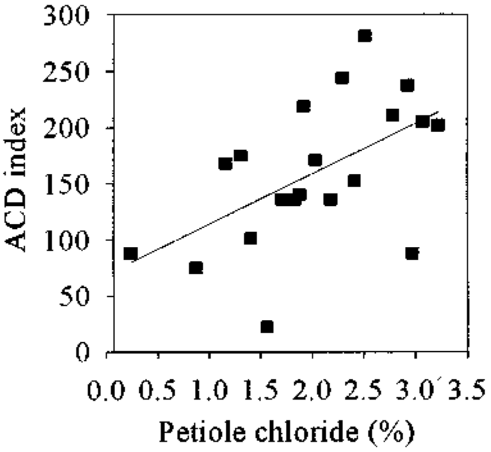


Figure 5 - Relationship between extractable soil potasium and ACD for the cv. Coliban (Mt. Lofty Ranges)

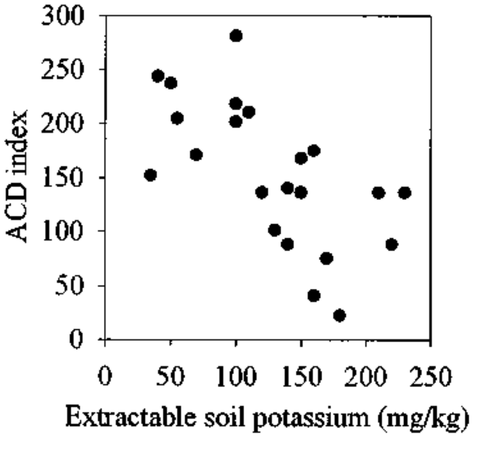


Figure 6 - Relationship between surface soil pH and ACD for the cv. Kennebec grown in the Mt. Lofty Ranges (▲) and Mundulla (■) districts.

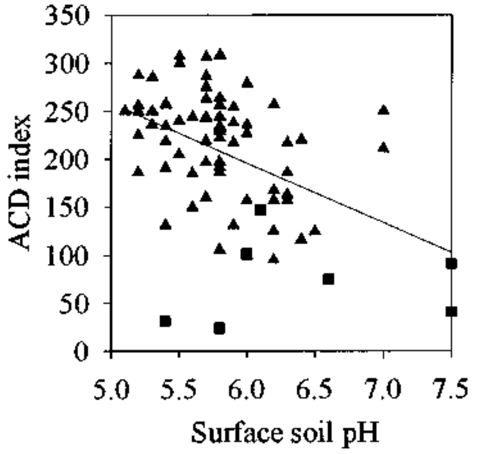


Figure 7 - Relationship between extractable soil potassium and ACD for the cv. Kennebec grown in the Mt. Lofty Ranges (▲) and Mundulla (■) districts.

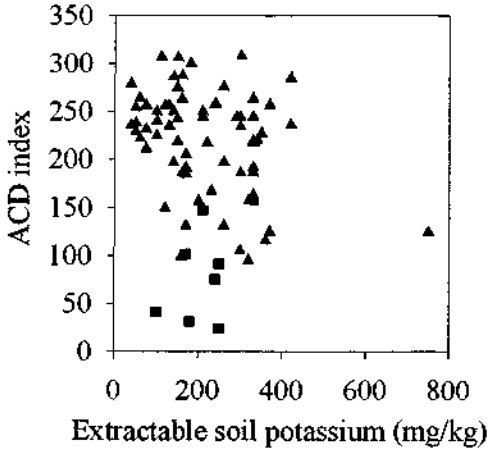
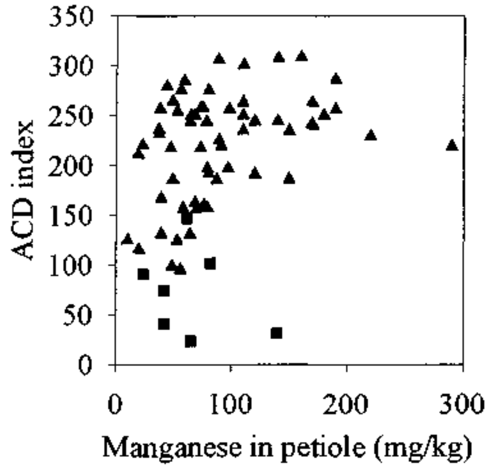


Figure 8 - Relationship between petiole manganese and ACD for the cv. Kennebec grown in the Mt. Lofty Ranges (▲) and Mundulla (■) districts.



4.1.3 Tuber nutrient correlation's with ACD

Principal component analysis loadings (Table 11) for the cv. Coliban suggest that ACD is high when:

* potassium is low
* phosphorus is low

For the cv. Kennebec, analysis of the combined data for the Mt. Lofty Ranges and Mundulla regions (Table 11) suggests that ACD is high when:

* potassium is low
* chloride is low
* phosphorus is low

Table 11 - Principle component analysis loadings for the tuber parameters measured and ACD for the cvv. Kennebec and Coliban.

VARIABLE	COLIBAN	KENNEBEC	
		MLR$^{(1)}$ ONLY	ALL SITES
ACD	0.4848	0.5492	0.5289
Kjeldahl nitrogen	-0.2926	-0.0523	-0.2222
Phosphorus	-0.4379	-0.1198	-0.4226
Potassium	-0.5671	-0.6304	-0.5034
Chloride	-0.2123	-0.4628	-0.4621
Iron	-0.1958	-0.2471	-0.0838
Manganese	-0.2874	-0.0928	0.1353

(1) MLR = Mt. Lofty Ranges

Figures 9 - 12 show selected typical relationships between these factors and ACD for the survey data.

Results from the survey relating to the major nutrients (NPK) will be discussed in conjunction with the results from the NPK interaction experiments (section 4.2).

Figure 9 - Relationship between tuber potassium and ACD for the cv. Coliban (Mt. Lofty Ranges).

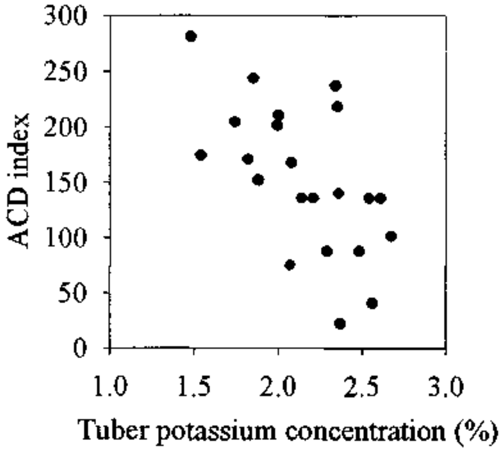


Figure 10 - Relationship between tuber potassium and ACD for the cv. Kennebec grown in the Mt. Lofty Ranges (▲), Mundulla (■) and Lower Murray (●) regions.

