HORTICULTURAL RESEARCH & DEVELOPMENT CORPORATION

The Research Arm of the Australian Horticultural Industries

Development and calibration of plant tests for nitrogen and potassium for brussel sprouts for sustainable nutrient management in Australia

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VG207

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Dr Chris Williams
South Australian R&D Institute

FINAL REPORT

VG207

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FINAL REPORT

HRDC PROJECT NO. VG207

DEVELOPMENT AND CALIBRATION OF PLANT TESTS FOR NITROGEN AND POTASSIUM FOR BRUSSELS SPROUTS FOR SUSTAINABLE NUTRIENT MANAGEMENT IN AUSTRALIA

Project Co-ordinator
Dr Chris Williams

South Australian Research And Development Institute

Lenswood Centre, Lenswood
South Australia

February 1996

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for
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Funded by
Horticultural Research And Development Corporation
And
Brussels Sprouts Section Of The South Australian Farmers Federation
and the
South Australian Research And Development Institute

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SUMMARY

1.1 Industry Summary

Little information existed on nutrient needs, plant tests and critical nutrient ranges (CNR) or 'target levels' for nitrogen (N) and potassium (K) in plant tests for maximum yield and quality for Brussels sprouts crops grown in Australia. Access to calibrated plant tests are particularly important in order to maximise yield and quality and yet minimise nutrient loads in runoff in all regions especially when Brussels sprouts crops are grown in sensitive water catchment regions.

A project funded by the **Horticultural Research and Development Corporation** (HRDC), **the Brussels Sprouts Group of the South Australian Farmers Federation** and the **South Australian Research and Development Institute** was conducted between July 1992 to June 1994 to assess the effects of nitrogen (N) and potassium (K) on the yield and quality of irrigated Brussels sprouts. A second objective was to develop and calibrate plant tests for N and K for improved and sustainable nutrient management of Brussels sprouts.

Responses to applied N by **the early season cultivar Oliver were inconsistent as rates of applied N of 0 and 383 kg N/ha** were required for 95% of maximum yield over the 9 month cropping period, at 2 sites. The requirement for fertiliser N was consistent for **the mid season cultivar Roger and was 319 and 377 kg N/ha for 95% maximum yield at the 2 sites**. At responsive sites, **N rates required to maximise total yield, also produced an increased size distribution of sprouts and were not detrimental to quality** (including a small increase in sprout colour at one of 2 sites tested).

Total yield, size grades and sprout colour were not affected by applied K. This indicated that the **soil test values for Colwell K of 140-260 mg/kg were adequate for maximum production on these soils.** We estimate that dried petiole K concentrations of 5-6% K at 8 weeks after transplanting and 1-2% K at 28 weeks after trasplanting are likely to be adequate.

Based on sensitivity and the ability to predict yield response across sites we found that **total-N was a better indicator than nitrate-N and the preferred indicator of plant N status, yield response and critical concentrations ("target levels" for maximum yield)** for Brussels sprouts crops grown in southern Australia. Critical nutrient values for total-N in dried petioles progressively **decreased from 3.13-3.44% at 10 weeks after transplanting to 1.22-1.38% at 28 weeks after transplanting.** We stress the need to sample the correct plant part and to specify sampling time for correct interpretation of results. **The petiole of the youngest fully expanded leaf (P-YFEL) was used.** Also, **crops should be sampled several times during the growing season (e.g. 10-12, 16, 20 and 24 weeks after transplanting) to detect intermittent N deficiencies. Use of this calibrated total-N test will assist growers in monitoring and adjusting their fertiliser programs and in developing sustainable nutrient management strategies for Brussels sprouts crops grown in water catchment areas and other districts.** We also concluded that nitrate assessed by any method (traditional laboratory or rapid sap tests) was too insensitive to either predict yield response to applied N or the nutrient status of Brussels sprouts. This should lead to a **greater use of analyses for total-N in dried petioles as the preferred index of the N status of irrigated Brussels sprouts and provide growers and consultants with the tools to apply just enough N to meet crop needs for maximum yield and quality in terms of plant nutrition and to minimise nutrient losses in runoff.**

1.2 Technical summary

A project funded by the **Horticultural Research and Development Corporation** (HRDC), **the Brussels Sprouts Group of the South Australian Farmers Federation** and the **South Australian Research and Development Institute** was conducted between July 1992 to June 1994 to assess the effects of nitrogen (N) and potassium (K) on the yield and quality of irrigated Brussels sprouts. **The specific objectives of the study were** to (i) assess the N and K requirements of Brussels sprouts for maximum yield and quality; (ii) to compare and determine if the laboratory tests on dried petioles and/or rapid sap tests have potential as tools to monitor the N or K status, predict yield response and derive critical concentrations or "target levels" for maximum yields. A subsidiary student project was conducted to assess the effects of potassium sulfate application on sprout bitterness.

At responsive sites, N rates required for 95% of maximum total yield were 0 and 383 kg N/ha for the early season cultivar Oliver and 319 and 377 kg N/ha for the mid season cultivar Roger), also produced an increased size distribution of sprouts and were not detrimental to quality, including a small increase in sprout colour at one of 2 sites tested.

Applied K did not affect total yield, size grades nor sprout colour. Soil test values for Colwell K of 140-260 mg/kg were adequate for maximum production on these soils. We stress the need **to sample the correct plant part and to specify sampling time** for correct interpretation of results. **The petiole of the youngest fully expanded leaf (P-YFEL) was used. We estimated that petiole K concentrations of 5-6% K at 8 weeks after transplanting and 1-2 %K at 28 weeks after transplanting are likely to be adequate.** At site 1, **thiocyanate concentrations and associated bitter taste in sprouts increased significantly as the rate of applied potassium sulfate increased.** Whereas at site 2 the effect was not significant. The differences between sites may have been due to **different amounts of sulfate based fertilisers being applied in previous years.** This finding, if substantiated in more extensive experiments, could have management implications for growers when they are selecting sites and fertilisers to produce milder flavoured sprouts. **Total-N was a better indicator than nitrate-N and the preferred indicator of plant N status; yield response and critical nutrient ranges for maximum yield** for Brussels sprouts crops grown in southern Australia. Critical nutrient ranges for total-N in dried petioles (P-YFEL) progressively **decreased from 3.13-3.44% at 10 weeks after transplanting to 1.22 - 1.38% at 28 weeks after transplanting.** Hence, crops should be sampled several times during the growing season, e.g. 10-12, 16, 20 and 24 weeks after transplanting to detect intermittent N deficiencies.

We also concluded that nitrate assessed by any method (laboratory or rapid sap tests) was too insensitive to either predict yield response to applied N or the **nutrient status of Brussels sprouts. This should lead to a greater use of analyses for total-N in dried petioles as the preferred index of the N status and in developing sustainable nutrient managment strategies for irrigated Brussels sprouts.** A new project application may be submitted in 1997. This would include many of the findings of this project VG 207 included **in information packages and decision support software for growers and technical staff.**

1.3 Publication schedule and extension/adoption by industry

Aspects of this work have been and will continue to be presented to industry and to the research community in; field days and handouts, grower meetings, industry articles, grower articles, seminars, final report and scientific papers. Examples of some of these are listed below.

Field days

"Brussels sprouts plant nutrition and taste field morning"

Samwell farm trial site, 10-12 am, March 24, 1993.

"Brussels sprouts field trial inspection meeting"

Cranwell farm trial site, 10-12 am, July 29, 1993.

Industry articles

"Growers fund nutrition research and development"

Good Fruit and Vegetables, September 1993, page 24.

"Discovering why sprouts taste bitter"

Good Fruit and Vegetables, September 1993, page 26.

"Adelaide Hills alive with the growing of sprouts"

by Tony Biggs (1993). Good Fruit and Vegetables, September, 1993, page 30.

Scientific papers

Papers contained in Appendices 1, 2 and 3 (as described below) will be submitted to scientific journals for publication.

Williams, C.M.J., Maier, N.A., Potter, M.J. and Collins, G.G. Effect of nitrogen and potassium on the yield and quality of irrigated Brussels sprouts (Brassica oleracea L. var. gemmifera) cvv. Roger and Oliver grown in southern Australia. This is to be submitted to the *Australian Journal of Experimental Agriculture.*

Williams, C.M.J. and Maier, N.A. Assessment of the nitrogen and potassium status of irrigated Brussels sprouts (*Brassica oleracea* L. var. *gemmifera*) by plant analysis. This is to be submitted to the *Australian Journal of Experimental Agriculture.*

Williams, C.M.J. and Maier, N.A. Evaluation of rapid sap tests for nitrate and potassium for assessing the nitrogen and potassium status of irrigated Brussels sprouts (*Brassica oleracea* L. var. *gemmifera*) crops in southern Australia. This is to be submitted to a scientific journal.

Facilitate adoption by industry

Complimentary copies of this report will be distributed via Mr John Cranwell, Chairman of the SA Brussels Sprouts Section, SA Farmers Federation to each SA grower who contributed to the voluntary levy.

Many of the findings of this project VG 207 could be included together with interstate and overseas information on plant nutrition in information packages and decision support software for growers and technical staff, as part of a new project application that is likely to be submitted in 1997.

Figure A attached from Appendix 2 illustrates important aspects of graphical presentation of the data for growers to access critical levels. They can compare nutrient concentrations in their current crops with critical concentrations for optimum yield as shown in Figure A.

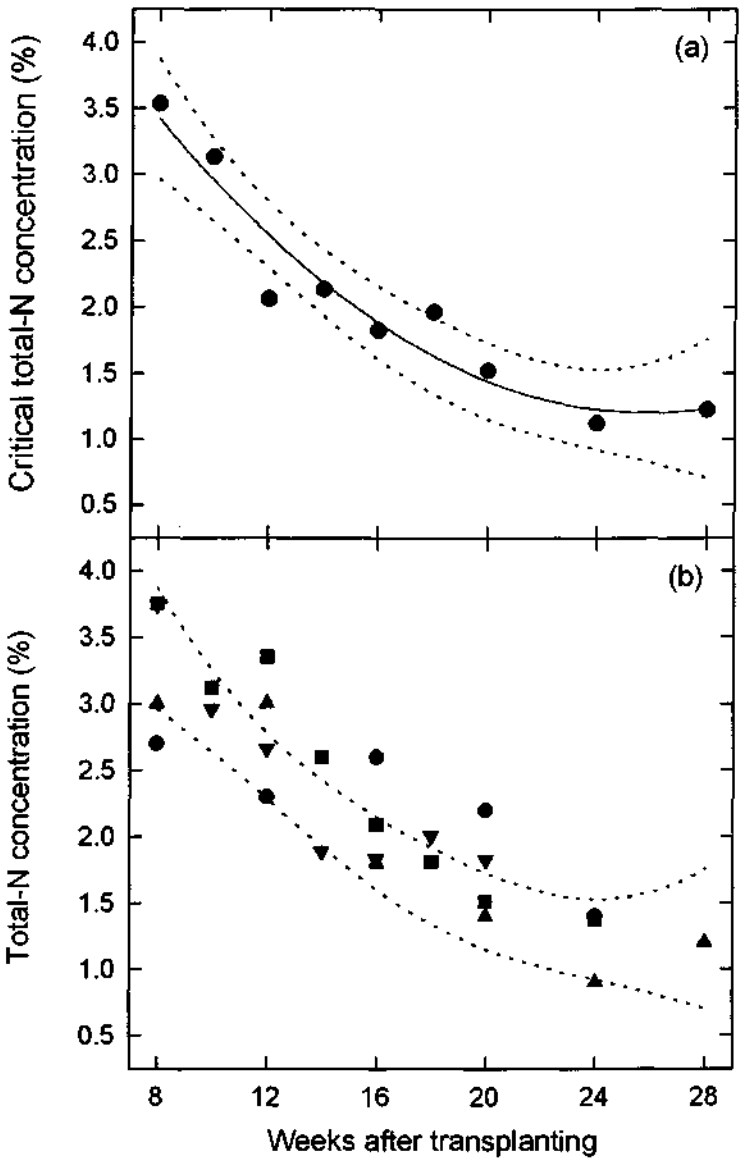

Figure A . Relationships between critical total-N concentration in dried petioles at 90% of maximum relative total yield and sampling time for (a) data pooled over all 4 experimental sites (●). The equation for the fitted curve is:

$$Y = 5.84 - 0.36X + 0.0069X^2 \quad (r^2 = 0.92, P < 0.001)$$

For (b) the relationship between total-N concentration and time of sampling for the growers commercial crops at each site. Sites were: 1 (●), 2 (▲), 3 (■) and 4 (▼). Dotted curves indicate the 95% confidence interval for the critical concentration for 90% of maximum relative total yield.

1.4 Directions For Future Research

Many of the major research findings of this project for N and K (see Appendices) should be integrated with other plant nutrition information in information packages and decision support software for Brussels sprouts growers and technical staff. Information on critical concentrations of other nutrients from interstate and overseas work and basic concepts of plant nutrition would be included in the decision support software proposed. The Horticultural Sections of Primary Industries (South Australia), PISA and SARDI have recently developed extension packages that apply the latest technology to growers properties. These packages have been largely based on the use of soil and plant analyses. **They have been extremely successful in transferring improved technology to growers.**

The packages include attractive and simple displays of information to growers eg. colour bar graphs of crop nutrient concentrations comparable to known standards or " target levels" and interpretation with a good " hands on" extension specialist dealing one on one with growers. This service is paid for on a fee for services basis.

A similar concept could be used for Brussels sprouts crops. An example of these technology transfer packages is the highly successful SE Potato Crop Management Service and SARDI development packages for nutrient management in potato crops in the current HRDC project PT 428. This, plus the fact that SA is the largest sprout producing state means that we in SA are well placed to develop nutrient management packages with back-up extension services to service Brussels sprouts growers across Australia from a cental office in SA. A new project application on the above is likely to be submitted to HRDC in 1997.

The efficiency of nitrogen uptake by Brussels spouts needs to be identified, particularly during the winter months so that this phenomenon can be identified and appropriate techniques developed for such situations so that N losses in runoff can be minimised. This is particularly important when Brussels sprouts crops are grown in or near to sensitive, water catchment regions.

Acknowledgements

We thank Kate Frost, Janice Cecil, Belinda Brant, David Buttrose and Louise Chvyl for capable assistance with field and laboratory work; officers of the Chemistry Division for laboratory nutrient analyses and to colleagues for useful comments during the course of this study. The Horticultural Research and Development Corporation and the Brussels Sprouts Section of the South Australian Farmers Federation are also thanked for their financial support and encouragement. Special thanks to those growers on whose land and crops these experiments were conducted and to Karen Hewett and Belinda Brant for typing parts of the final manuscript.

The enthusiastic help of Mr. John Cranwell (Chairman of the Brussels Sprouts Section, SAFF) and other industry leaders was invaluable both in the design and conduct of these experiments and for providing experienced labour to assist in the hand harvests of crops.

2. Technical Report

The research results are presented in 4 Appendices that follow which include the drafts for three scientific papers.

Appendix 1

Effect of nitrogen and potassium on the yield and quality of irrigated Brussels sprouts (*Brassica oleracea* L. var. *gemmifera*) cvv. Roger and Oliver grown in southern Australia.

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Short Title: Nitrogen and potassium nutrition of Brussels sprouts

Summary. This study was conducted to assess the effects of nitrogen (N) and potassium (K) on the yield and grade size distribution of Brussels sprouts, cultivars Oliver and Roger (early and mid season types, respectively) grown with sprinkler irrigation in southern Australia. The yields of swollen axillary buds or Brussels sprouts (hereafter referred to as sprouts) were assessed over 4-7 harvests depending on site. Five rates of N (0, 125, 250, 375, 600 kg/ha) with 3 rates of K (0, 150, 300 kg/ha) were applied over 8 side-dressings during the 9 month cropping period in randomised block experiments. Four experiments were conducted during 1992/93 (sites 1 and 2) and 1993/94 (sites 3 and 4) on silty loam, loam and sandy loam soils. The experiments were located in commercial plantings in the Mount Lofty Ranges. The effect of N and K on sprout colour was determined at sites 3 and 4. The effect of applied potassium sulfate on thiocyanate concentrations in sprouts and on the bitterness of sprouts, was determined at sites 1 and 2.

In 3 of the 4 experiments applied N significantly ($P<0.001$) increased the total yield of sprouts harvested. Yield increases due to applied N ranged from 51 to 78%. At site 1, there was no yield response to increasing N rates. Responses to N by the early season cultivar Oliver were inconsistent as rates of applied N of 0 and 383 kg N/ha were required for 95% of maximum yield, at sites 1 and 3, respectively. For the mid season cultivar Roger, 319 and 377 kg N/ha were required for 95% maximum yield at sites 2 and 4, respectively.