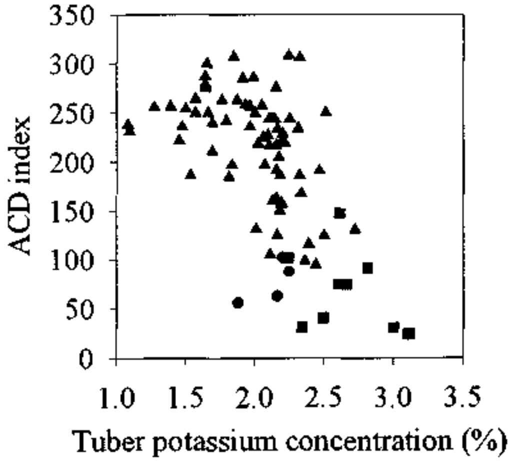


Figure 11 - Relationship between tuber chloride and ACD for the cv. Kennebec grown in the Mt. Lofty Ranges(▲), Mundulla (■) and Lower Murray (●) regions.

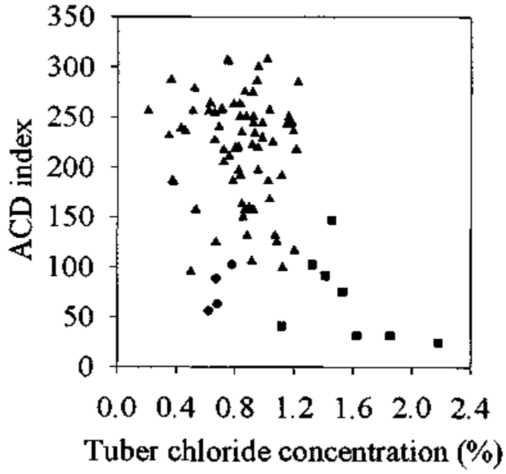
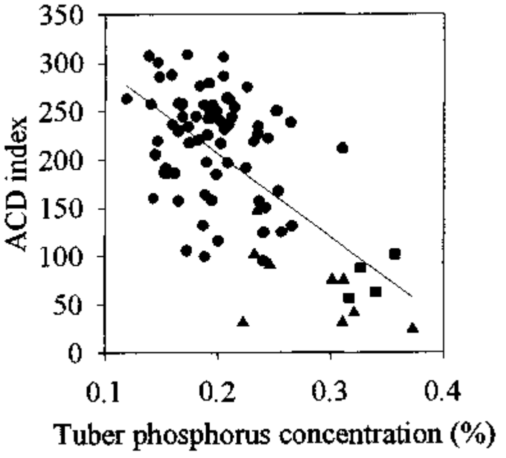


Figure 12 - Relationship between tuber phosphorus and ACD for the cv. Kennebec grown in the Mt. Lofty Ranges(●), Mundulla (▲) and Lower Murray (■) regions.



Studies in the United Kingdom and America (Evans, 1973; Hughes & Evans, 1967: Smith & Nash, 1940) have not identified manganese as a significant causal factor in relation to the degree of ACD. However, in our study, a high degree of ACD was associated with high petiole manganese concentration (Figure 14). Petiole manganese may therefore be a useful predictive factor for ACD.

4.1.4 Manganese as a predictive factor

With regard to manganese as a predictive factor the following points should be noted:

(*i*) High manganese concentrations in the petiole (> 90 mg/kg; Figure 14) were associated with a high degree of ACD.

(*ii*) For the cv. Kennebec, a scheme based on extractable potassium concentrations in surface soil samples and petiole manganese concentrations appears useful to predict the degree of ACD (Figure 13). When extractable potassium concentrations were < 150 mg/kg regardless of petiole manganese concentration, the incidence of ACD was high. However, at extractable potassium concentrations > 150 mg/kg the incidence of ACD appeared to be related to petiole manganese concentrations, for example, at petiole manganese concentrations > 90 mg/kg the incidence of ACD was high, while at concentrations < 50 mg/kg the incidence was low, only 1 site had an ACD index > 200 (Figure 13). At this site, the crop was grown on a black clay loam soil, not typical of soils used for potato production in the Mt. Lofty Ranges.

(*iii*) For the cv. Kennebec, grown at sites with extractable potassium concentrations > 150 mg/kg in surface soils, there was a curvelinear relationship between petiole manganese concentrations and ACD (Figure 14) but not between tuber manganese concentrations and ACD. These data suggest that while petiole manganese concentration may be a useful predictive factor, manganese *per se* is not a causal factor. A factor which may be involved is soil pH. Manganese concentrations in petioles were related to soil pH and the degree of ACD was correlated with soil pH (Section 4.1.6).

Figure 13 - Relationship between extractable potassium in the surface soil and petiole manganese for the cv. Kennebec with data seperated for ACD indices > 200 (■) and ACD indices < 200 (▲).

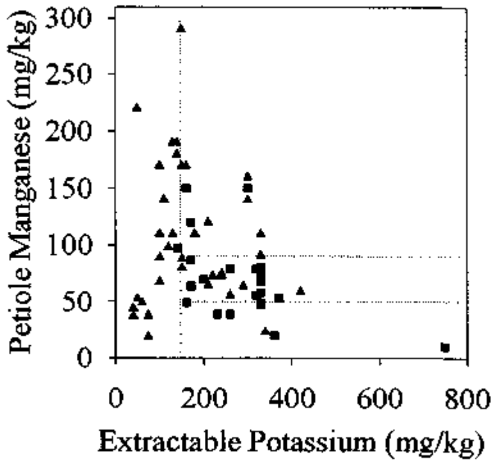
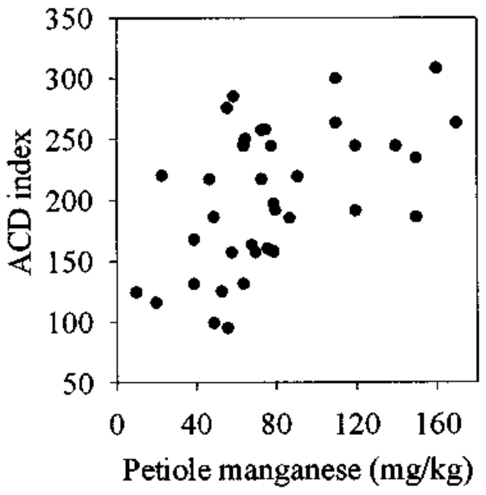


Figure 14 - Relationship between petiole manganese and ACD for crops grown on soils with extractable potassium concentrations > 150 mg/kg (cv. Kennebec, Mt Lofty Ranges).



4.1.5 Chloride as a predictive factor.

Data from the crop survey show that the relationships between chloride and the degree of ACD were contradictory. For example, for the cv. Coliban, there was a significant positive linear relationship between petiole chloride and ACD (Figure 4), in contrast with the cv. Kennebec principal component analysis of the combined data for the Mt. Lofty Ranges and Mundulla regions, suggested that ACD was high when tuber chloride was low. Inspection of data presented in Figure 11 shows:

(*i*) The relationship between the degree of ACD and tuber chloride concentration is variable and of limited predictive value.

(*ii*) The high chloride concentrations in tubers sampled from crops in the Mundulla district during the survey may be due to the moderate to high salinities of the irrigation waters used in the district. Whether the low degree of ACD was due to the high concentrations of chloride *per se* in tubers requires, further investigation. Samples collected from the Mundulla district during experiments and crop monitoring after the survey showed negligible ACD (Index < 50) associated with low tuber chloride concentrations < 0.80.

(*iii*) For the Lower Murray (Bow Hill) district, data presented in Figure 11 and data collected after the survey, show that tubers from this district have a low degree of ACD and tuber chloride concentrations < 0.80.

4.1.6 pH effects on ACD

Smith and Nash (1940; 1941) reported a negative relationship between pH and degree of ACD. Tubers grown in soils with low pH (4.92 to 6.36) showed a high degree of blackening; tubers grown in a soil of pH 7.88 showed very little ACD. In our study for the cvv. Kennebec (Figure 6) and Coliban the degree of ACD was significantly negatively correlated with pH of the surface soil samples. However, the percentage of the variation in ACD accounted for by pH was low, and therefore other factors had a significant effect on the degree of ACD.

4.2 NPK Interaction Experiments

Summary data for all the experiments are presented below in relation to each of the major nutrients (NPK) with comments on relations to information obtained in the survey and in relation to the developed hypothesis on the incidence of ACD.

4.2.1 Nitrogen

Previous studies in the United Kingdom showed that potatoes grown in fen soils developed a higher degree of darkening compared with potatoes from clay soils. It was suggested that this was due to the smaller amount of potassium and higher amounts of nitrogen in fen soils. Evans (1973) reported that increased concentrations of ammonium ions supplied to potato plants increased the degree of ACD by reducing potassium uptake which resulted in lower concentrations of potassium and citric acid in the tubers. Schippers (1968) reported that as the rate of applied nitrogen increased the degree of ACD increased and that there was a significant nitrogen x potassium interaction. The effect of nitrogen was greater at low rates of applied potassium than at high rates.

4.2.1.1 Crop survey

For the cvv. Kennebec and Coliban there were no significant correlations between Kjeldahl nitrogen concentrations in tubers and the degree of ACD. For the cv. Coliban, petiole Kjeldahl nitrogen concentrations > 3% were associated with a high degree of ACD (Figure 3). The poor relationships between Kjeldahl nitrogen and ACD, suggest that Kjeldahl nitrogen concentration in tubers is of no value as a predictive factor.

4.2.1.2 NPK interaction experiments

At the Pages Flat (1) and Mt. Barker (2) sites, which were located in the Mt. Lofty Ranges, there were significant relationships between rate of applied nitrogen and the degree of ACD with the cv. Kennebec. At the Pages Flat site, there was also a significant effect with the cv. Atlantic. In all cases, ACD indices increased as the rate of applied nitrogen increased (Tables 12 to 16). However, at the Pages Flat site, there were significant interactions between nitrogen and potassium (Table 12) and nitrogen and phosphorus (Table 13). At Mundulla there was a significant nitrogen X potassium interaction for the cv. Atlantic, with a trend for ACD indices to decrease with increasing rates of applied nitrogen when there was no potassium applied and no change when 240 kg/ha of potassium was applied (Table 16).

Table 12 - Effect of applied nitrogen and potassium on ACD indices for cv. Kennebec (Site 1).

NITROGEN RATE (kg/ha)	POTASSIUM RATE (kg/ha)		
	0	240	480
0	165	109	112
45	166	145	156
90	165	140	171
180	161	204	
360	206	269	246
LSD (5%) = 51			

Table 13 - Effect of applied nitrogen and phosphorus on ACD indices for cv. Kennebec (Site 1).

NITROGEN RATE (kg/ha)	PHOSPHORUS RATE (kg/ha)	
	50	100
0	104	153
45	154	158
90	175	142
180	215	158
360	279	203
LSD (5%) = 41		

Table 14 - Effect of applied nitrogen on ACD indices for cv. Atlantic (Site 1).

NITROGEN RATE (kg/ha)	ATLANTIC
0	118
90	160
180	195
360	246
LSD (5%) = 26	

Table 15 - Effect of applied nitrogen on ACD indices for cv. Kennebec (Site 2).

NITROGEN RATE (kg/ha)	KENNEBEC
0	197
90	221
180	226
LSD (5%) = 19	

The effect was greatest at the Pages Flat site where the degree of nitrogen deficiency was extreme and top growth response was large, and least at the Mt. Barker site, where nitrogen did not limit yield and no top growth response was evident. At the Pages Flat site, ACD also increased significantly as the rate of applied nitrogen increased for the cv. Atlantic (Table 14).

At the second Mt Barker experiment (Site 4) where the nitrogen was applied as split plot treatment across all other treatments, there was a significant positive correlation between nitrogen application and ACD. The plots receiving no nitrogen had an average ACD index of 160 whereas those plots receiving a 120 kg/ha side dressing of nitrogen had an average ACD index of 187 (lsd (5%) = 15).

Table 16 - Effect of applied nitrogen and potassium on ACD indices for cv. Atlantic (Site 3).

NITROGEN RATE (kg/ha)	**POTASSIUM RATE (kg/ha)**	
	0	**240**
0	139	92
45	126	74
90	79	104
180	95	79
360	90	87
LSD (5%) = 36		

4.2.1.3 General comments

With regard to the relationship between nitrogen and the degree of ACD the following points should be noted:

(*i*) We only determined Kjeldahl nitrogen, other nitrogen fractions may be better correlated with the degree of ACD.

(*ii*) Although rate of applied nitrogen affected the degree of ACD, the nitrogen status of tubers was poorly correlated with the degree of ACD

(*iii*) The effect of nitrogen on top growth, and therefore on the partitioning of nutrients between tops and tubers ("growth dilution effects"), may be more important in explaining the effects of nitrogen on the degree of ACD than arguing that nitrogen is a causal factor *per se*. For example, at the Pages Flat site, for the 240 kg/ha rate of potassium, tuber potassium concentrations corresponding to 0, 45, 90, 180 and 360 kg/ha of nitrogen were, 2.64, 2.26, 1.96, 1.64 and 1.35%, respectively.

(*iv*) Tissue tests are being increasingly used to monitor the nitrogen status of potato crops. Our study has shown that, while determination of nitrate nitrogen concentrations in petioles may be useful to ensure that nitrogen is not limiting yield, it is of no value to predict the degree of ACD.

4.1.2.4 Implications for nitrogen fertilizer strategy.

It is often claimed by growers that if they apply high rates of nitrogen, the tubers will "cook black". We believe this to be an over simplification and make the following points with regard to this claim:

(i) In the Mundulla, Lower Murray and Northern Adelaide Plains districts, the rates of nitrogen up to 200 - 250 kg/ha may be applied, yet tubers from these areas show a low degree of ACD. Nitrogen fertilizer strategies used on Kennebec crops grown in the Mt. Lofty Ranges are by comparison conservative, up to 50 -100 kg/ha is applied, yet the degree of ACD is high. In the NPK interaction experiments we applied up to 360 kg/ha of nitrogen at the Mundulla site with no effect on ACD and up to 180 kg/ha at the Mt. Barker site where the increase was significant, but of little practical importance (Table 15).