At responsive sites, the application of N significantly increased both the yield of sprouts at most individual harvests, and the yield within desirable size grades (20-<30 g and 30-<40 g) of

sprouts, and did not adversely affect the yield of >40 g sprouts. The effect of applied N on sprout colour was inconsistent. At site 4 the application of N significantly ($P<0.001$) increased the mean colour rating of sprouts, in contrast at site 3 the effect was not significant ($P\geq0.05$). At both sites, mean colour ratings decreased during the harvest period irrespective of N applied. The later harvests occurred during winter and were therefore associated with lower temperatures.

Total yield, size and colour of sprouts were not significantly ($P\geq0.05$) affected by rate of applied K. We suggest that extractable K concentrations in the range 140-260 mg/kg in the surface (0-15 cm) soil were adequate at these sites.

At site 1, thiocyanate concentrations in sprouts and sprout bitterness increased significantly ($P<0.05$) as the rate of applied potassium sulfate (K_2SO_4) increased. At site 2, the effect was not significant ($P\geq0.05$), however this site had received higher rates of sulfate based fertilisers in previous years. This finding suggests that application of high rates of sulfate based fertilisers to sprouts should be avoided to ensure bitterness does not adversely affect the marketability of sprouts.

Introduction

Brussels sprouts are grown commercially for their swollen axillary buds which are used as a vegetable throughout the world. Good quality sprouts are firm, dark green and mild to sweet in taste (Bartha 1979). They also contain high levels of essential vitamins and minerals (Rick 1978). In addition, isothiocyanates are produced within sprout tissue and recent studies have shown this class of molecules to induce the activity of natural enzymes in mammals thought to be responsible for the inhibition of carcinogenesis (Zhang *et al.* 1992). Aside from the dietary and nutritional benefits of sprouts, the crop has several production advantages. In Australia, sprouts are produced for at least 9 months of the year (from late December until September) therefore ensuring a supply of fresh produce to local, interstate and international markets (Biggs 1993).

The Mt. Lofty Ranges of South Australia (SA) is the major region for Brussels sprouts production in Australia (Biggs 1993). This region produced 81.4% of the South Australian crop which represented 43% of the 5,903 tonne Australian crop in 1993/94 (Australian Bureau of Statistics 1995). Average yields of sprouts in 1993/94 were 23.6 and 17.7 t/ha for South Australia and Australia, respectively (Australian Bureau of Statistics 1995). The climate of the Mount Lofty Ranges is Mediterranean type, with cool, wet winters and dry, warm summers (Donald and Allden 1959) and the cooler regions are ideal for the culture of sprouts (Rogers 1977). Continuity of sprout supply for the fresh market is based on the early season cultivar Oliver, which is harvested from late December to May, the mid season cv. Roger, which is harvested from late March to August; and the cv. Rasmunda, which is harvested from June to September, (Biggs 1993). Since 1993, Rasmunda has been replaced by Tavernos, Uniline and several other late season cultivars. Sprouts for the fresh market in Australia are hand harvested with crops usually being picked 4 to 7 times at 3 to 4 week intervals, starting about 3 months after transplanting and continuing until the end of winter.

In the Mt. Lofty Ranges, sprouts are usually grown in loamy sand to loam soils, in rotation with other vegetable crops or grazed pastures. In these situations, a survey of fertiliser use by sprout growers conducted in the summer of 1985, showed that growers used a wide range of strategies and rates of fertiliser (Robinson 1991). Nitrogen (N) applications for 13 sites in the Mt. Lofty Ranges ranged from 183-1877 kg/ha and potassium (K) from 13-616 kg/ha applied over 3 to 10 side-dressings. Robinson (1991) concluded that growers were not using the crop nutrient management tools (soil and plant analysis) available to them to assist in decision making on fertiliser applications. Furthermore, he found that N applied at a rate of 44 kg/ha/month over 8 months produced maximum sprout yields, and double this rate had no added benefits. Recently, SA growers have expressed on

interest in the use of soil and plant tests to assist in their fertiliser decision making. However, they have been hampered by both limited local research work on the effects of nutrient levels on sprout yield and quality and by a lack of calibrated soil and plant tests (Cranwell, pers. comm.). There is also a need to define sustainable nutrient management strategies for use in important water catchment areas such as the Mt. Lofty Ranges.

LeMay (1979) recommended total fertiliser rates of from nil to 300 kg of N and 250 kg of K/ha be applied to machine or hand picked sprouts grown in England. He used a N index based on the last crop grown to assist in making decisions on N rates to apply. If the previous crop was a vegetable or cereal he recommended that the highest rate be used. Kolota and Dobroilska (1991) recommended similar rates of fertilisers for sprouts grown in Poland. Booij *et al.* (1994) suggested rates of N greater than 300 kg/ha were still profitable to apply to sprouts. Work conducted in California by Welch *et al.* (1970), showed that sprouts removed large amounts of nutrients over the harvest period. For example, a 50 t/ha yield of sprouts removed 250 kg N, 33 kg P and 200 kg K/ha.

We are not aware of any published studies in Australia on the effects of N or K on the yield and quality of different cultivars of sprouts. Overseas studies have reported that applied N increased, (a) yield (Scaife and Turner 1987; Booij *et al.* 1994), (b) the green colour of the sprouts (North *et al.* 1965), (c) the incidence of loose sprouts (open rosette-like sprouts which are unsaleable), (Kolota and Dobromilska 1991; Nieuwhof 1969) and (d) bitterness (Scaife and Turner 1985). The application of N has also been reported to decrease reducing sugar content (Sciazko *et al.* 1990) and the firmness of sprouts (North *et al.* 1965; Scaife and Turner 1985). Rates of N did not cause significant differences in mean sprout size or in the percentage of sprouts with internal browning (North *et al.* 1965). Nieuwhof (1969), based on grower experience, reported that applied K improved the colour and firmness of sprouts.

Potassium sulfate (K_2SO_4) is a major source of K. Sulfate has been shown in studies to also effect sprout quality. For example, MacLeod and Pikk (1978 1979) reported that a reduction in extractable soil sulfate significantly reduced the concentration of glucosinolates and thiocyanates in sprouts. These compounds are the main chemicals associated with bitterness in Brussels sprouts (Fenwick *et al.* 1983).

The experiments reported here were designed to define N and K rates and their effects on the yield and quality of Brussels sprouts, cultivars Oliver and Roger grown in southern Australia.

Materials and methods

Field experiments

Four field experiments were conducted during 1992/93 and 1993/94 seasons within commercial crops grown in the Mt. Lofty Ranges. Details of location, transplanting dates and harvest dates are shown Table 1. Some chemical and physical properties of the soils at each site are presented in Table 2.

Table 1. Description of experiment sites and management practices

Site	Cultivar	Location	Date of transplant	Period for 8 side-dressings	Harvest period	Number of picks
1	Oliver	Mt Barker	30 Oct.92	1.xii.92 - 28.iv.93	27.i.93 - 27.v.93	4
2	Roger	Nairne	3 Dec.92	21.xii.92 - 9.viii.93	14.iv.93 - 9.viii.93	5
3	Oliver	Lobethal	18 Oct.93	2.xi.93 - 4.v.94	7.ii.94 - 8.vi.94	7
4	Roger	Nairne	4 Dec.93	4.i.94 - 25.v.94	19.iv.94 - 27.vii.94	4

The experimental design was a randomised block with 4 replicates at each site. The rates of N and K applied and their application strategies are presented in Table 3. At all sites, 60 -150 kg of P/ha, as superphosphate, and trace elements were applied as a basal dressing before transplanting by the growers. The rates applied varied according to soil test values.

Table 2. Chemical and physical properties of the soil at each site

Nutrients analysed as described by Maier *et al.* (1995).

Depth (cm)	pH	EC (mS/cm)	Extractable nutrients (mg/kg)						Organic C (%)	Total N (%)	Sand (%)	Silt (%)	Clay (%)
			P	K	Cu	Zn	Mn	Fe					
Site 1													
0-15	5.6	0.34	29	230	1.4	1.2	38.0	180.0	1.8	0.15	73	13	14
15-30	5.9	0.34	30	130	1.0	0.8	18.0	130.0	1.5	0.13	74	12	14
30-45	6.6	0.39	7	190	0.6	0.1	2.9	20.0	0.6	0.06	39	11	50
45-60	6.7	0.29	2	190	0.3	0.1	0.8	9.0	0.3	0.05	36	13	51
60-75	6.8	0.25	2	340	0.3	0.1	0.4	8.3	0.2	0.04	42	12	46
75-90	6.6	0.21	6	440	0.4	0.2	3.8	25.0	0.4	0.09	59	14	27
90-100	6.4	0.25	4	160	0.5	0.3	2.7	18.0	0.3	0.04	44	16	40
Site 2													
0-15	5.1	0.13	33	160	0.9	5.1	6.4	200.0	1.9	0.15	68	21	11
15-30	4.9	0.08	8	120	0.7	6.7	11.0	160.0	1.2	0.10	66	22	12
30-45	5.4	0.05	4	90	0.3	1.1	4.2	85.0	0.6	0.04	67	20	13
45-60	6.1	0.08	2	190	0.5	0.3	0.8	16.0	0.4	0.05	42	11	47
60-75	6.9	0.06	2	230	0.4	0.1	0.9	4.9	0.3	0.04	45	10	45
75-90	6.9	0.08	3	210	0.5	0.2	1.6	24.0	0.5	0.05	60	8	32
90-100	7.3	0.06	2	220	0.4	0.2	1.5	13.0	0.3	0.03	62	9	29
Site 3													
0-15	6.6	0.16	63	140	0.9	1.5	1.9	85.0	1.0	0.10	68	26	6
15-30	6.0	0.17	61	110	0.9	1.9	2.0	130.0	1.0	0.09	65	28	7
30-45	6.2	0.13	23	91	0.5	0.9	0.9	76.0	0.5	0.07	56	27	17
45-60	6.2	0.17	4	110	0.3	0.1	0.2	6.5	0.3	0.05	42	21	37
60-75	6.3	0.17	3	120	0.1	0.1	0.1	3.4	0.2	0.03	43	24	33
75-90	6.5	0.17	2	140	0.1	0.1	0.4	5.0	0.2	0.03	35	30	35
90-100	6.7	0.19	4	140	0.2	0.2	0.8	4.9	0.2	0.02	38	30	32
Site 4													
0-15	6.3	0.20	39	260	2.3	1.5	34.0	120.0	2.5	0.19	66	25	9
15-30	6.1	0.09	9	97	1.3	0.3	21.0	47.0	0.8	0.06	58	24	18
30-45	5.8	0.18	5	140	1.1	0.1	10.0	17.0	0.4	0.05	27	16	57
45-60	6.0	0.22	3	140	0.7	0.1	2.0	9.3	0.3	0.04	19	14	67
60-75	6.0	0.23	4	140	0.7	0.1	1.8	9.0	0.3	0.04	18	14	68
75-90	6.4	0.18	2	110	0.6	0.1	0.9	7.2	0.2	0.02	23	25	52
90-100	6.6	0.15	2	89	0.6	0.1	1.2	10.0	0.3	0.02	30	30	40

Table 3. Total rates (kg/ha) and amounts of N and K applied at each side-dressing 2 to 28 weeks after transplanting

N was applied as ammonium nitrate and K as potassium sulfate at side-dressings.

Treatment Code	Total rate applied (kg/ha)		Side-dressings (kg/ha) 2,4,8,20,24,28 weeks		12,16 weeks	
	N	K	N	K	N	K
N0	0	150	0	16.6	0	25.0
N1	125	150	13.9	16.6	20.8	25.0
N2	250	150	27.8	16.6	41.7	25.0
N3 (=K1)	375	150	41.7	16.6	62.5	25.0
N4	600	150	66.6	16.6	100.0	25.0
K0	375	0	41.7	0	62.5	0
K2	375	300	41.7	33.3	62.5	50.0

The field procedure at each site was as follows: (*i*) A uniform area of land into which Brussels sprouts seedlings (each 5-8 cm high with 4 to 8 leaves) had been transplanted, was selected. (*ii*) At sites 1, 2 and 4 there were 24 plants per plot and at site 3, there were only 12 plants. (*iii*) Depending on the site, seedlings were planted from 50-60 cm apart in double rows 60-70 cm apart and the space between pairs of double rows was 70-107 cm. (*iv*) The N and K were applied by hand to each plot over 8 side-dressings, from 2 to 28 weeks after transplanting (Table 3) and then irrigated into the soil. (*v*) At sites 1 and 2, immediately prior to the application of side dressings, 10-20 petioles of the youngest fully expanded leaves (P-YFEL) from each plot of the nil and 723 kg/ha potassium sulfate treatments were collected at harvest 3 and 4 for sulfur (S) analysis. Other plant data will be presented in the second paper in this series (Williams and Maier unpublished data). (*vi*) Sprouts from each plot were hand harvested by experienced pickers 4 to 7 times depending, on the site (Table 1). At each harvest, the total yield of sprouts was recorded for each plot and a 2 kg sample was collected for laboratory measurements. At sites 1 and 2, selected plants adjacent to the experimental area (hereafter termed the growers plots) were also sampled for petiole S analysis and yield.

Cultivation, pest and disease management, and irrigation were carried out by the growers. All crops were sprinkler irrigated, receiving 10-30 mm every 7 to 10 days in summer and up to 10 mm every 14 days in winter, depending on weather conditions.

Laboratory measurements

The 2 kg sample of sprouts from each plot was size graded and the yields of <10, 10-<20, 20-<30, 30-<40, and >40 g sprouts were determined. Sprout colour was assessed by visually rating the colour of each sprout on a scale from 1 (light green) to 3 (dark green). The Australian market prefers dark green, shiny sprouts.

From sites 1 and 2, the samples of sprouts from the nil and 300 kg/ha K treatment, and the growers plots, were presented to a 5 person taste panel to assess bitterness. Sprouts were cooked in a microwave for 45 seconds, until they had begun to soften. Each sprout was cut longitudinally and each half was then cut into 4 pieces. The pieces were presented to taste panel and were ranked on a scale 1 (least) to 3 (most) bitter (Potter 1993).

Analytical methods

The soil samples collected to characterise the sites were air-dried and ground to < 2 mm before chemical analysis. The soils were analysed for total N using a modified Kjeldahl method, electrical conductivity (EC) and pH (in a 1:5 soil:water extract), extractable P and K, organic carbon and DTPA extractable trace elements (Maier *et al.* 1994). Petiole samples were dried at 65°C and ground to <1 mm and analysed for S (Potter 1993). Thiocyanate concentration was measured by colorimetric analysis (Josefsson 1968) as modified by Potter (1993).

Statistical methods

Linear and quadratic functions were used to investigate the relationships between rate of applied N and total yield of sprouts. Single factor analysis of variance was used to determine the effects of rate of applied N and K on total yield and the yield of sprouts in each size grade. Factorial analysis was used to determine the effect of N and K, and harvest, on sprout colour and yield.

The results of taste panel tests for sprout bitterness were analysed by Friedman's non-parametric test and compared against a Chi-squared distribution (Meilgaard *et al.* 1987).

Results and discussion

Soil chemical and physical properties

Soil acidity of the surface (0-15 cm) soils ranged from highly acid at site 2, moderately acidic at sites 1 and 4 and near neutral at site 3 (Table 1). The ideal soil pH for sprouts was suggested to be 6-6.5 (Bartha 1979). The mean total yield in kg/plant (t/ha) of sprouts was 2.50 (48.5); 1.87 (38.0); 2.39 (47.8) and 2.15 (43.7) at sites 1, 2, 3 and 4, respectively. We therefore suggest that the Brussels sprouts cultivars grown were tolerant of high to moderate soil acidity because they produced high yields, which were well above the Australian average yield of 17.7 t/ha, ABS 1995. Electrical conductivity (EC) values ranged from 0.08-0.39 mS/cm (Table 1), showing that soil salinity was low at all sites and not likely to limit yield.

We are not aware of any published critical concentrations for soil P and K for Brussels sprouts. For other vegetable crops, Maier and Robinson (1986) classified soils as low in P if soil test values were ≤ 30 mg/kg and recommended 60 to 100 kg P/ha be applied. In our study, similar rates of P were applied before transplanting at all sites. Maier and Robinson (1986) also proposed that 150-250 mg/kg extractable K to be adequate for maximum yields of vegetables grown in these soil types similar to those occurring at our sites. This standard suggests that soils were marginal to adequate in residual K status.

For annual vegetable crops, Maier and Robinson (1986) classified soil fertility with regard to N on the basis of percentage organic carbon as low (<1%), large response to applied N, moderate (1-2%), response to applied N uncertain and high (>2%), no response to applied N. Using this system the top soils at sites 1, 2 and 3 would be classified as moderately infertile, with response to N uncertain. At site 4, the top soil would be classed as highly fertile. The subsoils below 30 cm were of low N fertility at all sites. The significant response which occurred at site 4 was not consistent with the classification proposed by Maier and Robinson (1986). However, many factors for example, soil temperature, soil moisture and cultural methods may influence the mineralisation and uptake of soil N over the 9 month cropping period of Brussels sprouts. Therefore, soil N and organic carbon should only be used as a general guide to N fertility (Williams and Maier 1990; Williams *et al.* in press).