(ii) Where the application of nitrogen, through "growth dilution effects" results in a decrease in potassium and phosphorus concentrations in tubers, the tubers may be more susceptible to ACD. In these situations the application of potassium and phosphorus in the fertilizer is important to ensure ACD is minimised (cf. Pages Flat site). Rates of phosphorus and potassium in excess of those required to maximise yield, may need to be applied. This highlights the importance of using a "balanced" fertilizer program to ensure that ACD is minimised.

(iii) No local data are available in relation to the effect of source of nitrogen on the degree of ACD.

(iv) In the Mt. Lofty Ranges, extractable soil potassium concentrations were often low and due to the pasture phase of the crop rotations practiced, nitrogen reserves may be high (total soil nitrogen values in range 0.15-0.25%). Studies in the United Kingdom have shown that this situation (i.e. high soil nitrogen : low soil potassium) is associated with a high degree of ACD.

4.2.2 Potassium

Previous studies in the U.K. and U.S.A. have clearly established the importance of potassium nutrition in relation to the degree of ACD. In our study, potassium was shown to be significantly related to ACD in both the survey and the NPK interaction experiments

4.2.2.1 Crop Survey

Survey data showed that extractable potassium concentrations < 150 mg/kg in the surface soil samples were associated with a high degree of ACD for the cv. Kennebec (Figure 7) and < 120 mg/kg for the cv. Coliban (Figure 5). A significant relationship was also found between potassium concentration in the tuber samples and the degree of ACD for cvv. Kennebec (Figure 10) and Coliban (Figure 9). The degree of ACD was related to potassium concentrations in tubers as follows:

Tuber Potassium Concentration (%)	Incidence of ACD
< 2.1	High
2.1 – 2.4	Uncertain
> 2.4	Low

4.2.2.2 NPK Interaction Experiments.

In the NPK interaction experiments, potassium significantly affected the degree of ACD at all sites. Increasing rates of potassium were generally associated with reduced ACD for both cvv. Kennebec and Atlantic. At the Pages Flat site (1) there was an interaction with both applied nitrogen and phosphorus, as the rate of applied nitrogen increased, the trend with increasing rates of potassium changed from a negative effect to a positive effect (Table 12). At 50 kg/ha of applied phosphorus, increasing rates of potassium increased ACD indices, whereas at 100 kg/ha of phosphorus, ACD indices decreased (Table 17). At all other sites there were no interaction effects measured and at all sites there was a consistent positive trend between rate of applied potassium and the incidence of ACD (Table 18). At the Mt. Barker site (4), very high rates of potassium (up to 960 kg/ha) were applied to determine whether the incidence of ACD would continue to decline to a commercially acceptable level if sufficient potassium were applied. Application rates greater than 450 kg/ha were required to reduce the degree of ACD to moderate to low levels (index values < 200) (Figure 15).

4.2.2.3 Source of applied potassium.

At sites 4 – 7 where both sulphate and murite of potash were tested, there was no significant effect of source of potash on ACD at sites 4 – 6 and a reduced incidence associated with the use of muriate of potash at site 7 (Table 19).

Table 17 - Effect of applied phosphorus and potassium on ACD indices for the cv. Kennebec (Site 1).

POTASSIUM RATE (kg/ha)	PHOSPHORUS RATE (kg/ha)	
	50	100
0	163	182
240	192	154
480	200	152
LSD (5%) = 32		

Figure 15 - Relationship between potassium as sulphate of potash (■) and muriate of potash (●) and ACD for the cv. Kennebec (Site 4).

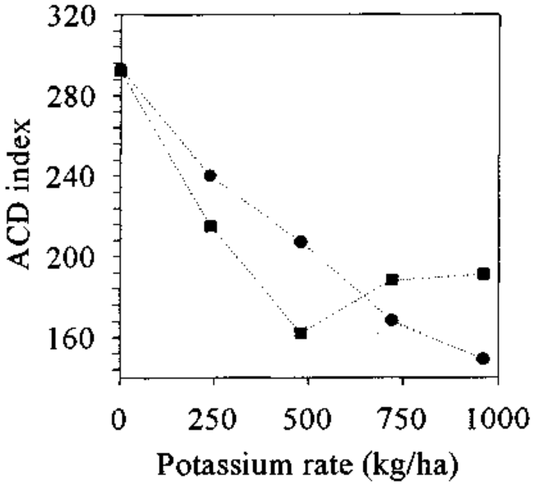


Table 18 - Effect of applied potassium on ACD indices for the cvv. Kennebec and Atlantic at sites 2 and 3, Atlantic at site 1 and Kennebec at sites 4 – 7.

SITE	CULTIVAR	RATE OF APPLIED POTASSIUM (kg/ha)					
		0	120	240	480	960	lsd (5%)
1	Atlantic	197		182	161		22
2	Kennebec	262		208	175		19
	Atlantic	201		175	154		26
3	Kennebec	91		67			20
	Atlantic	106		87			16
4	Kennebec	211	247	206	160	148	22
5	Kennebec	288		266	253		18
6	Kennebec	284	231	268	225		29
7	Kennebec	209		142	138		38

4.2.2.4 Timing of application of applied potassium.

There was no effect on the incidence of ACD in relation to changes in the timing of application of the potassium (Table 6) used at sites 5 – 7.

Table 19 - Effect of source of applied potassium on ACD indices for the cv. Kennebec (Site 7).

SOURCE OF POTASSIUM	ACD SCORE
Sulphate	137
Chloride	97
LSD (5%) =38	

4.2.2.5 Tuber potassium and ACD.

For the Pages Flat site (1), tuber potassium concentrations > 2.4% were associated with a low degree of ACD for the cvv. Atlantic (Figure 1) and Kennebec (Figure 2). For sites 2 - 4, the reduction in ACD associated with increasing rates of applied potassium are also associated with increasing tuber potassium concentrations (Table 20). This data supports the findings and conclusions regarding tuber potassium concentrations and the incidence of ACD reported above (see section 4.2.2.1) (Figure 16)

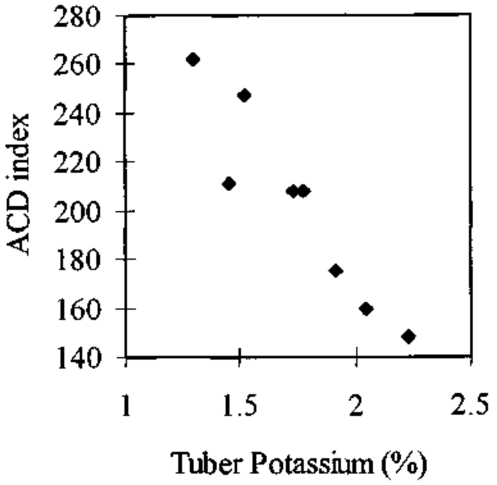
Table 20 - The incidence of ACD and tuber potassium concentration (%) for the cv. Kennebec for various rates of applied potassium at sites 2 – 4.

RATE OF APPLIED POTASSIUM (kg/ha)	SITE 2		SITE 3		SITE 4	
	ACD SCORE	TUBER % K	ACD SCORE	TUBER % K	ACD SCORE	TUBER % K
0	262	1.30	91	-	211	1.45
120	-	-	-	-	247	1.52
240	208	1.78	67	-	206	1.73
480	175	1.92	-	-	160	2.05
960	-	-	-	-	148	2.23

4.2.2.6 Implications for potassium fertilizer strategy.

For the cv. Kennebec, while potassium concentrations in petioles of 11-13% may be adequate to maximise total tuber yield, concentrations in this range were frequently associated with tuber potassium concentrations < 2.1% and therefore, the tubers may be susceptible to ACD. These data show that while potassium fertilizer strategies used in the Mt. Lofty Ranges may be adequate to maximise total tuber yield, they are inadequate if the objective is to minimise ACD. Data collected as part of statewide soil and plant nutrient surveys of irrigated potato crops during 1986/87 and 1987/88, showed that the percentage of sites sampled with petiole potassium concentrations > 14% was 17.6 and 4% for the Mt. Lofty Ranges, respectively and

Figure 16 - Relationship between ACD and tuber potassium concentration (%) for the cv. Kennebec at sites 2-4.



62.7 and 70% for the Mundulla district, respectively. Petiole potassium concentrations > 14% were associated with tuber potassium concentrations > 2.4% and a low degree of ACD.

4.2.3 Phosphorus

Earlier studies in U.K. did not identify phosphorus nutrition as a significant factor in relation to the degree of ACD. However, Lujan and Smith (1964) working in America, reported that increased rates of phosphorus had a negative relationship with the degree of ACD. In our study, rate of applied phosphorus had a significant effect on the degree of ACD and tuber phosphorus concentrations were useful to predict the degree of ACD.

4.2.3.1 Crop Survey

Based on the crop survey data, there were significant negative linear relationships between tuber phosphorus concentration and the degree of ACD for the cvv. Kennebec (Figure 12) and Coliban.

4.2.3.2 NPK Interaction Experiments

At the Pages Flat site (1) there were significant interactions between phosphorus and potassium and phosphorus and nitrogen. At the rates of nitrogen (360 kg/ha) and potassium (240 kg/ha) required to maximise tuber yield, increasing the rate of applied phosphorus caused a decrease in the ACD indices. Significant main effects and first order interactions occurred in relation to rate of applied phosphorus (Tables 13 and 17). For the cv. Kennebec the relationship between the phosphorus and potassium concentrations in tubers and the degree of ACD is shown in Figure 2.

At sites 3,4,6 and 7 increasing the rate of applied phosphorus decreased the ACD indices (Table 21).

Table 21 - Effect of applied phosphorus on ACD indices for the cvv. Kennebec and Atlantic at site 3 and the cv. Kennebec at sites 4,6 and 7.

SITE	CULTIVAR	RATE OF APPLIED PHOSPHORUS (kg/ha)							
		0	50	80	100	160	200	360	lsd (5%)
3	Kennebec	-	95	-	63	-	-	-	20
	Atlantic	-	111	-	82	-	-	-	16
4	Kennebec	205	-	-	178	-	137	-	22
6	Kennebec	269	-	280	-	255	-	202	29
7	Kennebec	192	-	160	-	137	-	-	38

There were no significant effects of applied phosphorus on ACD indices at the Mt. Barker (2) and Woodside (5) sites.

4.2.3.3 Source and timing of application of phosphorus.

At sites 5 and 6, tests with the application of both single super and triple super showed no difference between the 2 sources on the incidence of ACD. At site 6, the timing of the application of the phospshorus was also varied with no significant impact on ACD.

4.2.3.4 Tuber phosphorus and ACD.

The survey data and interaction experiment at site 1 lead to the development of the hypothesis on the relationship of ACD to tuber potassium and phosphorus concentration (see section 3.2). We showed that with the cv. Kennebec at site 4 tuber phosphorus concentrations can be increased with added applications of phosphorus to the crop during the growing season (Table 22).

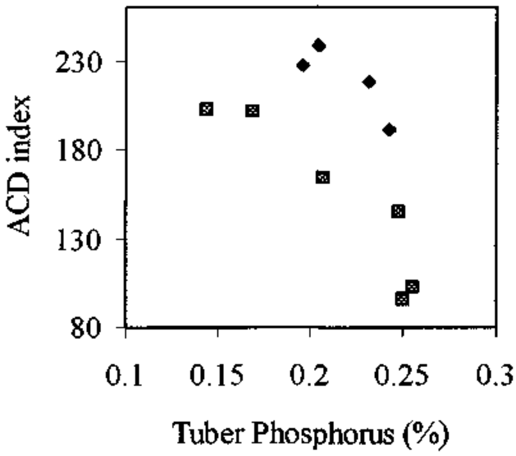
In the ACD hypothesis a critical phosphorus concentration of >0.27% was proposed as necessary for a low incidence of ACD. This is supported by the data for the cv. Kennebec collected at site 4 which indicates that only low ACD scores were obtained with tuber phosphorus concentrations >0.25% (Figure 17).

However, the effect of increased tuber phosphorus concentration on other tuber quality attributes has to be considered. For example, the survey results showed that for the cv. Kennebec while high tuber phosphorus concentrations were associated with low degree of ACD, they were also associated with low specific gravity.

Table 22 - Tuber phosphorus concentration (%) for the cv. Kennebec in relation to applied phosphorus and potassium (Site 4).

P RATE (kg/ha)	K RATE (kg/ha)		
	0	480	960
0	0.196	0.168	0.143
50	0.204	-	-
100	0.232	0.248	0.207
200	0.242	0.255	0.250

Figure 17 - Relationship between tuber phosphorus concentration (%) and ACD indices for the cv. Kennebec (Site 4) with data seperated for tuber potassium concentration >2%(■) and <2%(◆).



4.2.3.5 Implications for phosphorus fertilizer strategy.

Compared with Mundulla and Lower Murray districts, phosphorus concentrations in tubers sampled from the Mt. Lofty Ranges were low (Figure 12). The difference may be due to :

- Differences in rates of fertilizer phosphorus applied. Rates of phosphorus applied range from 40 - 100 kg/ha.
- Differences in the method of applying phosphorus, (broadcast vs banding) which will affect the efficiency of phosphorus uptake. At the Mundulla and Lower Murray sites, phosphorus fertilizer was usually banded at planting, whereas in the Mt. Lofty Ranges, phosphorus was usually broadcast before planting.
- Differences in soil type, particularly with regard to differences in P-sorptivity of soils.
- Differences in growing conditions, for example, temperature and water quality, which may affect nutrient composition and partitioning of nutrients between tops and tubers.