Hannam (1985) presented data showing that for DTPA-extractable Cu, Zn, Mn and Fe, deficient concentrations in soils were 0.2, <0.5, <1.0 and <2.5 mg/kg respectively. Based on these interpretation standards, the concentrations of these micronutrients in the surface soils were not deficient (Table 1) and should not have limited yield response.

Yield response to applied nitrogen

Total yield. Rate of applied N significantly ($P<0.001$) increased the total yield of sprouts at sites 2, 3 and 4 (Figure 1). At site 1 the mean and range in yields were 2.50 (2.28-2.71) kg/plant and no significant yield response to applied N occurred. The relative yield increases in response to applied N ranged from 51-78% at these sites. Rates of applied N required for 95% of maximum total yield were 319, 383 and 377 kg N/ha at sites 2, 3 and 4, respectively. Nitrogen rates required for 100% of maximum total yield were in the range 500 - 620 kg N/ha applied over the 9 month cropping period. The requirement for fertiliser N was consistently high (319-377 kg N/ha) for the mid season cv. Roger which was harvested from April to August. Cool, wet conditions prevailed for much of this time which was likely to inhibit mineralisation of soil N reserves. Responses to applied N by the early season cv. Oliver were inconsistent, with 383 and 0 kg N/ha required for 95% of maximum yield at sites 3 and 1, respectively. Site 1 had been in permanant pasture for at least 10 years before being planted with Brussels sprouts. The seedlings were planted in mid spring 5-6 weeks earlier than cv. Roger and harvested over summer and autumn only. Organic carbon levels (Table 2) indicated moderate N fertility (Maier and Robinson 1986) and a greater degree of mineralisation of soil N reserves from pasture residues during spring and summer crop growth may have occurred and therefore, no response to applied N occurred.

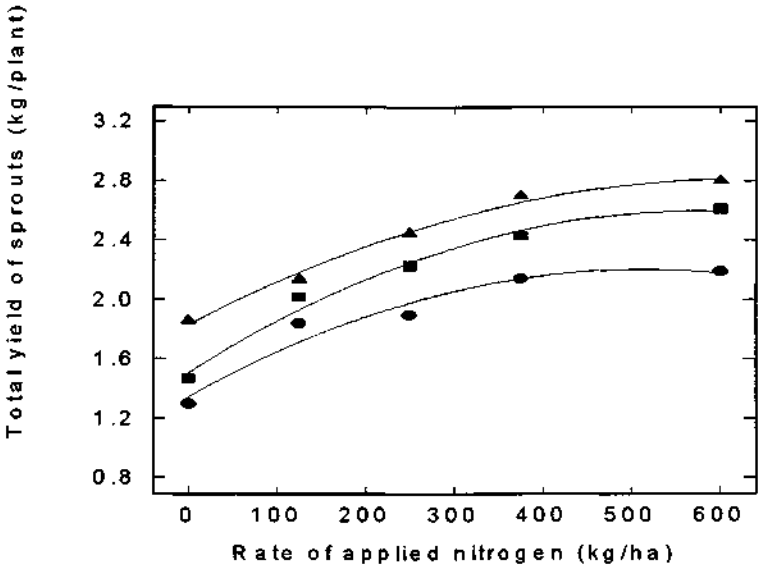

Figure 1. Relationships between rate of applied nitrogen and total yield of Brussels sprouts at (a) site 2(●), (b) site 3(▲) and (c) site 4(■).
The equations for the fitted lines are:
Site 2:
$Y=1.35 + 0.0033X - 0.0000033X^2$ ($r^2=0.95$, $P<0.001$)
Site 3:
$Y=1.83 + 0.0031X - 0.0000025X^2$ ($r^2=0.99$, $P<0.005$)
Site 4:
$Y=1.51 + 0.0038X - 0.0000033X^2$ ($r^2=0.99$, $P<0.001$)

Olsen and Lyons (1994) found rates of applied N to be different for autumn and spring sown capsicum crops. Potatoes grown in the Mount Lofty Ranges have also shown inconsistent responses to applied N. Williams and Maier (1990) reported from 0 to 162 kg N/ha were required for 95% maximum yield of potatoes at different sites. Such variable responses to applied N were associated with differences in duration of the pasture rotation, soil type, planting time and cultural factors.

A comparison of our results with rates used by growers in the survey reported by Robinson (1991) indicates that some growers applied inadequate N and others excessive N rates. The mean ± s.e.m. rate of N applied by growers was 772 ± 133 kg N/ha with rates ranging from a range 183-1877 kg N/ha. In our work, the highest rate of N applied was 600 kg N/ha. This rate produced total yields of sprouts that were not significantly ($P<0.05$) different from the 375 kg N/ha rate. In our experiments, 8 side-dressings applying a total of 320-400 kg N/ha, was sufficient to achieve high yields (38.0 to 48.5 t/ha). Overseas studies recommended 250-300 kg N/ha be applied to machine or hand-picked Brussels sprouts grown in England (LeMay 1979), Holland (Snoek 1984; Booij 1994) and to irrigated, hand-harvested crops in Poland (Kolota and Dobroilska 1991). Data reported by Kolota and Jablonska-Ceglarek (1977), suggested that in dry years the optimal N rate was 100 kg /ha and in wet years, or under irrigation with removal of the growing point mid-season (pinching), maximum yields were obtained with 300 kg N/ha. Clearly, irrigated and non-irrigated crops may require different N fertiliser strategies to optimise yield and quality.

Yields at each harvest. The main effects of N and harvest time on yields at each harvest were variable, but significant at sites 2, 3 and 4. Significant interactions between nitrogen and harvest time occurred at sites 2 and 4. At harvest 1, rate of applied N did not significantly ($P\geq0.05$) affect yield, whereas at later harvests, applied N significantly ($P<0.05$) increased yield, but such effects were variable (Figure 2). Our work indicates that N rates required for maximum total yield were also desirable to achieve maximum yields at harvests 2-5 for site 2 and 2-4 at site 4.

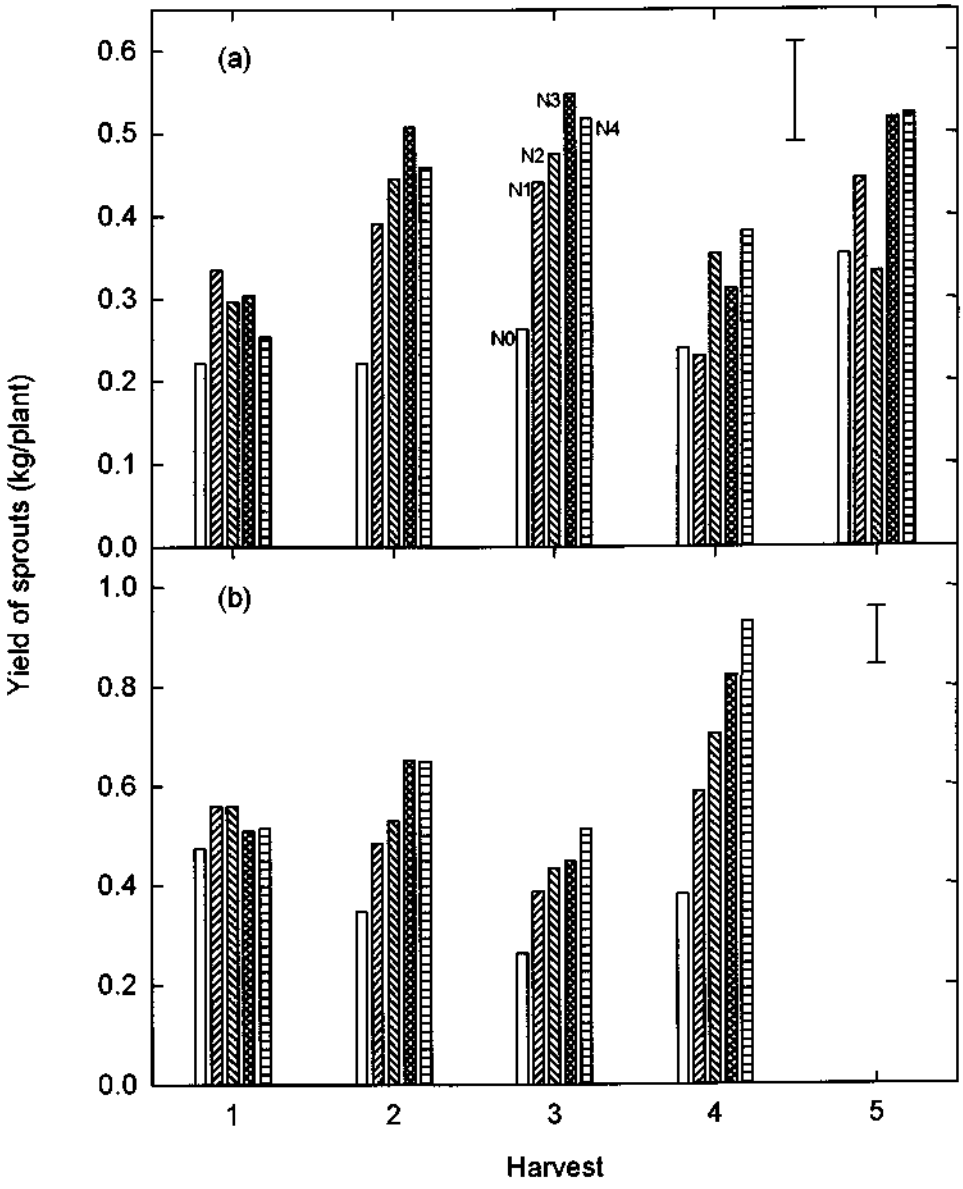

Figure 2. Effect of harvest and rate of applied nitrogen on the total yield of Brussels sprouts at (a) site 2 and (b) site 4. Vertical bars indicate l.s.d. at P=0.05.

Effects of applied N on the size distribution of sprouts

There were no grade standards for Brussels sprouts in Australia when our study commenced. Bartha (1979) suggested sprouts vary in individual weight from 20 to 40 g, and have leaves tightly packed. Therefore, we graded sprouts in 10g increments to cover the size range produced by the plants.

At site 2 application of N significantly ($P<0.001$) increased the yield of 20-<30 g sprouts by 40% (Figure 2). At sites 2 and 4, as the rate of applied N increased, the yield of 30-<40 g sprouts increased significantly ($P<0.001$) by 137 and 185%. At sites 2, 3 and 4 the yield of >40 g sprouts also increased (Figure 3). Application of N did not significantly ($P\geq0.05$) affect the yield of <10 g sprouts at any site and significantly ($P<0.001$) decreased the yield of 10-<20 g sprouts at site 4 by 33%. At site 1, applied N did not significantly affect the size of sprouts. The mean (range) yields were, <10 g, 0.04 (0.029-0.041); 10-<20, 0.40 (0.36-0.44); 20-<30 g, 0.89 (0.84-0.91); 30-<40 g, 0.73 (0.62-0.80) and >40 g, 0.45 (0.33-0.53) kg/plant. North *et al.* (1965) reported that although the application of N increased the total yield of sprouts, it did not significantly affect sprout size. Nitrogen rates required for 95% of maximum yield (319-383 kg/ha) optimised the yield of 20-<30 g and 30-<40 g sprouts (Figure 3), which are the preferred size range for marketing. Care should be taken to avoid application of rates of N above those recommended as this further increased the yield of oversize (>40 g) sprouts (Figure 3). In Britain, North *et al.* (1965) found that increasing amounts of N side-dressings increased the percentage of blown (open, loose or rosette) sprouts which are unsaleable.

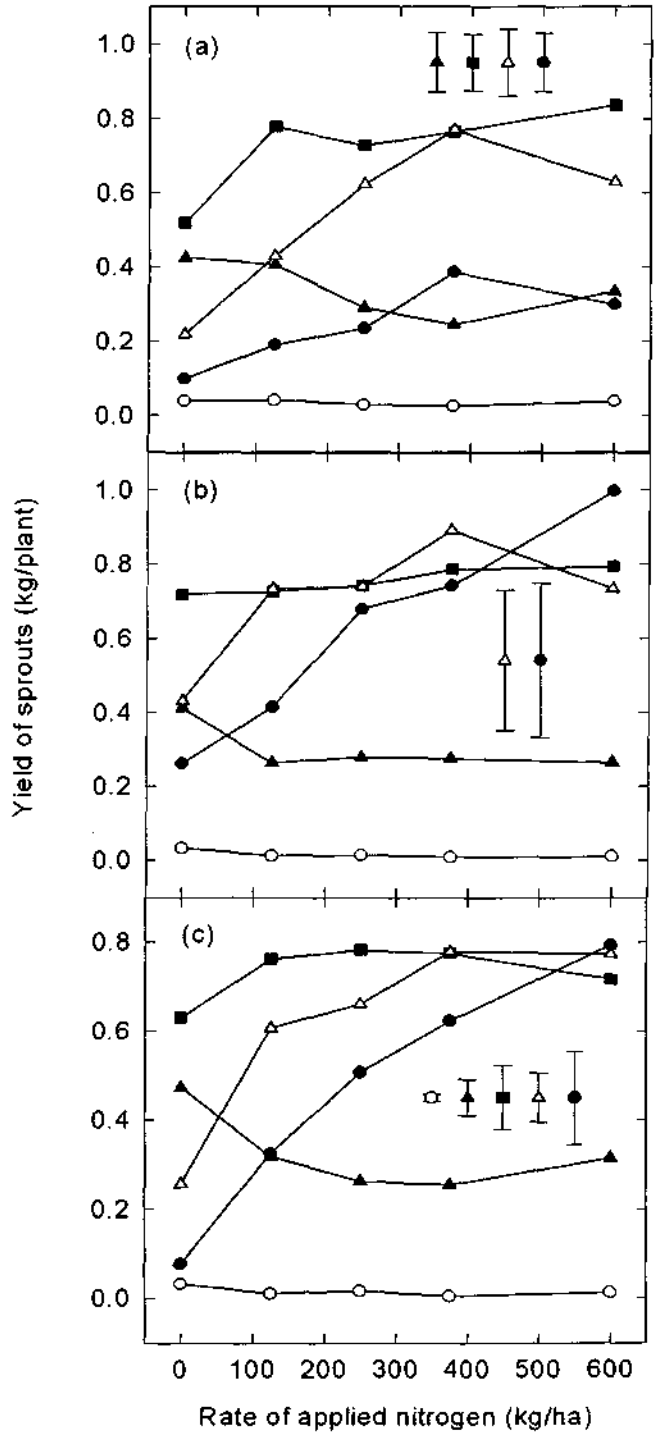

Figure 3. Effects of rate of applied nitrogen on the size (○, <10 g; ▲, 10-<20; ■, 20-<30 g; △, 30-<40 g and ●, >40 g) of Brussels sprouts at (a) site 2, (b) site 3 and (c) site 4. Vertical bars indicate l.s.d. at *P*=0.05.

Effect of applied N on sprout colour

Main effects Applied N significantly ($P<0.001$) increased the mean colour ratings of sprouts at site 4 but not at site 3. The mean ratings pooled across all harvests increased from 1.7 to 2.2 as N increased from nil to 600 kg N/ha. A major influence on sprout colour was harvest time. At both sites mean colour rating significantly ($P<0.05$) decreased with later harvests irrespective of the rate of N applied. We suggest that sprout colour became lighter with the onset of cold, wet growing conditions or with increasing plant age.

Interactions There was a significant interaction ($P<0.01$) between harvest and N rate at site 4 (Figure 4). The effect of N was inconsistent and varied between harvest times. Robinson (1991) reported discussions with grower industry leaders who suggested that high rates of N were necessary to achieve the intense dark green colour required by the market place in Australia. However, our results showed that once N nutrition is optimised, there was no significant improvement in sprout colour with higher rates of N. North *et al.* (1965) reported that applications of N improved the colour of sprouts, however the increases although measurable, were quite small. We conclude that for Brussels sprouts crops, application of N at rates required for 95% of maximum yield also resulted in acceptable sprout colour for a given harvest. For harvest during late autumn-winter, cold wet weather conditions may be a major factor affecting sprout colour and not N nutrition.

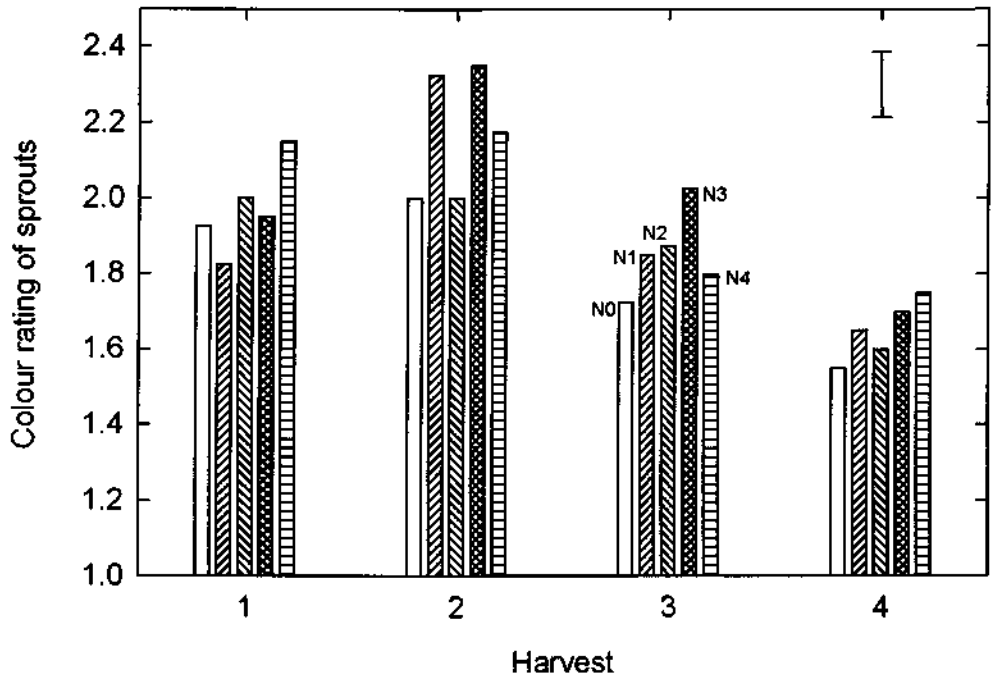

Figure 4. Effects of harvest and rate of applied nitrogen on the colour rating of Brussels sprouts. Vertical bar indicates l.s.d. at P=0.05.

Effect of applied K on the total yield, size and colour of sprouts

Application of K did not significantly ($P \geq 0.05$) affect the total yield or size of sprouts at any site. For example, at site 4, application of 0, 150 and 300 kg K/ha resulted in mean total yields of 1.96, 2.0 and 1.93 kg/plant, respectively. Also at site 4, the yield of <10 , 10-<20 , 20-<30 , 30-<40 and >40 g sprouts ranged from 0.004-0.008, 0.25-0.27, 0.77-0.87, 0.63-0.68 and 0.58-0.62 kg/plant, respectively.

Increasing rates of K did not significantly ($P \geq 0.05$) affect sprout colour. However, harvest time was again a significant factor and sprout colour ratings decreased significantly ($P < 0.05$) as the season progressed, presumably associated with the onset of cold wet weather and/or increased plant age. Nieuwhof (1969) cited that applied K had a beneficial effect on the colour and firmness of sprouts but presented no data to support the claim.

Bicarbonate extractable K concentration in the surface (0-15 cm) soils varied from 140-260 mg/kg and from 89-220 mg/kg at 100 cm depth (Table 1). The lack of yield responses to applied K suggests that residual soil K concentrations were adequate. Robinson (1991) also found that the application of up to 300 kg K/ha at a site with extractable soil K concentration of 228 mg/kg did not significantly affect sprout yield. Maier and Robinson (1986) also suggested soil K values of 150-250 mg/kg were adequate for maximum yield of vegetable crops in soils similar to those used in our study.

Bitterness of sprouts

As part of this study Potter (1993) examined the effects of K_2SO_4 applications on thiocyanate levels and the bitterness of sprouts. At site 1, there was a significant increase in thiocyanate concentrations in sprouts and in bitterness of taste as potassium sulfate application increased from nil to 723 kg/ha (Table 4).

Table 4. Thiocyanate concentration and sensory evaluation for the degree of bittterness of sprouts from the nil and highest K treatment and from growers plots

Site/Variable/ Statistics	K_2SO_4 (kg/ha) 0	723	Grower plots	Significance
(a) Site 1 (harvest 3)				
Thiocyanate(ug/g)	0.0685	0.08675	n.a.	***
s.d.	0.0035	0.003		
Bitterness Mean rank	1.083	2.417	2.50	Q, sign.
s.d.	0.204	0.665	0.548	
(b) Site 2 (harvest 4)				
Thiocyanate(ug/g)	0.115	0.116	n.a.	n.s.
s.d.	0.004	0.0045		
Bitterness Mean Rank	1.189	2.375	2.125	Q, n.s.
s.d.	0.829	0.737	0.883	

n.a.=not available
s.d.=standard deviation.
*** analysis of variance differences are highly significant at $P<0.001$.
n.s. is not significant from analysis of variance.
Q, sign. indicates Friedman's statistic (Q)>Chi^2 value and significant differences exist.
Q, n.s. is Friedman's statistic no significant differences.

The bitterness of the sprouts from the growers plots were similar to our highest K treatment (723 kg/ha K_2SO_4) and received a similar source and rate of K fertiliser. At site 2, the effects of K_2SO_4 were not significant (Table 4). Petiole sulfur concentrations and sprout yield were not significantly affected by the application of K_2SO_4 (Potter 1993). Similarly, we obtained no significant yield response to the application of K_2SO_4 at either site.

The differences between the sites in the effect of K_2SO_4 may reflect different fertiliser histories. Site 1 had received little sulfate fertiliser for the previous 10 years whereas site 2, had a history of high sulfate fertiliser applications.

The effect of K_2SO_4 on bitterness of sprouts has important implications for the nutrient management of Brussels sprouts crops. Growers should take care when selecting both sites and fertilisers to ensure that sprout taste is not adversely affected.

Conclusions

(i) For crops of the early season cv. Oliver, response to applied N was inconsistent. In contrast, for the mid season cv. Roger transplanted in December and grown as part of an intensive vegetable-pasture rotation, N rates of 319 and 377 kg N/ha were required for 95% of maximum yield.

(ii) At responsive sites, application of 319-383 kg N/ha optimised the yield of sprouts in the preferred size ranges (20-<30 and 30-<40 g). Application of high rates of N (eg. 600 kg N/ha) only increased the yield of oversize (>40 g) or small (10-<20) sprouts.
(iii) The effect of N on sprout colour was inconsistent. As the harvest progressed from summer to winter sprouts became significantly lighter in colour irrespective of N or K side-dressings.
(iv) The application of K had no significant effects on the yield, or colour of sprouts. The lack of yield responses to applied K suggests that bicarbonate extractable K concentrations of 140-260 mg/kg in the surface (0-15 cm) soil were adequate.
(v) The increase in thiocyanate concentration and associated bitterness of sprouts associated with the use of K_2SO_4 has implications for the nutrient management of crops. Growers should assess the residual S status of the soil and use N, P and K sources which contain low amounts of S. For example, the use of KCl instead of K_2SO_4 should be investigated. An alternative would be to select new genotypes which contain reduced concentrations of thiocyanates. This could be more effective and simpler than changing sites or fertiliser to achieve a milder tasting sprout.
(vi) Organic carbon and total N were not reliable to assess soil N status and predict crop response to applied N. The rate of mineralisation of organic matter, which is dependent on soil temperature and moisture content, may change as the season progresses from summer, autumn to winter. The requirement for applied N may therefore change depending on the planting time of the crop. Calibration of a plant test which indicates N status and yield responsiveness of Brussels sprouts would assist growers in monitoring and evaluating their fertiliser programs and in developing sustainable N management strategies. Results of such work are presented in a second paper in this series (Williams and Maier unpublished data).

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Appendix 2

Assessment of the nitrogen and potassium status of irrigated Brussels sprouts (*Brassica oleracea* L. var. *gemmifera*) by plant analysis.

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Short Title: Nitrogen and potassium tissue tests for Brussels sprouts.

Summary. Four field experiments were carried out during 1992/93 (sites 1 and 2) and 1993/94 (sites 3 and 4) to assess the effects of nitrogen (N), at rates up to 600 kg N/ha and potassium (K), at rates up to 300 kg K/ha on total-N, nitrate-N and K concentrations in petioles of the youngest fully expanded leaves (P-YFEL) of Brussels sprouts. The experiments were located in commercial plantings in the Mount Lofty Ranges. Plant samples were collected at 2-4 week intervals from 4 to 28 weeks after transplanting of the crops. Seasonal variation and the effect of sampling leaves next in age to the index leaf on the concentrations of total-N, nitrate-N and K were also studied.

Total-N concentration in dried petioles was more sensitive to variations in N supply than nitrate-N at all sites. Total-N and nitrate-N concentrations in petioles also varied with the age of the leaf sampled. Total-N concentrations decreased with leaf age and nitrate-N concentrations increased, depending on sampling time and site. Potassium concentrations in petioles did not show consistent differences between the leaves sampled (YFEL-1 to YFEL+2).

From 4 to 6 weeks after transplanting, relationships between total-N or nitrate-N and relative total yield were non-significant ($P \geq 0.05$). We therefore concluded that the use of total-N or nitrate-N concentrations in P-YFEL sampled 4 to 6 weeks after transplanting were not useful to assess the N status of Brussels sprouts.

Linear and quadratic models were used to study relationships between total-N and nitrate-N concentration in P-YFEL and relative total yield during the period 8 to 28 weeks after transplanting. Total-N accounted for a greater amount of variation in relative total yield at 10, 12, 14, 16, 18, 20, 24 and 28 weeks after transplanting compared with nitrate-N. Coefficients of determination (r^2) were in the range 0.52 to 0.93. Relationships between nitrate-N concentration in P-YFEL and relative total yield were only significant 8, 10, 14 and 16 weeks after transplanting and the r^2 values were in the range 0.49-0.82.

Critical nutrient concentrations for total-N decreased from 3.13-3.44% at 10 weeks after transplanting to 1.22-1.38% at 28 weeks after transplanting. This decrease highlights the importance of carefully defining sampling time to ensure correct interpretation of plant test data. Potassium concentrations also decreased during the period 4 to 28 weeks after transplanting. Critical concentrations were not determined for K, because the sites were non responsive to applied K.

Based on sensitivity (as indicated by the range in tissue concentrations in response to variations in N supply) and on the correlations between total-N and nitrate-N concentrations and relative total

yield, we concluded that total-N was a better indicator of plant N status and yield response of Brussels sprouts than nitrate-N. We suggested that growers sample P-YFEL several times during the growing season, starting 10 weeks after transplanting. Plant analysis can be used to monitor N status and to detect N deficiencies which may arise during the growing season of Brussels sprouts which may be up to 9 month in duration. Growers can adjust their fertiliser N program to ensure deficiencies are quickly corrected.

Introduction

In a previous paper we reported on the effect of nitrogen (N) and potassium (K) on the yield and quality of Brussels sprouts cultivars Oliver and Roger (Williams *et al.* unpublished data). The calibration of plant tests for N and K would be useful to allow growers to assess the N and K status of their crops and so determine the adequacy of their N and K fertiliser programs. Furthermore, use of such tests would assist growers to develop sustainable nutrient management strategies. Well defined curves and equations describing the relationship between yield and nutrient concentration in an appropriate plant part at different stages of plant growth, are required for derivation of critical nutrient concentrations (Smith 1986; Williams and Maier 1990a). An appropriate level of yield is selected (eg. 90% of maximum yield) and the nutrient concentration in the tissue sampled is accepted as the critical nutrient concentration. This can be used by consultants or growers as "target levels" to assess the adequacy of their fertiliser programs. However, the critical concentrations may vary under different growing conditions (Lewis *et al.* 1993). Therefore, Dow and Roberts (1982) proposed a critical nutrient range (CNR), or a range of uncertainty above which the crop is likely to be amply supplied with the nutrient in question and below which the crop is likely to be deficient in the nutrient. The need to accurately sample the correct plant tissue at the specified sampling time is essential to ensure correct interpretation of plant test data (Lewis *et al.* 1993).

Previous studies have reported that leaf analysis was useful in defining concentration ranges within which maximum yield of Brussels sprouts could be expected. Robinson (1991) reported that a total-N concentration of 3.5%, K concentration of 2.4% and 0.3-0.35% P concentration range in leaves sampled 3-4 months after transplanting were adequate for optimum sprout yield. Robinson (1991) also showed that nitrate-N critical concentrations in leaves declined rapidly from 2,000 mg/kg at 2 to 3 months after transplanting to 250 mg/kg at 4 months after transplanting. Piggott (1986) cited that 3.0-5.0% total-N and 2.4-3.4% K, at the 7 cm heart growth stage, were adequate for maximum yield. In the USA, Lorenz and Tyler (1978) found that for mid-ribs of youngest mature blades (YMB) sampled at mid growth, 0.9% nitrate-N and 5% K were adequate. Use of these data to interpret plant test results is complicated because the authors have sampled different plant tissues, at either different or poorly defined sampling times (eg. mid growth or 7 cm heart). Therefore, before local growers can reliably use plant tests to interpret results, (i) the best nutrient fraction needs to be selected (ie. total-N or nitrate-N), and (ii) critical nutrient ranges for clearly defined sampling times and plant parts, need to be developed for southern Australia conditions. Development of critical nutrient ranges for plant analysis is a means to reduce residual fertiliser at the end of a crop cycle and prevent deficiencies by tailoring fertiliser supply to crop demand.

Nitrogen and K nutrition can also have major effects on sprout quality as well as yield. Excess N can increase the production of loose (open) sprouts which are unsaleable, increase bitterness and reduce the firmness of sprouts (North *et al.* 1969; Scaife and Turner 1985). Alternately, K has been claimed to improve the colour and firmness of sprouts (Nieuwhof 1969).

In this paper we report on 4 field experiments conducted to provide data to (i) define changes in total-N, nitrate-N and K in petioles during the growing season; (ii) determine the relationship between total-N and nitrate-N in petioles and total yield of sprouts for specific sampling times; (iii) evaluate the diagnostic value of total-N and nitrate-N at different sampling times during crop growth; (iv) determine

the effect of sampling leaves next in age to the index tissue on the concentration of total-N, nitrate-N and K in petioles sampled during the growing season; and (v) calculate critical nutrient ranges at different stages during the growing season.

Materials and methods

Field experiments

Site, treatment, plot size and yield response details of the 4 field experiments involved in this study were described in the first paper in this series (Williams *et al.* unpublished data). Briefly, the data were obtained from field experiments conducted in the Mount Lofty Ranges of South Australia during 1992-93 (sites 1 and 2) and 1993-94 (sites 3 and 4). The experimental design was a randomised block with 5 rates of N, up to 600 kg/ha and 3 rates of K, up to 300 kg/ha replicated 4 times. Nitrogen and K were applied over 8 side-dressings during the period 2-28 weeks after transplanting. At each site 4 replicated plots, equal in size to experimental plots, were pegged out in the grower's crop adjacent to the experimental plots (hereafter called grower plots). These plots were used to monitor petiole nutrient concentrations in each commercial crop grown with the grower's standard fertiliser practice.

Plant sampling procedure

At sites 1, 2 and 4, 20 youngest fully expanded leaves (YFEL) were collected in the morning before the side-dressings of N and K were applied. At site 3, 10 plants were sampled. The 4 growers plots were also sampled concurrently with experimental plots. The sampled leaves were immediately placed in labelled paper bags within a large plastic bag, stored over ice in an insulated box prior to transport and transported to the laboratory. At the laboratory, the samples were held in a cool room at 4°C. Petioles of the youngest fully expanded leaves (P-YFEL) were excised and leaf blade tissues discarded. Half of the petiole sample was used for sap analysis and the remaining petioles were oven dried at 65°C and ground through 1 mm mesh prior to chemical analysis. Results of the sap analysis will be presented in a separate paper.

Analytical methods

For the treatments, N4 (600 kg N/ha + 150 kg K/ha) and K2 (375 kg N/ha + 300 kg K/ha), petioles collected from each replicate were bulked for chemical analysis. For all other treatments, samples for each replicate were analysed separately. The dried petioles were analysed for nitrate-N by the method of Heanes (1982) and for total-N and K as described by Maier *et al.*(1986).

Statistical methods

Linear and quadratic functions were used to investigate the relationships between relative total yield and total-N and nitrate-N in P-YEL at each sampling time. Relative yields were determined for each site by expressing the average yields as percentages of the maximum mean yield for that site. For the linear and quadratic models, critical values were concentrations at a relative yield of 90 and 95%. Critical K concentrations were not determined because yield responses to applied K were not significant at any site.

Holland (1983) concluded that for a range of nutrients there was only a small loss of precision if plant tissue replicate samples were bulked prior to analysis. We have presented means $\pm$ standard error for the nil N and K treatments at all sites to indicate variability and expect these to be typical for the other treatments. The error terms were small, indicating satisfactory precision. Similar procedures were used by Huett and Rose (1988, 1989) and Maier *et al.* (1992, 1994).

Results and discussion

Seasonal changes of total-N and nitrate-N in P-YFEL

Early in the growing season (up to 8 weeks after transplanting) there was little difference in either total-N or nitrate-N concentration in P-YFEL at the various rates of applied N at all sites (Figures 1 and 2). From 8 weeks after transplanting to 24 weeks after transplanting, total-N concentrations in P-YFEL declined at all sites. The extent of this decline varied considerably (by up to 533%) depending on the rate of N applied with the nil N treatments declining at the greatest rate. Nitrate-N concentrations declined rapidly 6 weeks from transplanting. The rate of decline was similar irrespective of the rate of N applied. Low concentrations were reached at 12-14 weeks after transplanting and at approximately 20 weeks after transplanting were close to zero and remained at that level until the final sampling time. Robinson (1991) who sampled the YFEL at one site, reported that total-N concentrations remained constant at 3.0-3.3% from 12 to 28 weeks after transplanting. He also reported that nitrate-N concentrations declined rapidly from 2000 mg/kg at 8-12 weeks after transplanting to zero at 20 weeks after transplanting.