4.3 Foliar Sprays

Smith & Muneta (1954) tested a range of foliar chemical applications and found some of them significantly reduced the incidence of ACD (Table 23). The chemical sprays used can be separated into several groups in relation to their possible mode of action in reducing the incidence of ACD. Table 24 summarises the chemical groups involved, the actual foliar sprays used and their possible mode of action.

Table 23 - Effect of a range of foliar sprays on the incidence of ACD on the cv. Katahdin (Smith & Muneta, 1954).

CHEMICAL AND CONCENTRATION (0.2%)	COLOUR RATING *
Unsprayed	4
Tri-sodium EDTA	5
Ammonium gluconate	5
Gluconic acid	5
Sodium gluconate	5-6
Citric acid	5-6
EDTA	6
Bi-sodium EDTa	6-7
Glucatase	6-7
Sodium bisulphite	7
Sodium citrate	7
Chelate 242L	7
Quaternary-sodium EDTA	7
Bi-sodium copper EDTA	8
Sodium iron EDTA	8
* 9 = white, no darkening, with progressively lower numbers indicating increasing amount and intensity of discolouration Variety Katahdin, single spray 75 days from planting	

There was no significant affect of any spray applications on ACD, SG or Crisp Colour (Table 7) for the cv Kennebec in this experiment.

Table 24 - Spray groups used in foliar applications to potato crop (cv. Kennebec) at Mt Barker and the possible mode of action for each group in the reduction of ACD.

SPRAY GROUP	SPRAYS USED	REASON FOR USE
Growth Regulator	Cycocel	Alter top/root distribution of nutrients
Chelating Agents	Sodium (Na)-EDTA Sodium (Na)-Citrate Citric Acid	Alter ACD reaction pathway or chemicals available for reaction
Nutrient Sprays	Mangasol Pot. (K) Nitrate Pot. (K) Chloride	Increase nutrient uptake in tubers
Other	Bravo Na Metabisulphite	Suggested to be effective

4.4 Organic Soil Amendments

For all experiments with organic soil amendments, (sites 5, 6 and 7) the results were analysed in 2 groups. The first group included the lime, dolomite and gypsum treatments with the chicken manure, base organic and blood and bone in the second group. None of the treatments applied had any significant effect on the incidence of ACD (Table 8).

Further experimental work since the completion of this project has been undertaken with the use of lime at up to 30t/ha. This work has shown that application rates of lime at 10-15t/ha can decrease the incidence of ACD by up to 60-65% (Maier et.al., 1995). In those experiments where the maximum ACD index was >150, there was a significant negative relationship between rate of applied lime and relative ACD index (Figure 18). However, lime applied at high rates such as this in the same season as the potato crop is grown is likely to induce or significantly increase tuber scab infections.

4.5 Regional Variations

Tubers from crops grown in the Mt. Lofty Ranges and Lower South East have a higher incidence of ACD than tubers from crops grown in the Upper South East (Mundulla) and Northern Adelaide Plains regions (Tables 25 and 26).

The higher and relatively similar incidence of ACD in tubers grown in the Lower South East and Mt. Lofty Ranges is not surprising as the characteristics of the soils in these regions is similar ie, low pH and low extractable potassium and phosphorus levels. Experimental work on these soils showed that the application of potash and phosphorus fertilisers can reduce the incidence of ACD (Tables 18, 19 and 21).

Figure 18 - Relationship between rate of applied lime and relative ACD indices. (Source: Maier et.al.)

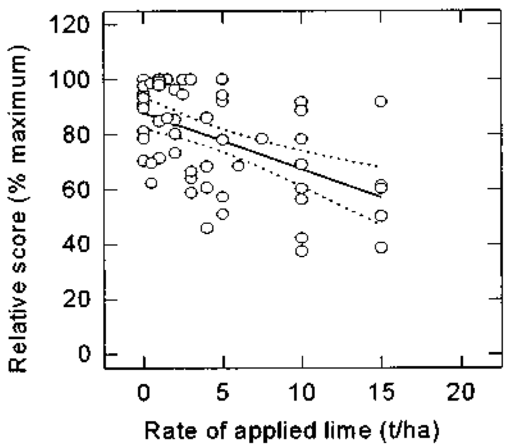


Table 25 - Mean ACD scores for tubers from the ACD survey and variety experiments from four different production regions in South Australia over 3 seasons (1987/88, 1989/90 and 1990/91).

REGION	87/88 (1)	89/90 (2)	90/91 (2)
Northern Adelaide Plains (NAP)	-	70	128
Mt. Lofty Ranges (MLR)	209	208	-
Upper South East (USE)	92	-	-
Lower South East (LSE)	-	247	288

Notes: (1) From ACD Survey - USE mean at 13 sites, 4 cultivars
- MLR mean at 122 sites, 10 cultivars
(2) From Variety Trials - NAP mean at 33 cultivars
- MLR mean at 39 cultivars
- LSE mean at 32 cultivars
(3) From Variety Trials - NAP mean at 31 cultivars
- LSE mean at 31 cultivars

Table 26 - ACD scores for a range of cultivars grown in the Lower South East, Mt Lofty Ranges and Northern Adelaide Plains regions of South Australia in 1989/90 and 1990/91.

VARIETY	L/SOUTH EAST		MT LOFTY RANGES	N/ADELAIDE PLAINS	
	89/90	90/91	89/90	89/90	90/91
Russet Burbank	-	336	213	-	122
Atlantic	217	242	138	25	126
Coliban	-	-	212	-	-
Denali	-	296	234	-	165
Tarago	312	309	237	114	127
Sebago	228	238	143	79	37
Desiree	265	-	228	9	31
Snowchip	209	322	237	144	138
Kennebec	189	321	227	80	69
Sequoia	238	279	218	94	172
Crystal	234	277	126	9	142
Pontiac	219	230	177	68	124

4.6 Varietal Variations

During the 1988/89 survey there were 122 crops which included 10 cultivars sampled from the Mount Lofty Ranges (Table 27). There were more than 5 crops sampled for the varieties Atlantic, Coliban, Kennebec and Pontiac. From the mean ACD indices obtained for these cultivars it was concluded that their susceptibility would be rated as:

Kennebec > Pontiac > Atlantic > Coliban

Similar susceptibility ratings were evident through all the variety evaluation trials with Kennebec being the most susceptible cultivar. Except for the Mt. Lofty Ranges site, the susceptibility of Pontiac and Atlantic were very similar (Table 26).

Table 27 - Mean ACD indices for cultivars assessed during the grower survey for the Mt. Lofty Ranges region.