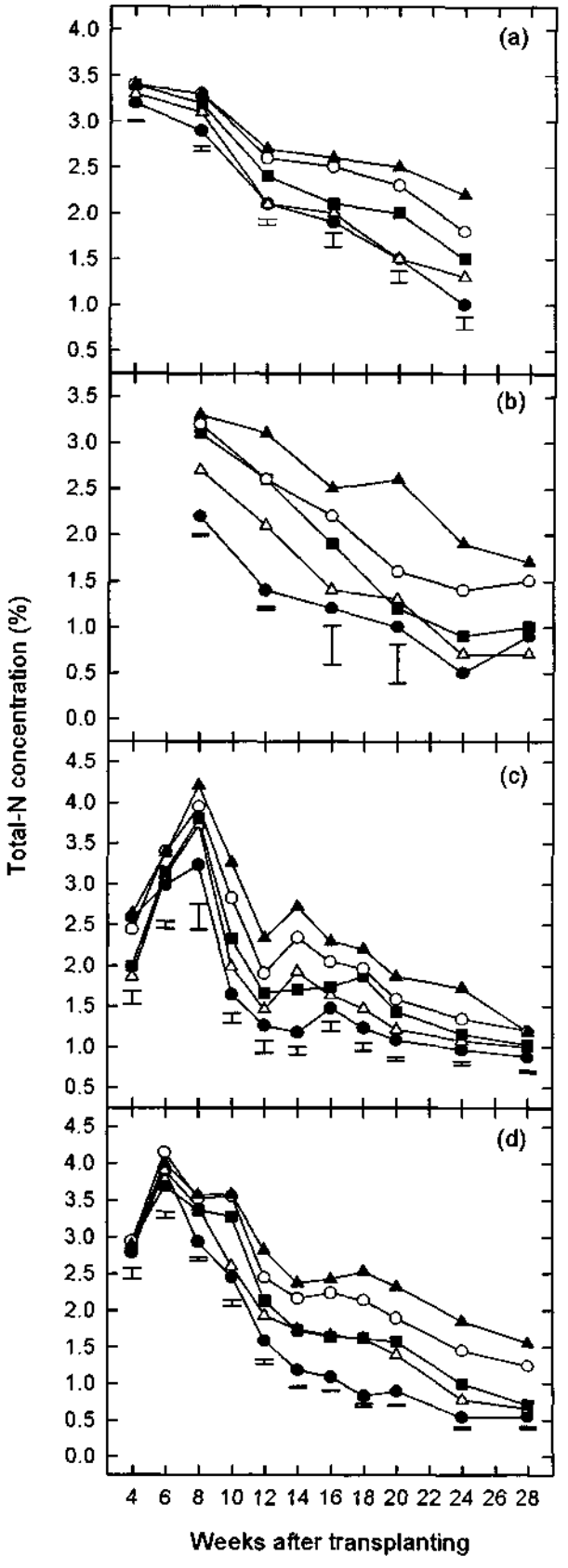

Figure 1. Relationships between total-N in Brussels sprouts petioles grown at (a) site 1, (b) site 2, (c) site 3 and (d) site 4 and sampling time for 5 rates of applied N.

N0 or 0 kg N/ha (●), N1 or 125 kg N/ha (Δ), N2 or 250 kg N/ha (■), N3 or 375 kg N/ha (O), N4 or 600 kg N/ha (▲). Vertical bar indicates standard errors of means for the nil N rate.

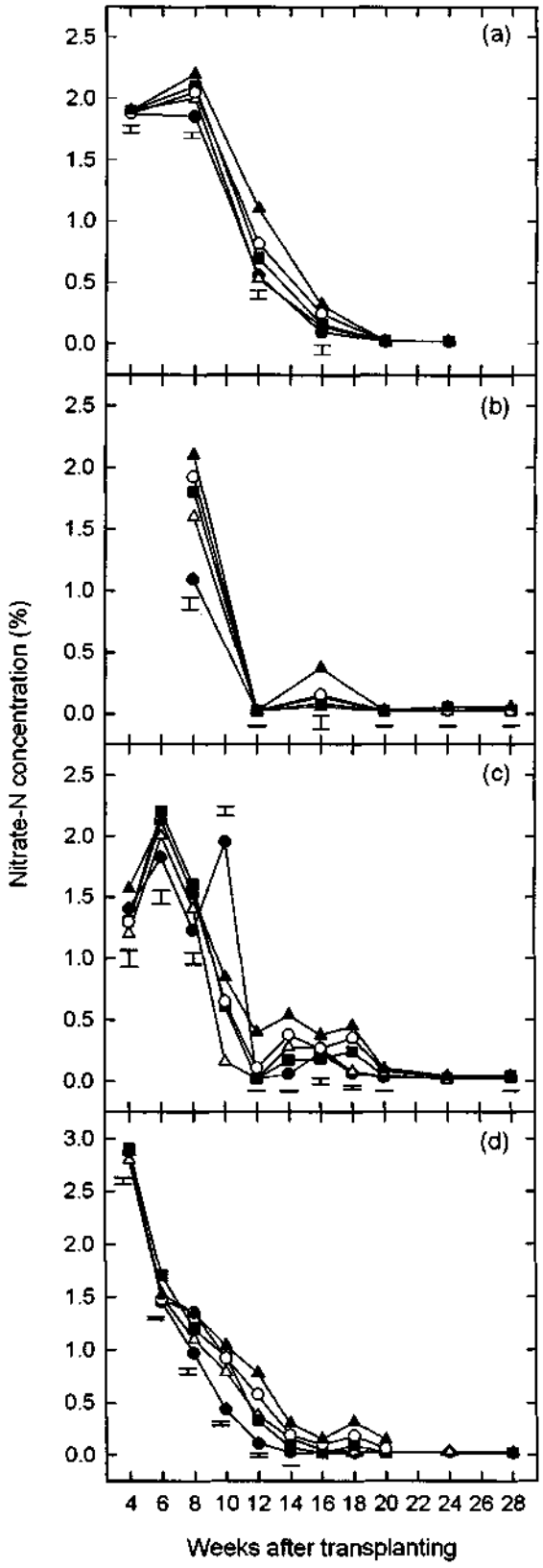

Figure 2. Relationships between nitrate-N in Brussels sprouts petioles grown at (a) site 1, (b) site 2, (c) site 3 and (d) site 4 and sampling time for 5 rates of applied N.
N0 or 0 kg N/ha (●), N1 or 125 kg N/ha (Δ), N2 or 250 kg N/ha (■), N3 or 375 kg N/ha (O), N4 or 600 kg N/ha (▲). Vertical bar indicates standard errors of means for the nil N rate.

The large seasonal changes in total-N and nitrate-N concentrations have important implications for plant testing and emphasises the importance of sampling at the correct time. Williams and Maier (1990 a, b) also reported rapid changes in nitrate-N concentrations in potato petioles within a 4-6 week period and emphasised the importance of carefully defining sampling time to ensure correct interpretation of test results from predetermined critical nutrient ranges.

Sensitivity of total-N and nitrate-N concentrations in P-YFEL to variations in N supply Eight weeks after transplanting, total-N concentration in P-YFEL was far more sensitive to changes in N supply, compared to nitrate-N concentrations (Figures 1 and 2). Nitrate-N concentrations declined rapidly regardless of the rate of N applied (Figure 2). The greater responsiveness of total-N concentrations to additions of N compared with nitrate-N concentration in P-YFEL, indicated that total-N was a more sensitive indicator of plant N status for Brussels sprouts crops.

Seasonal changes in K concentrations in P-YFEL and sensitivity to variations in K supply

The application of K did not significantly ($P \geq 0.05$) affect yield at any site (Williams *et al.* unpublished data). At all sites, there was very little difference in K concentrations in P-YFEL at different rates of applied K (Figure 3). However, even where K was adequate for maximum yield, K concentrations in P-YFEL declined rapidly from 5-6% at 6 weeks from transplanting to 1-2% at 28 weeks after transplanting (Figure 3).

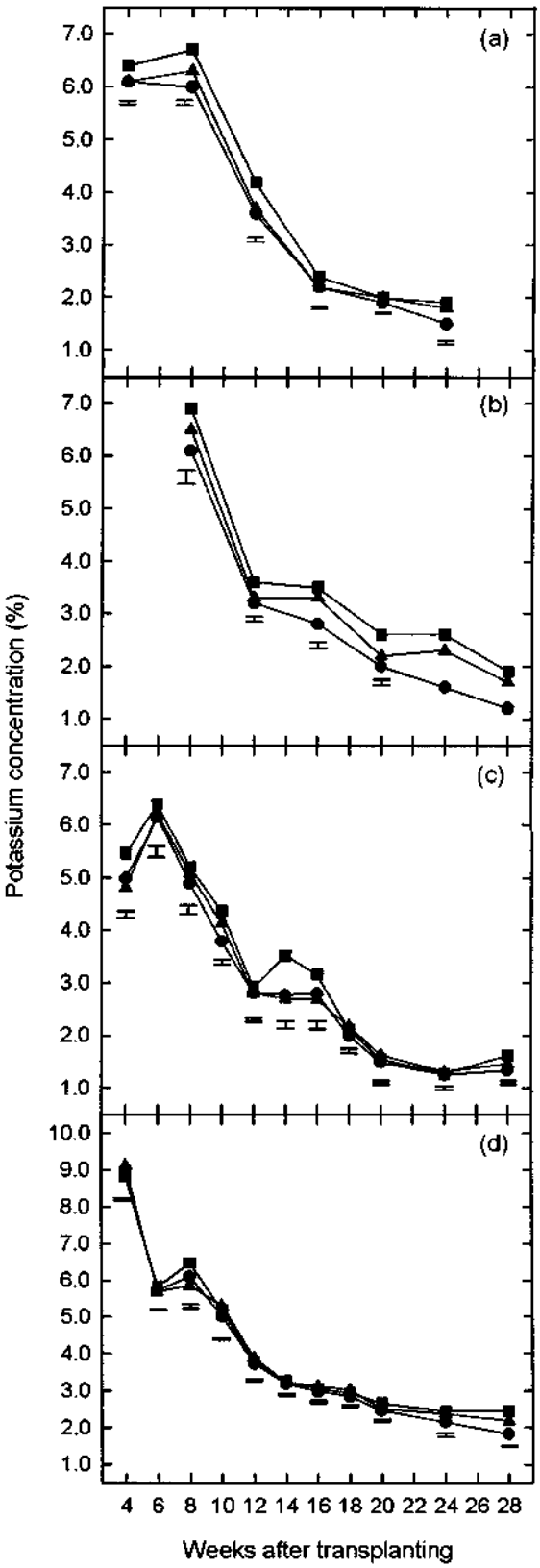

Figure 3. Relationships between K concentration in dried petioles of Brussels sprouts and sampling time at (a) site 1, (b) site 2, (c) site 3 and (d) site 4 for 3 rates of applied K. K0 or 0 kg K/ha (●), K1 or 150 kg K/ha (▲), K2 or 300 kg K/ha (■). Vertical bars indicate standard errors of means for nil K treatments.

Variation in N and K concentrations with leaf position along the stem

For both annual and perennial crops the effect of sampling leaves next in age to the chosen index leaf on nutrient concentrations and on interpretation can be significant, depending on the species and leaves studied (Bell *et al.* 1987; Cresswell 1989; Maier *et al.* 1990). We found large changes in total-N concentrations between petioles from leaves of different ages, especially early in the growing season (Figure 4a). Total-N concentrations decreased with increasing leaf age. For nitrate-N the reverse occurred, with concentrations tending to be lower in younger petioles early in the season (Figure 4b). However, by mid to late season, the differences were negligible and of little practical importance. At these sites where K supply was adequate, we found no consistent differences in K concentrations in petioles of different leaves at any sampling time. Other workers have also reported that greater emphasis should be given to defining the effects of leaf age or position and plant growth stage at sampling when calibrating plant tests (Smith 1986; Lewis *et al.* 1993; Olsen and Lyons 1994).

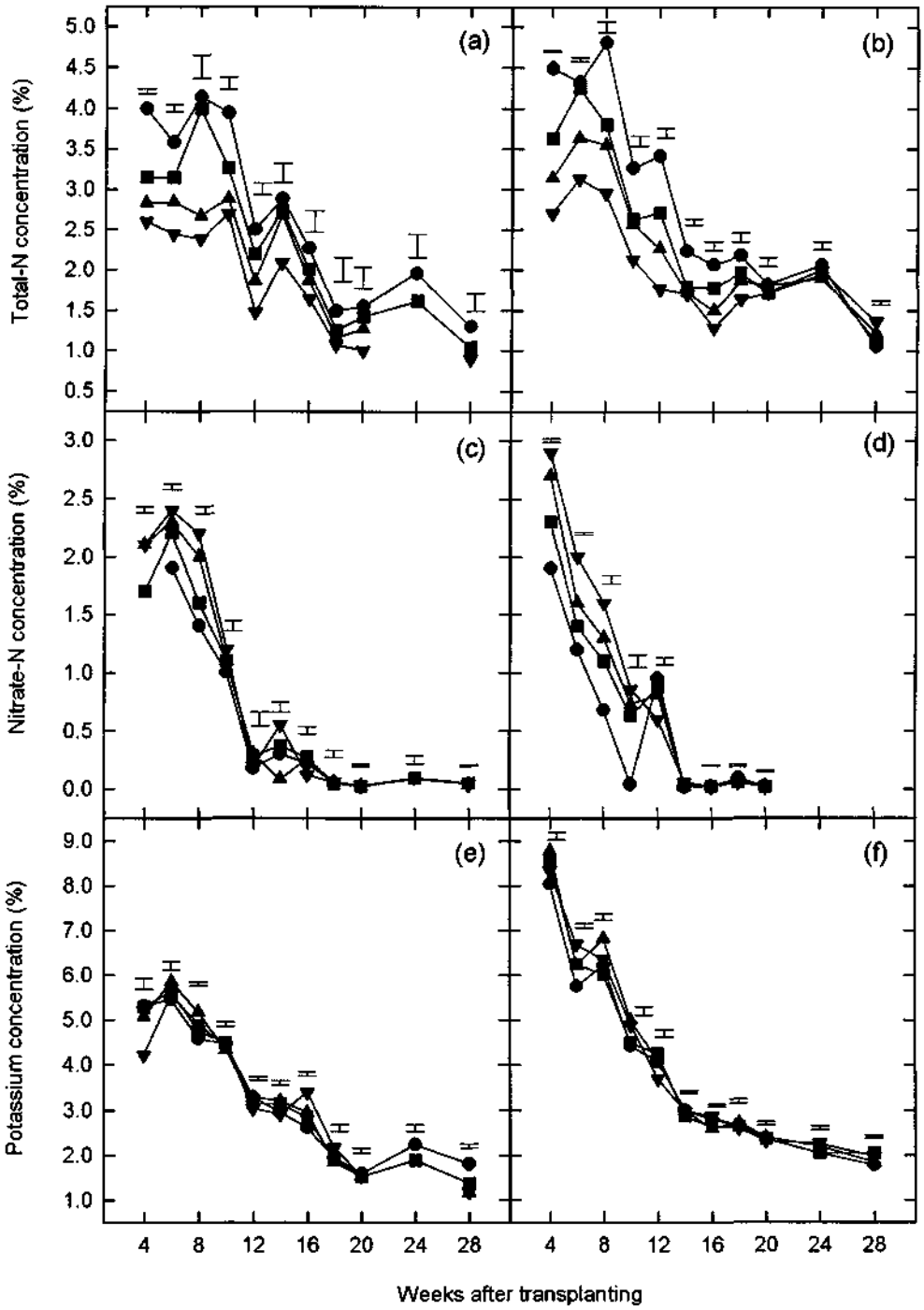

Figure 4. Effects of leaf position on the total. N at site 3 (a) and site 4 (b), nitrate-N at site 3 (c) and site 4 (d) and K concentration changes at site 3 (e) and site 4 (f) in petioles with sampling time. YFEL-1 (●), YFEL (■), YFEL+1 (▲), YFEL+2(▼). Vertical bars are standard errors of means for YFEL.

Relationships between total and nitrate-N and yield

Equations of best fit (based on r^2 values) for the relationships between relative total yield of sprouts and total-N and nitrate-N in P-YFEL are given in Table 1. At all sampling times, except at 8 weeks after transplanting, relationships between total-N concentration and relative total yield had greater r^2 values than the relationships between nitrate-N concentration and total relative yield (Table 1). The relationships between total-N and relative yield for the period 10-28 weeks after transplanting are shown in Figure 5 when significant and useful relationships were obtained. During this period total-N in P-YFEL is clearly a more accurate indicator of plant N status and yield responsiveness than nitrate-N for Brussels sprouts crops.

Table 1. Equations of best fit relating relative total sprout yield (Y,%) to either total. N concentration (X,% dry weight) or nitrate-N (X, % dry weight) at different sampling times for data pooled over all sites. Critical concentration at 90 and 95% of relative total sprout yield is shown.

Sampling time (weeks)	Equation	r^2	Significance of regression	Concentration at	
				90%	95%
		Total-N (%)			
4	Y=64.5+7.85X	0.086	n.s.		
6	Y=66.3+4.96X	0.020	n.s.		
8	Y=33.1+16.1X	0.29	$P<0.05$	3.53	3.84
10	Y=40.3+15.9X	0.52	$P<0.05$	3.13	3.44
12	$Y=-12.7+74.9X-12.8X^2$	0.67	$P<0.001$	2.06	2.31
14	Y=33.2+26.7X	0.84	$P<0.001$	2.13	2.31
16	$Y=-35.0+105.6X-21.1X^2$	0.86	$P<0.001$	1.82	2.02
18	Y=34.4+28.4X	0.93	$P<0.001$	1.96	2.13
20	$Y=-26.5+119.5X-28.2X^2$	0.84	$P<0.001$	1.52	1.70
24	$Y=27.4+78.9X-22.1X^2$	0.77	$P<0.001$	1.12	1.31
28	Y=50.5+32.3X	0.56	$P<0.01$	1.22	1.38
		Nitrate-N (%)			
4	Y=91.6-2.38X	0.014	n.s.		
6	Y=55.5+15.9X	0.11	n.s.		
8	$Y=-55.9+162.0X-43.5X^2$	0.60	$P<0.001$	1.40	1.54
10	Y=61.9+33.6X	0.49	$P<0.005$	0.84	0.99
12	Y=81.0+16.5X	0.18	n.s.		
14	$Y=61.5+166.9X-164.0X^2$	0.65	$P<0.005$	0.23	0.30
16	Y=77.9=50.2X	0.17	n.s.		
18	$Y=61.4+202.3X-269.1X^2$	0.82	$P<0.01$	0.18	0.24
20	Y=80.7+151.8X	0.14	n.s.		
24	Y=75.9+349.4X	0.065	n.s.		
28	Y=67.4+602.8X	0.16	n.s.		

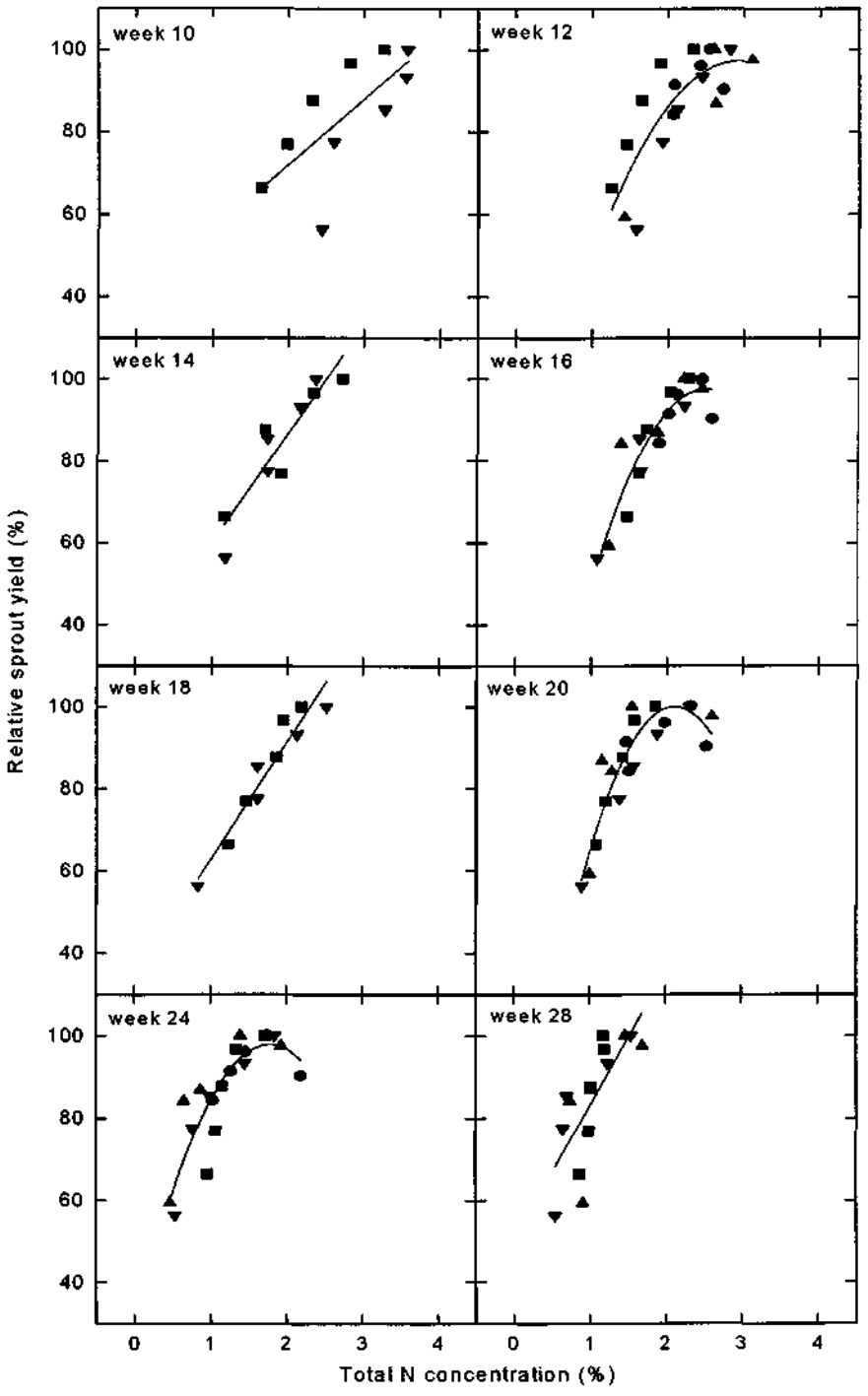

Figure 5. Relationships between relative total yield of Brussels sprouts and petiole total-N concentration at 8 sampling times for site 1 (●), site 2(▲), site 3(■), site 4(▼).

Critical concentrations

Calculation of a critical concentration for relative yield at any instant involves a subjective decision as to the percentage of maximum yield selected, values selected include 90, 95, 99 or 100%. In our study total-N concentrations of 3.53, 3.84 and 4.16% were associated with 90, 95 and 100% of relative total yield at 10 weeks after transplanting. Clearly, it is important, when comparing critical concentrations from different studies to document differences in the percentage of the relative yield value, used to determine the critical concentrations (Scaife 1988). Concentrations at 90 and 95% of relative yield are often used to define critical concentrations (Smith 1986; Maier *et al.* 1990) and values for all sampling times are presented in Table 1.

Critical total-N concentrations declined significantly ($P<0.05$) during crop growth and the rate of decline decreased as the season progressed (Figure 6a, Table 1). Total-N concentrations associated with 90 and 95% of maximum sprout yield declined from 3.13 and 3.44 %, at 10 weeks after transplanting to 1.22 and 1.38%, at 28 weeks after transplanting. Decreases in critical total-N concentrations with time have also been reported for tomato (Huett and Rose 1988), cabbage (Huett and Rose 1989) and onion (Maier *et al.* 1992). These changes in critical values highlight the need to define sampling time accurately, to ensure correct interpretation of plant test data.

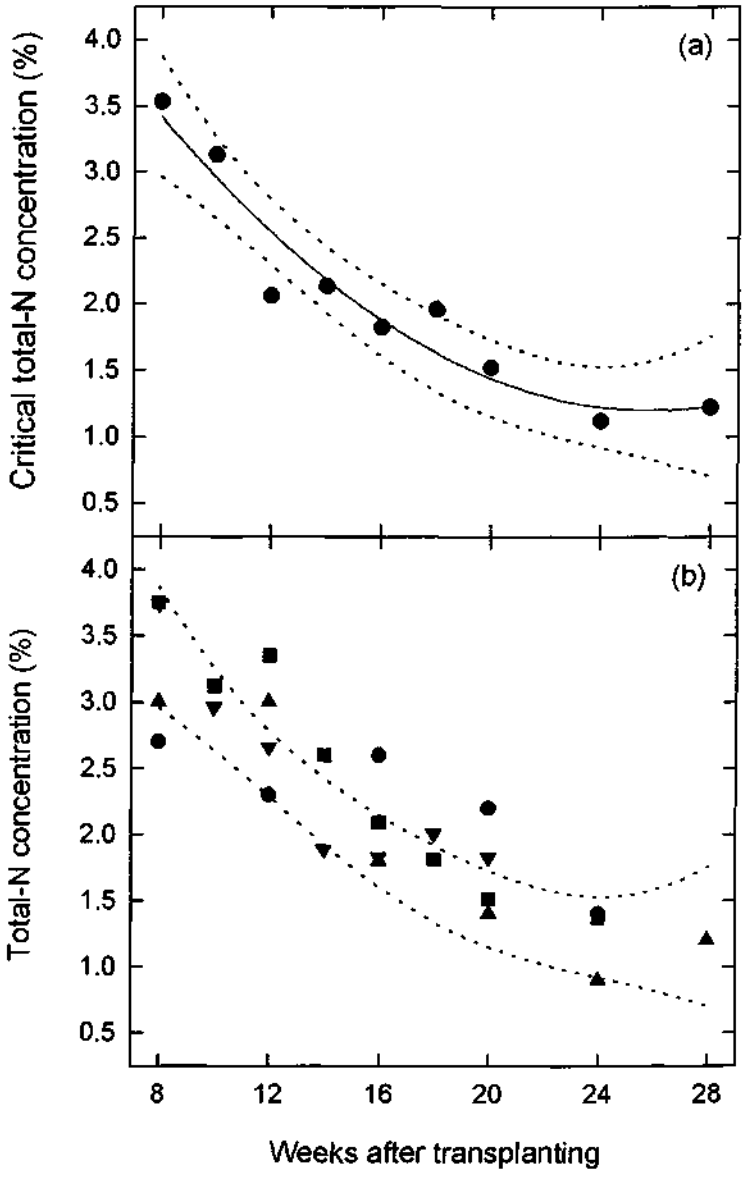

Figure 6. Relationships between critical total-N concentration in dried petioles at 90% of maximum relative yield and sampling time for (a) data pooled over all 4 experimental sites (●). The equation for the fitted curve is:

$$Y = 5.84 - 0.36X + 0.0069X^2 \quad (r^2 = 0.92, P < 0.001)$$

For (b) the relationship between total-N concentration and time of sampling for the growers plots at each site. Sites were: 1 (●), 2 (▲), 3 (■) and 4 (▼). Dotted curves indicate the 95% confidence interval for the critical concentration for 90% of maximum relative yield.

Total-N concentrations in P-YFEL of plants in the grower plots were also monitored at all sites and are presented in Figure 6b. In general, total-N concentrations of the growers plots at the 4 sites were within or above our calculated critical concentration ranges (Figure 6b). The growers applied from 360-520 kg N/ha per crop to these areas and obtained similar yields as recorded for our highest yielding trial plots. This suggests the growers N fertiliser practice was adequate to meet the N needs of these crops at all sites.

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Appendix 3

Evaluation of rapid sap tests for nitrate and potassium for assessing the nitrogen and potassium status of irrigated Brussels sprouts (*Brassica oleracea* L. var. *gemmifera*) crops in southern Australia.

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Short Title: Rapid sap test for Brussels sprouts

Summary Rapid, field-based sap nutrient tests have been advocated by several groups because they provide quick on-the-spot information and have an advantage over the more time-consuming laboratory analysis of plant samples in optimising fertiliser decisions. Four field experiments were carried out during 1992/93 (sites 1 and 2) and 1993/94 (sites 3 and 4) to assess the effects of nitrogen (N), at rates up to 600 kg N/ha and potassium (K), at rates up to 300 kg K/ha applied in incomplete factorial combinations on sap nitrate (assessed by 2 rapid test methods) and potassium concentrations in petioles of the youngest fully expanded leaves (P-YFEL) of Brussels sprouts. The experiments were located in commercial plantings in the Mount Lofty Ranges which contains the main water catchment area for Adelaide's potable water supply. Plant samples were collected at 2-4 week intervals from 4 to 28 weeks after transplanting of the crops.

A description is given of the plant tissue to sample, sap extraction and measurement of sap nitrate and potassium. 10-20 petioles of the youngest, fully expanded leaves (P-YFEL) per plot were collected and bulked. Segments 10-20 mm long were excised near the centre of half the petioles, crushed and sap collected. Sap nitrate was measured by 2 rapid test procedures. The first method termed Nitrachek nitrate; measured the colour development of Merckoquant® test strips (which had been dipped in 1:100 dilute sap) by reflectometric analysis with a Nitrachek® meter. For the second procedure, neat sap was placed on the sensor pad of a Cardy Horiba® specific nitrate ion meter to assess sap nitrate (hereafter termed Cardy nitrate). Sap potassium (K) concentration was also measured using a Cardy Horiba specific K ion meter. The other half of the petioles from each sample were oven dried and analysed for total-N, nitrate-N and K by standard procedures.

Sap nitrate concentrations in petioles as assessed by both methods were relatively insensitive to variations in applied N from 0 up to 600 kg N/ha, over the 9 month cropping period. In general, Cardy nitrate showed more differences in sap nitrate due to applied N compared to Nitrachek nitrate. However, there was an anomaly at site 3, Cardy nitrate showed a sharp fall, from 6,000 to 1,000 mg/L from weeks 8-10 and then a dramatic rise from 1,000 mg/L to 7,000 mg/L from 14-16 weeks after transplanting. This could not be explained in terms of plant nutrition.

Overall, sap nitrate concentrations in P-YFEL declined very rapidly with time so that by 12-14 weeks after transplanting sap nitrate concentrations were near zero and insensitive to applied N from then onwards.

Correlations between all 2 way possible comparisons of the 2 methods of sap nitrate and total-N and nitrate-N in dried petioles, were all highly significant ($P<0.001$) for the data pooled over all sites and r ranged from 0.65 to 0.82. However, further work is needed to determine if one can convert a measurement in one system to another method and use such converted values to interpret a calibrated plant test. Sap K had a significant ($P<0.001$) but low correlation ($r=0.19$) with K concentration in dried petioles. This suggests the sap K method may have limited sensitivity as an index of the K status of Brussels sprouts.

Critical nutrient ranges of petiole sap nitrate for maximum yield could not be derived at most sampling times during crop development - despite significant ($P<0.05$) yield responses to applied N at 3 of the 4 sites. Both the Nitrachek and Cardy sap nitrate procedures were not sensitive enough to determine the N status of the crop, nor predict yield response nor to assess the adequacy of the fertiliser program. Determination of total-N in dried petioles was found to be an appropriate and useful index of the N status of Brussels sprouts.

We concluded that the negative results for the value of sap testing for nitrate to predict yield response and the N status of Brussels sprouts although disappointing should now lead to a greater use of analyses for total-N in dried petioles as the useful and preferred index of the N status of irrigated Brussels sprouts.

Introduction

Rapid sap testing

Plant analysis is being increasingly used to monitor and evaluate the nutrient status of crops (Reuter and Robinson 1986; Scaife 1988; Williams and Maier 1990a). Analytical methods are improving and rapid tissue tests are now available on the market, which enable the grower to monitor certain plant nutrients, notably nitrate, with precision on the farm (Scaife and Turner 1983; Williams and Maier 1990b).

Commercial companies have recently produced nitrate rapid test kits (eg. 'Nitrachek test kit for cereals and potatoes by Aghitec Pty Ltd and 'Nit-rate' service for cereals by Pivot Fertilisers). Cardy Horiba have introduced a range of specific ion electrode meters to measure nitrate, or potassium etc. However, the 'critical concentrations', that is the minimum sap concentrations required for maximum yield or crop quality, have not been determined for most crops at different stages of growth using these new analytical procedures (Nitsch 1984; Scaife 1988; Williams *et al.* 1991).

Well defined curves and/or equations describing the relationship between yield and nutrient concentration in an appropriate plant part at different stages of plant growth are required for derivation of critical nutrient concentrations (Smith 1986; Williams and Maier 1990a). An appropriate level of yield is then selected (eg. 90%) and the nutrient concentration in the selected tissue at this yield is accepted as the critical nutrient concentration at each sampling time. This can be used by consultants and/or growers as "target levels" to assess the adequacy of their N fertiliser programs. The critical point may vary under different conditions (Lewis *et al.* 1993). Therefore, Dow and Roberts (1982) proposed a critical nutrient range (CNR), or a range of uncertainty above which the crop is likely to be amply supplied and below which the crop is likely to be deficient in the relevant nutrient.