VARIETY	MT LOFTY RANGES	
	NO OF SAMPLES	MEAN ACD INDICES
Atlantic	7	168
Coliban	22	152
Denali	4	241
Exton	3	218
Katahdin	1	227
Kennebec	70	219
Norchip	2	256
Pontiac	11	188
Sebago	1	175
Snowchip	1	244
MEAN	-	209

The ACD ratings for all cultivars tested in the variety evaluation trials of 1989/90 and 1990/91 are shown in Table 28. Results from these trials show a natural variation in the incidence of ACD with cultivar. At the high susceptibility sites, a reduction in ACD index by approximately 50% was achieved between the worst and best scoring cultivar. However, this is across the full range of cultivars and in practice where the cultivars selection would be less due to end use requirements, the difference will be further reduced. It is also of significance that the cultivars do not perform consistently across regions or between seasons.

Breeding of potatoes in Australia has not placed a high priority on the reduction of the incidence of ACD. However, there is sufficient natural variation to suggest that significant gains could be made by breeding for a low susceptibility to ACD provided it was considered by the industry to be of higher priority than other characteristics.

Table 28 - ACD indices for cultivars tested in variety evaluation trials in 1989/90 and 1990/91.

VARIETY	AFTER COOKING DARKENING INDEX (SE)				
	NORTHERN ADELAIDE PLAINS		MT LOFTY RANGES	LOWER SOUTH EAST	
	89/90	90/91	89/90	89/90	90/91
77.16.5	85 (19)	176 (28)	241 (17)	285 (29)	
77.48.3			241 (45)		
78.11.4	33 (14)	137 (31)	258 (10)	277 (42)	288 (10)
78.26.7	59 (28)	69 (16)	234 (6)	269 (6)	317 (12)
79.5.2	54 (21)	148 (9)	221 (0)	240 (3)	306 (4)
80.103.4			229 (8)		
80.146.5	31 (0)				
80.176.5	109 (8)		198 (23)	295 (49)	
80.82.4			255 (29)		
80.93.4	124 (44)	123 (5)	187 (29)	227 (8)	270 (6)
80.98.14	62 (23)	83 (10)	210 (9)	211 (32)	290 (20)
80.98.16	90 (34)	86 (37)	153 (46)	291 (42)	262 (19)
85.11.9	168 (63)	289 (25)		267 (33)	352 (9)
85.34.6	29 (23)	121 (39)		254 (17)	315 (27)
85.46.10	86 (32)		169 (0)	247 (18)	
85.51.1	78 (27)	177 (21)		243 (6)	281 (7)
Atlantic	25 (6)	126 (19)	138 (31)	217 (7)	242 (6)
Belchip			179 (15)		
Chipbelle	24 (14)	69 (6)	212 (16)	221 (29)	298 (9)
Coliban			212 (49)		
Crystal	9 (5)	142 (20)	126 (5)	234 (37)	277 (9)
Denali		165 (28)	234 (44)		296 (12)
Desiree	9 (3)	31 (12)	228 (24)	265 (22)	
Down Des	41 (31)		253 (0)	271 (15)	
Kenn L2	80 (35)	69 (9)	227 (8)	189 (38)	321 (23)
Kenn PT	123 (24)	189 (30)	243 (0)	267 (1)	291 (19)
Kennebec		136 (7)	166 (19)		
Lem Russ	72 (15)	133 (8)	241 (9)	256 (3)	251 (14)
Lindsay					242 (12)
Net Gem	29 (3)			259 (15)	
Nooksack			156 (25)		256 (10)
Onka			249 (10)		
Patrones	11 (5)	56 (24)	232 (80)	277 (5)	274 (7)
Pontiac	68 (6)	124 (28)	177 (30)	219 (7)	230 (5)
Rideau	47 (15)		237 (6)	194 (32)	
Russ Burb		122 (32)	213 (25)		336 (21)
Russ B SE					338 (23)
Sangre	137 (10)	140 (4)	138 (38)	178 (47)	254 (8)
Sebago	79 (38)	37 (4)		228 (10)	238 (7)
Sebago B			143 (10)		
Sequoia	94 (24)	172 (23)		238 (12)	279 (10)
Sequoia B			218 (16)		
Shepody					261 (11)
Snowchip	144 (13)	138 (36)	237 (14)	209 (35)	322 (16)
Spunta	41 (10)	92 (17)	173 (32)	244 (3)	275 (19)
Tarago	114 (51)	127 (51)	237 (0)	312 (13)	309 (8)
Tarago B			218 (0)		
Toolang D	85 (21)	98 (29)		192 (23)	265 (6)
Whitu		168 (33)	200 (31)		
Yank Chip	87 (0)	239 (26)	216 (27)	320 (53)	342 (21)

4.7 Planting Time

Crop monitoring work allowed for comparisons to be made on the effect of planting time during the irrigated summer crop production season, on the incidence of ACD and other tuber characteristics. The planting time has been measured by the date of the hook stage of tuber development. There is a negative correlation between ACD index and the earlier the crop is planted in the season (Figure 19). There is also a negative correlation between specific gravity and the date of hook stage (Figure 20) which is the positive benefit from earlier crop establishment but is associated with a higher level of ACD.

Figure 19 - Effect of planting time as measured by date of hook stage on ACD score for 80-350gm tubers of the cv Kennebec.

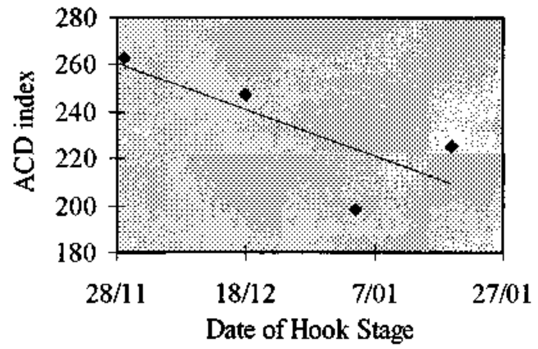
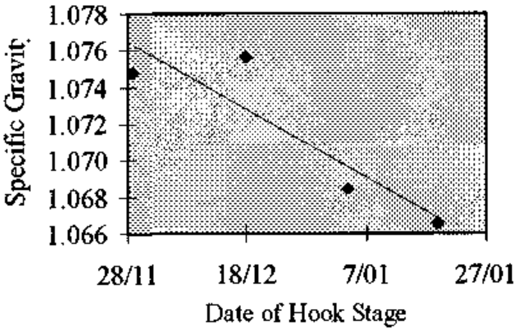


Figure 20 - Effect of planting time as measured by date of hook stage on specific gravity for 80-350gm tubers of the cv Kennebec.



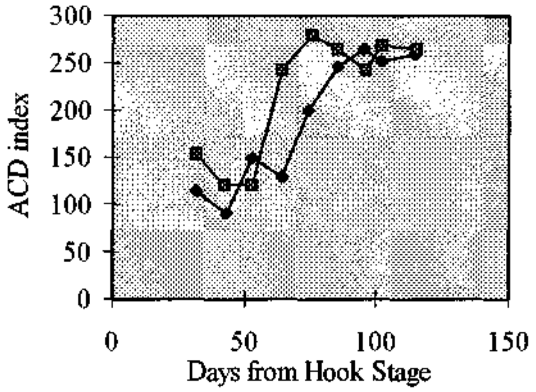
4.8 Crop Maturity

Figure 21 shows typical changes in ACD indices as the crop matures. For crops grown in the Mt. Lofty Ranges, ACD index values are usually low (100-150) in the early stages of tuber development and start to increase at around 50-60 days from hook stage. The degree of darkening increases rapidly at this time and then slows down or remains constant after 70-90 days from hook stage.

Similar trends in ACD were observed when comparing the age of Kennebec tubers (days from hook stage) for all crop monitoring samples collected in the Mount Lofty Ranges.

It would be impossible to commercially take advantage of the initially lower ACD incides as the tubers are not sufficiently sized or mature at that stage of growth.

Figure 21 - Relationship between tuber maturity as measured by days from hook stage and ACD index for two cv Kennebec crops grown in the Mt. Lofty Ranges.



4.9 Tuber Size

Kennebec tubers from four monitoring sites in the Mount Lofty Ranges all showed a greater incidence of darkening in tubers, greater than 350 grams when compared to tubers in the 80-350 grams size range (Table 29). The mean ACD index for all tuber samples represented in Figure 22 was 210 in comparison to a mean value of 250 for all tubers greater than 350gm from the same samples.

Table 29 - Mean ACD index for cv Kennebec tubers 80-350gm and greater than 350gm from four crop monitoring sites in the Mt Lofty Ranges.

SITE	TUBER SIZE	
	80 - 350 gm	> 350 gm
(i)	192	244
(ii)	241	280
(iii)	244	265
(iv)	210	229
MEAN	222	255

4.10 Storage

Analysis of the crop survey data for various combinations of cultivars and growing regions showed that ACD indices increased during the first 3 months of storage (Table 30). For the Mundulla region, analysis of the combined data for the cvv. Atlantic and Kennebec showed a significant increase in ACD during the 3 to 6 month storage period (Table 30). This trend occurred with other combinations but was not significant. There was no significant difference in the degree of ACD between storage at 12 ± 0.5°C and storage in an uninsulated shed in the Mt. Lofty Ranges. Tuber temperatures in the shed were initially (March) 16 - 18°C, decreasing slowly to near 9°C in late July, and then increasing to reach 16 - 20°C at the completion of the 6 months storage period (October).

Table 30 - Effect of storage on ACD indices for the cvv. Kennebec and Atlantic grown in the Mundulla and Mt. Lofty Ranges regions.

TREATMENT	ALL SITES	MLR(1) ONLY	MUN(2) ONLY	KEN(3) ONLY	ATL(4) ONLY
At harvest	184	204	84	187	148
3 Mths storage					
- 12°C	224	242	117	233	169
- Shed(5)	221	242	104	226	182
6 Mths storage					
- 12°C	233	256	150	245	168
- Shed	232	251	168	241	162
No. of Samples	83-91	68-76	9	60-68	11
Mean	218	239	125	226	166
LSD (5%) (6)	21.8	17.5	55.4	24.8	ns(7)

(1) MLR = Mt Lofty Ranges, cvv. Atlantic & Kennebec combined
(2) MUN = Mundulla, cvv. Atlantic & Kennebec combined
(3) KEN = cv. Kennebec, all sites
(4) ATL = cv. Atlantic, all sites
(5) SHED = Storage in uninsulated shed in the Mt Lofty Ranges
(6) LSD (5%) = Least significant difference at the 5% level
(7) ns = Not significantly different

Hasegawa (1965) reported that cold storage (4.5°C) caused a significant increase in the concentration of chlorogenic acid in the tuber, whereas there was no increase at 15.5°C. As chlorogenic acid is one of the compounds responsible for ACD in potatoes, storage at low temperatures may influence the degree of ACD. In our study, there were no significant differences in the degree of ACD between the 2 storage systems (Table 30). This may be due to the temperatures in both regimes not being low enough to effect chlorogenic acid synthesis. However, tubers stored in uninsulated sheds in the Mt. Lofty Ranges during cold seasons may be exposed to temperatures below those recorded in the survey and hence show an increased degree of ACD.

Growers storing tubers on farm should consider controlled temperature storage systems to avoid the adverse effects of low temperatures on crisp colour and the potential effects on ACD.

In some seasons, growers will delay the harvesting of potato crops till well after haulm senescence. This is in effect `in ground' storage of the tubers and is likely to influence the incidence of ACD. Observations during crop monitoring suggests that there is often increased darkening associated with this practice.

6. ACKNOWLEDGEMENTS

The following groups and personnel are acknowledged for their assistance and support in this project:

- Potato growers throughout the Mt. Lofty Ranges, Mundulla and Lower Murray regions for cooperation in the sampling of crops and supply of tubers for testing and storage.
- Processing sub-committee of Potato Growers of South Australia for the provision of funds for operating expenses and the employment of casual labour.
- Horticulture Research and Development Corporation for funding the later part of this research project.
- Ms A. Frensham for advice on statistical analysis and for principal component analysis of the data.
- Mr M. Butt, Mrs Janice Cecil for collection of samples, assistance with post harvest testing and storage, computer data collation and analysis and the preparation of tables and graphs for this report.
- Ms K. Sellar for assistance with the post harvest testing.

7. REFERENCES

Evans, J.L. (1973). A review of NIAB studies on after cooking blackening in potatoes. *Journal of the National Institute of Agricultural Botany* **13** : 9-20.

Hasegawa, S. (1965). Studies on chlorogenic acid in potatoes : Effects of cold storage on changes in it's content and in it's inhibitory action on phosphorylase. Ph.D. Thesis, Ohio State University 1965.

Hughes, J.C. and Evans, J.L. (1967). Studies on aftercooking blackening in potatoes. IV. Field experiments. *European Potato Journal* **10** : 16-36.

Lujan, L. and Smith, O. (1964). Potato quality XXV. Specific gravity and aftercooking darkening of Katahdin potatoes as influenzed by fertilizers. *American Potato Journal* **41** : 274-78.

Maier, N.A., Heap, M., Butt, M., Mclaughlin, M.J. and Smart, M. (1995). Development of crop management strategies for improved productivity and quality of potatoes grown on highly acid soils. HRDC Project PT428, Final Report, South Australian Research and Development Institute.

Smith, O. and Muneta, P. (1954). Potato quality. VIII. Effect of foliar applications of sequestering and chelating agents on after cooking darkening. *American Potato Journal* **31** : 404 - 410.

Smith, O. and Nash, L.B. (1940). Potato quality. I. Relation of fertilizers and rotation systems to specific gravity and cooking quality. *American Potato Journal* 17 : 163-169.

Smith, O. and Nash, L.B. (1941). Potato quality III. Relation of soil reaction, irrigation and mineral nutrition to cooking quality. *Proceedings of the American Society of Horticultural Science* **38** : 507-12.