Furthermore, the technology is reasonably new and testing of the ease of use, reliability, accuracy of the equipment and the availability and interpretation of plant standards will determine their life in the marketplace (Hochmuth 1992; Lewis *et al.* 1993)

In this study we report on 4 field experiments conducted to (i) define changes in sap nitrate and potassium in petioles during the growing season; (ii) compare Nitrachek and Cardy methods of analysing nitrate in terms of changes during the growing season and for determining the N status and yield response of irrigated Brussels sprouts; (iii) to evaluate the diagnostic value (CNR) of Nitrachek nitrate and Cardy nitrate at different sampling times during crop development; (iv) to define the interrelationships between Nitrachek and Cardy nitrate in sap and nitrate-N and total-N in dried petioles and (v) to determine if theses rapid sap tests have potential as tools to monitor the N status, predict yield response and have a role in sustainable nutrient management strategies for irrigated, Brussels sprouts in southern Australia.

Materials and methods

Field experiments

Details of the sites, experimental design, field procedures and tissue sampling in the 4 field experiments involved in this study were described in the first 2 papers in this series (Williams *et al.* submitted; Williams and Maier submitted). In brief, the data were obtained from field experiments conducted in the Mount Lofty Ranges of South Australia during 1992/93 (sites 1 and 2) and 1993/94 (sites 3 and 4). The experimental design was a randomised block with 5 rates of N, (up to 600 kg/ha) and 3 rates of K (up to 300 kg/ha) applied in incomplete factorial combinations; replicated 4 times. The plant samples were collected each morning, before each of the 8 N and K side-dressings were applied (from 2 up to 28 weeks after transplanting).

Petiole sampling procedure

Each morning, usually before side-dressings of N and K were applied, the youngest fully expanded leaf and petiole (YFEL+P) was collected from each of the 20 middle plants per plot (except at site 3, where 10 plants were sampled). The 4 growers plots were also petiole sampled concurrently with experimental plots at each sampling time. Sampled material was immediately placed in labelled paper bags and placed within a large plastic bag (to prevent dehydration) and stored over ice in an insulated box and transported to the laboratory, where samples were held at 4°C before preparation. Petioles (P-YFEL) were excised and leaf blade tissues discarded. Half of the petiole sample was used for sap analysis. The remaining petioles were oven dried at 65°C and ground through 1 mm mesh prior to chemical analysis and the results for dried petioles have been reported by Williams *et al.* (submitted).

Laboratory methods

For the treatments N4 (600 kg N/ha + 150 kg K/ha) and K2 (375 kg N/ha + 300 kg K/ha), petioles collected from each replicate plot were bulked for sap analysis. For all other treatments, samples for each replicate were analysed separately. The laboratory procedure at each site and sampling time was (i) 10-20 petioles of the youngest fully expanded leaves (P-YFEL) were collected from each plot. (ii) Half of each sample were used to determine nitrate and potassium concentrations in extracted sap as described below and the remainder was oven dried for nitrate-N and total-N analysis as described in paper 2 in this series (Williams and Maier submitted). (iii) Segments 10-20 mm in length were excised from near the centre of each petiole per sample. These samples were diced into 2-4 mm pieces to aid sap extrusion. (iv) These were then crushed in a stainless steel garlic crusher (pore size 1-2 mm) and 2-3 ml of sap was collected. (v) A 2 ml plastic syringe was used to extract 1.0 ml of sap which was diluted with deionised water to 100 ml (called the x100 diluted sap extract) to bring the sap into the measurement range of the Nitrachek® meter (ie. 10-500 mg/L nitrate). (vi) The colour development of Merckoquant® test strips was measured

by reflectometric analysis with the Nitrachek® meter as described by Williams and Maier (1990b). Hereafter, results obtained by this method will be termed Nitrachek nitrate. (vii) Standard solutions were used to monitor the variability of test strips (Williams and Maier 1990b). (viii) A further sample 0.5-1.0 ml of neat sap was taken from each initial sample and placed on the sensor pad of the Cardy Horiba® specific nitrate ion meter to assess sap nitrate (hereafter termed Cardy nitrate). (ix) The same neat sap sample from the Cardy Horiba nitrate ion meter was then placed on the sensor pad of a Cardy Horiba specific potassium ion meter to assess sap potassium (K).

Statistical methods

Data for nitrate concentrations from quick tests results on sap by both methods and for nitrate-N and total -N from the analysis of dried petioles were compared using regression procedures to calculate correlation coefficients. Cardy sap K was compared to K data obtained from oven dried petioles by the same method as above. Linear and quadratic functions were used to investigate the relationships between the relative total sprout yield and Nitrachek nitrate in sap at each sampling time. For the linear and quadratic models, critical values were concentrations at a relative yield of 90 and 95% of the maximum.

Certain replicate samples were bulked as described in paper 2 of this series (Williams and Maier submitted). We present means ±standard errors for the nil N and K treatments at all sites to indicate variability and expect these to be typical for the other treatments. The error terms were small, indicating satisfactory precision. Similar procedures were used by Huett and Rose (1989) and Maier *et al.* (1994).

Results and discussion

Sap nitrate changes over time

Sap nitrate concentrations in petioles of the youngest fully expanded leaf were relatively insensitive to variations in applied N; however the magnitude of the effects varied between the two methods of sap analysis (Figures 1 and 2). In general, the Cardy method showed more differences in petiole sap nitrate concentrations due to the application of N, than the Nitrachek method of sap nitrate assessment (Figures 1 and 2). However, there was an anomaly at site 3, the Cardy method showed a sharp fall in sap nitrate (from week 8 to 10) from 6,000 mg/L to 1,000 mg/L and a dramatic rise from week 14 to 16 from 1,000 mg/L to 7,000 mg/L. This is difficult to explain in terms of plant nutrition; an alternative possible reason is that chloroplasts in sap samples may impregnate the soft gel around the electrode after repeated use and cause suspect readings (Vitosh pers. comm.).

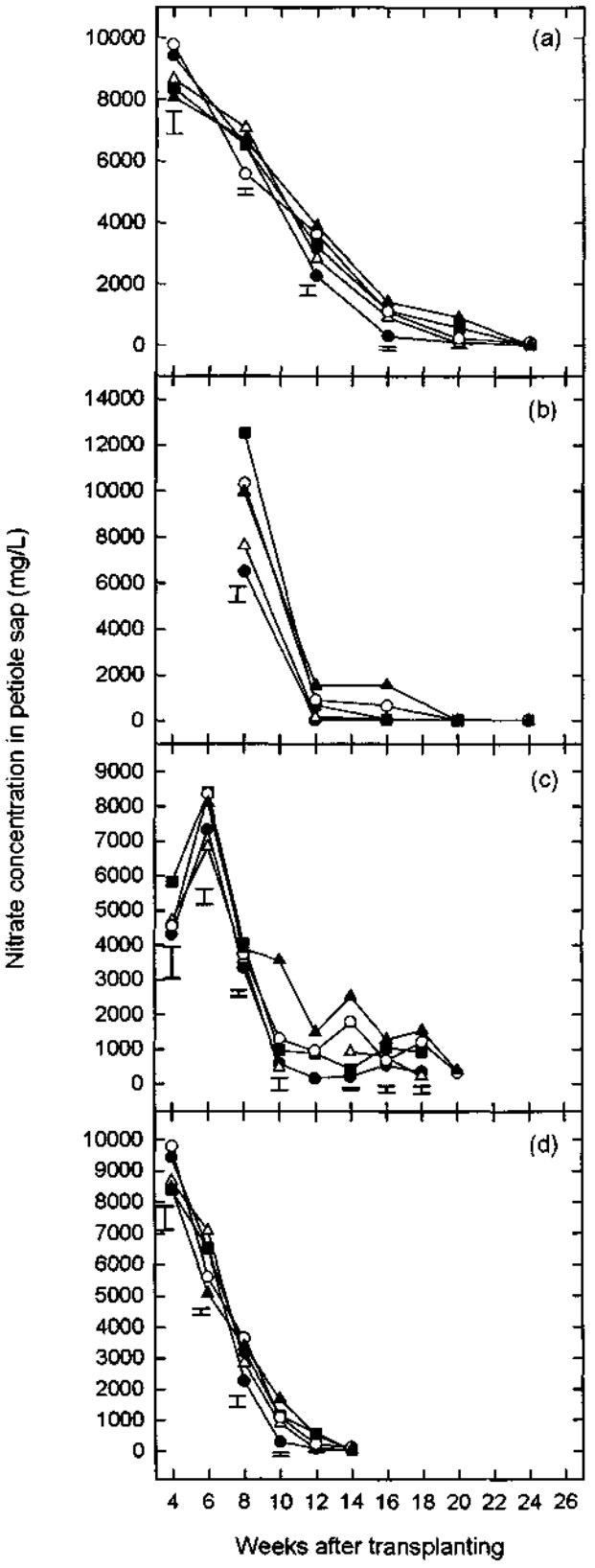

Figure 1. Relationships between Nitrachek nitrate in Brussels sprouts petioles grown at (a) site 1, (b) site 2, (c) site 3 and (d) site 4 and sampling time for 5 rates of applied N.

N0 or 0 kg N/ha (●), N1 or 125 kg N/ha (Δ), N2 or 250 kg N/ha (■), N3 or 375 kg N/ha (O), N4 or 600 kg N/ha (▲). Vertical bar indicates standard errors of means for the nil N rate.

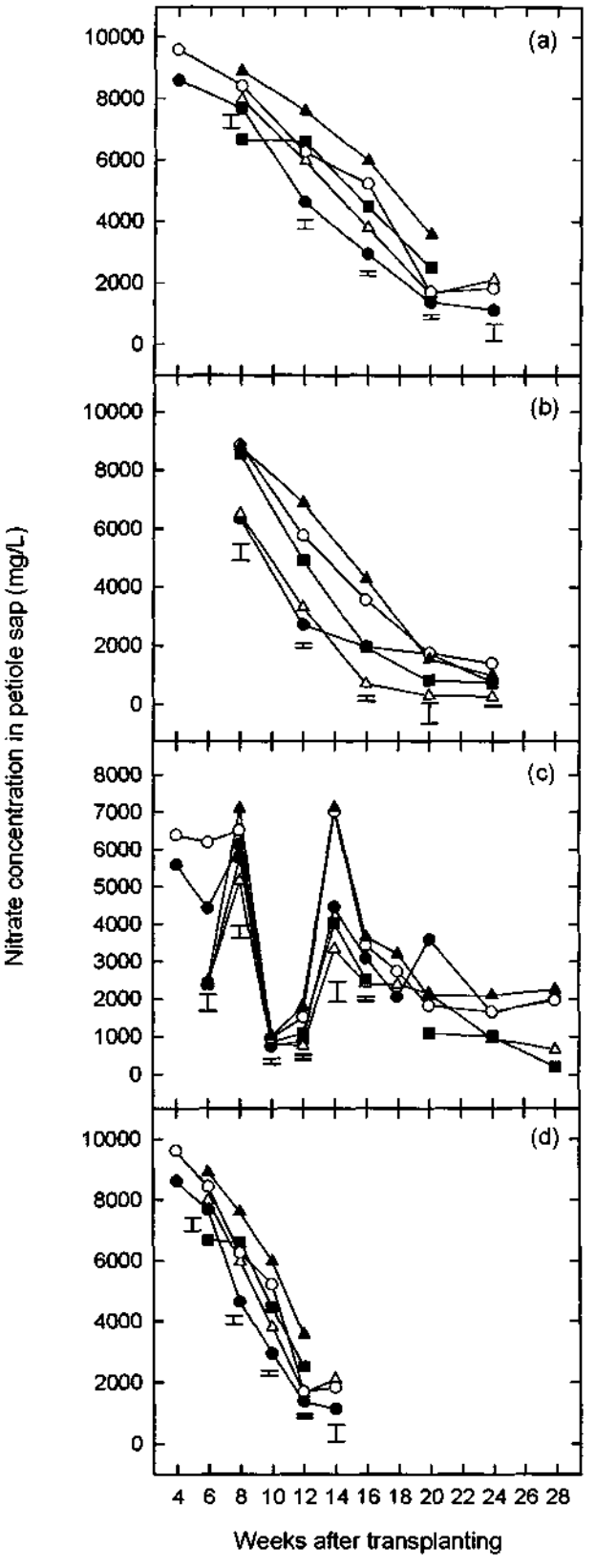

Figure 2. Relationships between nitrate concentration in petiole sap measured by the Cardy method in Brussels sprouts grown at (a) site 1, (b) site 2, (c) site 3 and (d) site 4 and sampling time for 5 rates of applied N.

N0 or 0 kg N/ha (●), N1 or 125 kg N/ha (Δ), N2 or 250 kg N/ha (■), N3 or 375 kg N/ha (O), N4 or 600 kg N/ha (▲). Vertical bar indicates standard errors of means for the nil N rate.

Overall, sap nitrate concentrations in the petiole of the YFEL declined very rapidly with time so that by 12-16 weeks after transplanting sap nitrate concentrations were near zero and insensitive to applied N from that time onwards.

Correlations between sap nitrate, and nitrate-N and total-N in dried petioles

Correlations between each of (i) the 2 methods of sap nitrate determination, (ii) each sap nitrate test and each test on dried petioles, and (iii) the total-N and nitrate-N tests on dried petioles, were all highly significant ($P<0.001$) for the data pooled over all sites (Table 1), r ranged from 0.65 to 0.82. This indicates some interrelationships between

Table 1. Correlation coefficients (r) between nutrients
Relationships presented are significant at $P=0.001$

	Total-N	Lab NO_3-N	Nitrachek NO_3
Lab NO_3-N	0.76		
Nitrachek NO_3	0.65	0.82	
Cardy NO_3	0.73	0.73	0.76

the sap and laboratory methods, however further work is needed to determine if one can convert a measurement in one system to another method and use such converted values to interpret a calibrated plant test(Williams and Maier 1990b).

Relationships between sap nitrate and total yield

For all sites and most sampling times the linear and quadratic regression equations for relationships between relative total yield and petiole sap nitrate (by either rapid sap test method) were non-significant (Table 2). Because of the extreme lack of sensitivity to applied N, repeatability and lack of correlation with total yield; sap nitrate as assessed by either method, or nitrate-N (dried petioles), are estimated to be little value to use as an index of the N status of Brussels sprouts. Other workers obtained similar findings when sap nitrate was assessed using Merckoquant test strips (Robinson, 1991) or Merckoquant strips read on a Nitrachek meter (Scaife and Turner 1987). The latter workers found no simple relationships with sap or soil nitrate measured just prior to top dressing and yield response. Also, in paper 2 of this series (Williams and Maier submitted) we found nitrate-N in dried petioles was not a useful index of the N status of Brussels sprouts. Hence, nitrate assessed by any method is unlikely to be a useful index of the N status of Brussels sprouts.

Table 2. Equations of best fit relating total relative sprout yield (Y, %) to either Nitrachek nitrate concentration (X, mg/L) or Cardy nitrate (X, mg/L) at different sampling times for data pooled over all sites

Critical concentration at 90 and 95% of relative total sprout yield is shown.

Sampling time (weeks)	Equation	r^2	Significance of regression	Concentration at	
				90%	95%
	Nitrachek nitrate				
4	Y=82.7+0.000089X	0.0001	n.s.		
6	Y=56.3+0.0039X	0.058	n.s.		
8	Y=76.9+0.0017X	0.12	n.s.		
10	$Y=44.05+0.053X-0.000010X^2$	0.89	$P<0.001$	1581	1894
12	Y=83.6+0.0026X	0.059	n.s.		
14	Y=79.2+0.0079X	0.22	n.s.		
16	Y=81.5+0.0081X	0.11	n.s.		
18	Y=65.7+0.023X	0.87	$P<0.05$	1057	1274
20	Y=88.1+0.011X	0.068	n.s.		
24	Y=81.6+0.19X	0.12	n.s.		
	Cardy nitrate				
4	Y=59.8+0.0023X	0.039	n.s.		
6	Y=84.3+0.000049X	0.0001	n.s.		
8	Y=45.1+0.0059X	0.31	$P<0.05$	7610	8458
10	Y=80.0+0.0015X	0.044	n.s.		
12	Y=79.0+0.0021X	0.13	n.s.		
14	Y=65.1+0.0043X	0.40	n.s.		
16	Y=79.1+0.0026X	0.081	n.s.		
18	Y=4.29+0.031X	0.91	$P<0.05$	2765	2926
20	Y=91.9-0.0022X	0.026	n.s.		
24	Y=83.5+0.002X	0.015	n.s.		
28	Y=81.0+0.0032X	0.045	n.s.		

Petiole sap potassium

The main effect of K addition on total yield of sprouts was not significant ($P>0.05$) at each of the 4 sites (Williams *et al,* submitted). Likewise, there were little changes in petiole sap K concentrations in response to applied K at any site (Figure 3). Petiole sap K concentrations at nil K and 300 kg K/ha were not significantly ($P>0.05$) different at most sampling occasions. Given that no yield response to K addition occurred at any site, an evaluation of the sensitivity of sap K was not possible.

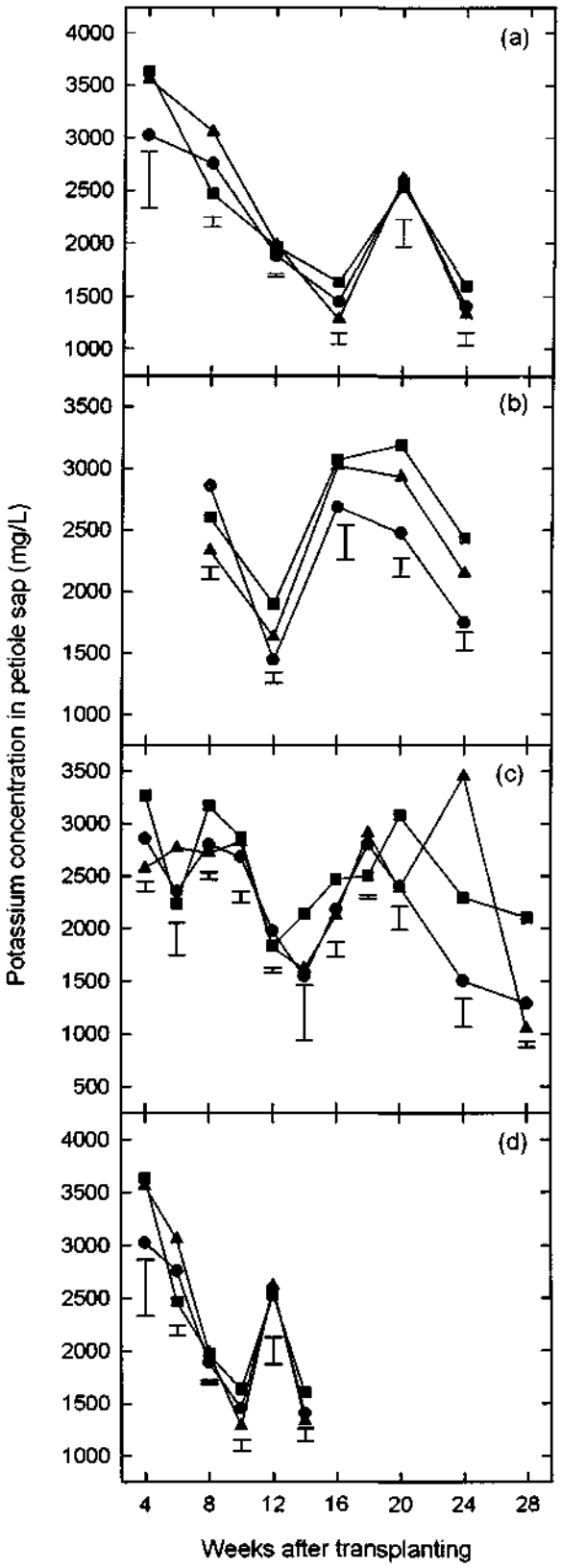

Figure 3. Relationships between K concentration in petiole sap determined by the Cardy method in Brussels sprouts and sampling time at (a) site 1, (b) site 2, (c) site 3 and (d) site 4 for 3 rates of applied K. K0 or 0 kg K/ha (●), K1 or 150 kg K/ha (▲), K2 or 300 kg K/ha (■). Vertical bars indicate standard errors of means for nil K treatments.

However, the correlation between total K (in dried petioles) and sap K (in fresh petioles assessed by the Cardy method) was low ($r = 0.185$) but significant ($P<0.001$). This suggests the sap K method may have limited sensitivity (as an index of the K status of Brussels sprouts). Weir (pers. comm.) as cited in Piggott (1986) suggested concentrations of total K in dried leaves of 2.4 to 3.4% at the heart growth stage (7 cm) some 3 to 4 months after planting for maximum yield of Brussels sprouts. We found levels of 2 to 3% K in dried petioles at this same period (Williams *et al.*, submitted) were associated with maximum yield plots.

Conclusions

This study demonstrated that petiole sap nitrate was neither a sensitive nor useful indicator of the N status and yield response for Brussels sprouts grown in temperate southern Australia.

Critical N ranges for petiole sap nitrate could not be derived at most sampling times during crop development - despite significant ($P<0.05$) yield responses to applied N at 3 of the 4 sites (Williams *et al.* submitted). Both the Nitrachek and Cardy sap nitrate procedures were not sensitive enough to determine the N status of a crop or to predict yield response nor to assess the adequacy of fertiliser programs. Determination of total-N in dried petioles was found to be a more appropriate and useful index of the N status of irrigated Brussels sprouts (Williams and Maier submitted).

Overall, the negative results for the value of sap testing for nitrate to predict the N status and yield response of Brussels sprouts although disappointing should now lead to a greater use of analyses for total-N in dried petioles as the useful and preferred index of the N status and for assessment of the adequacy of fertiliser programs for irrigated Brussels sprouts in southern Australia..

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APPENDIX 4

Interstate survey of plant nutrient concentrations in Brussels sprouts petioles.

Introduction

Petiole samples were collected from commercial crops in SA and other states to monitor nutrient concentrations in Brussels sprouts across a range of growing regions and states. A second aim was to compare the absolute and relative changes in nutrient concentrations in petioles from commercial crops grown elsewhere with both those values obtained in our experimental plots over the same range of sampling times and with the critical nutrient concentrations defined in our experiments. This would help to clarify if our results can be extrapolated to Brussels sprouts crops grown in other regions.

Methods

Petioles of the youngest fully expanded leaves (P-YFEL) were collected by collaborators and forwarded by airmail to the Lenswood Centre. Petiole samples were examined in SA and some had to be discarded due to severe wilting or odour. The remainder of samples were stored at 4°C before sap testing or oven-drying. Half of the petioles were oven dried and analysed for nutrients as described in Appendix 2. Sap was extracted from the remaining half of the petioles and rapid tests conducted for sap nitrate and potassium as described in Appendix 3.

Results and Discussion

In general, major trends in the survey data for each nutrient concentration changes over time were similar to those recorded in our experiments (Figures 1 and 4). For example, nitrate values as analysed by any method, declined rapidly to reach values near zero nitrate from 15-20 weeks after transplanting onwards (Figures 1 and 2). Also a proportion of commercial crops surveyed had nutrient concentrations close to our critical nutrient ranges (CNR) for total-N and K in dried petioles (Figures 1 and 3), other surveyed crops were below and others above our CNR. This highlights the need for decision support software and extension services for growers for improved nutrient management as described in Section 1.4 'Directions for Future Research'.

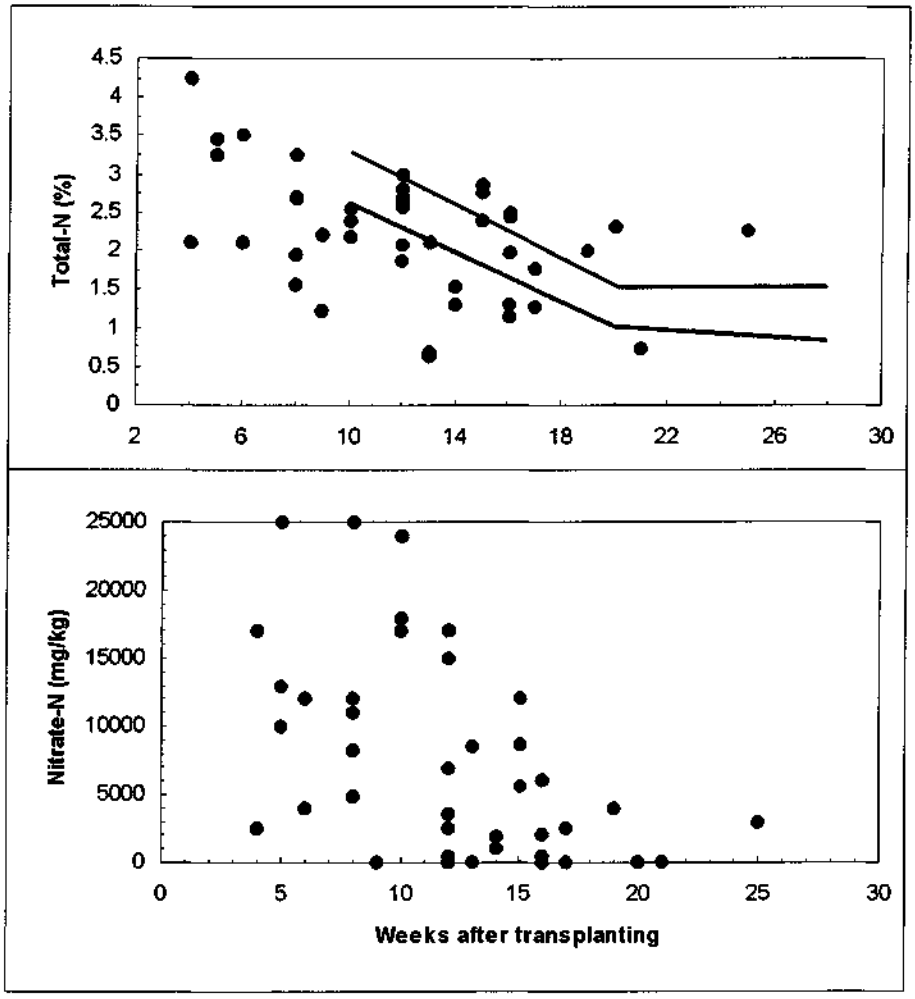

Figure 1. Relationships between total-N (top) and nitrate-N (bottom) concentrations in dried petioles and sampling time for survey samples from SA, NSW, VIC and TAS. Critical nutrient ranges for total-N for optimum yield derived from our experiments are shown in diagram form as solid lines in the top graph.

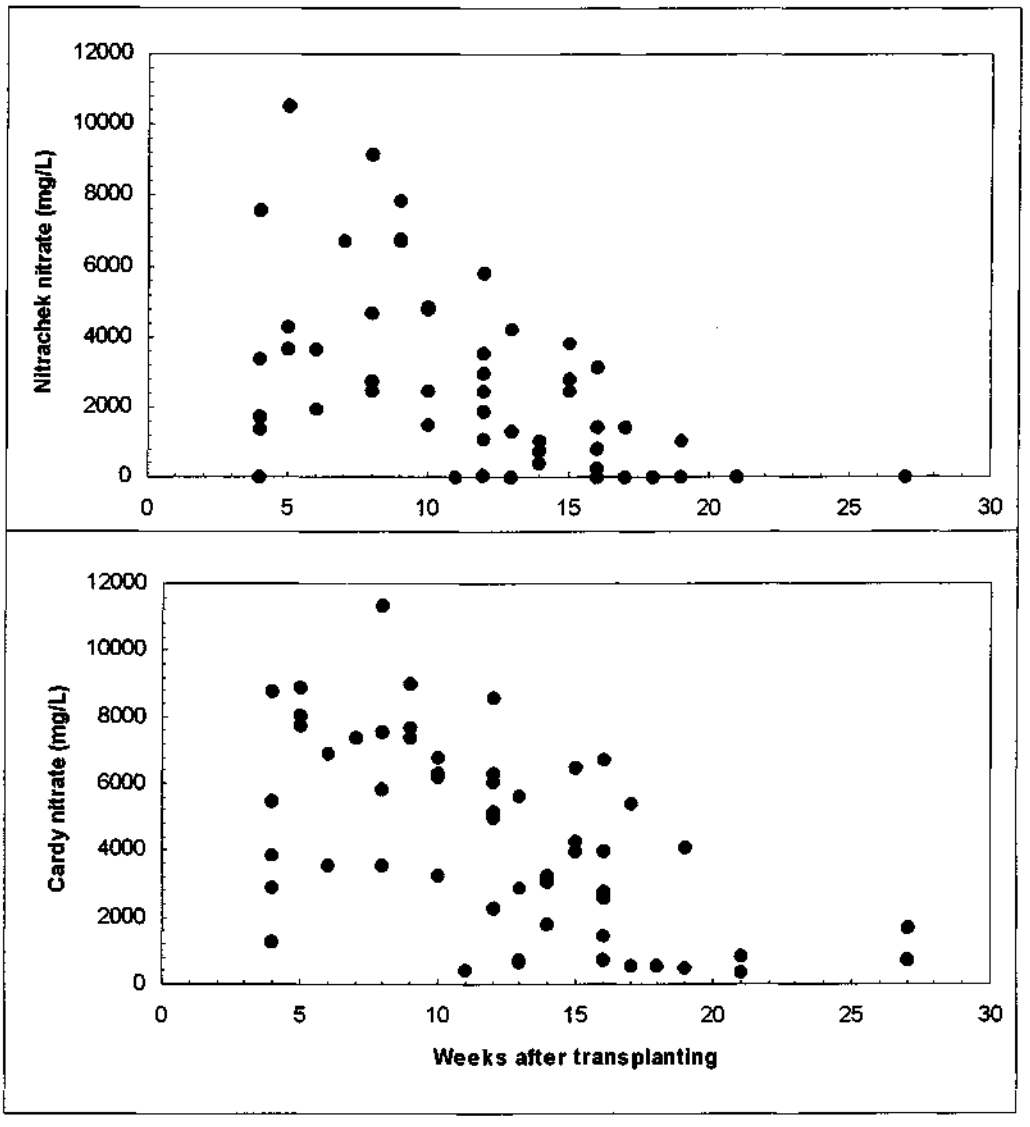

Figure 2. Relationships between Nitrachek nitrate (top) and Cardy nitrate (bottom) concentrations in petiole sap and sampling time for survey samples from SA, NSW, VIC and TAS.

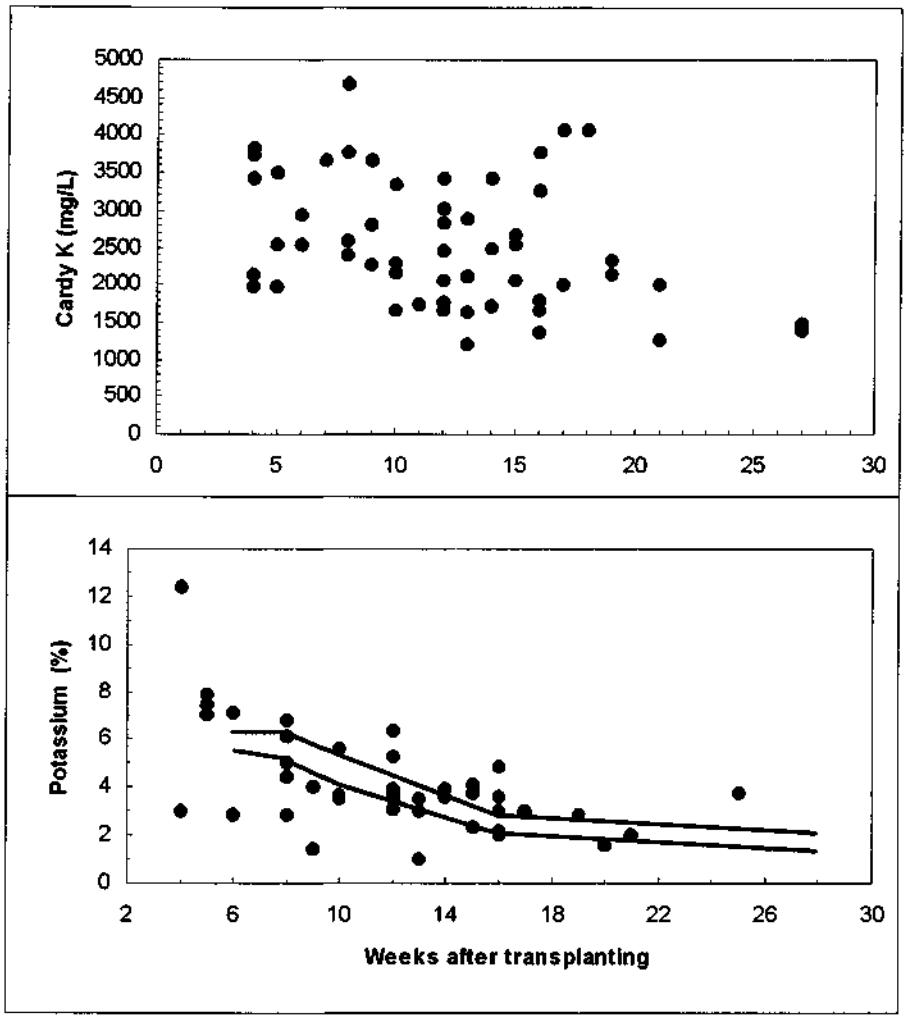

Figure 3. Relationships between Cardy potassium concentrations in petiole sap (top) and potassium in dried petioles (bottom) and sampling time for survey samples from SA, NSW, VIC and TAS. Critical nutrient ranges for potassium in dried petioles for optimum yield derived from our experiments are shown in diagram form as solid lines.

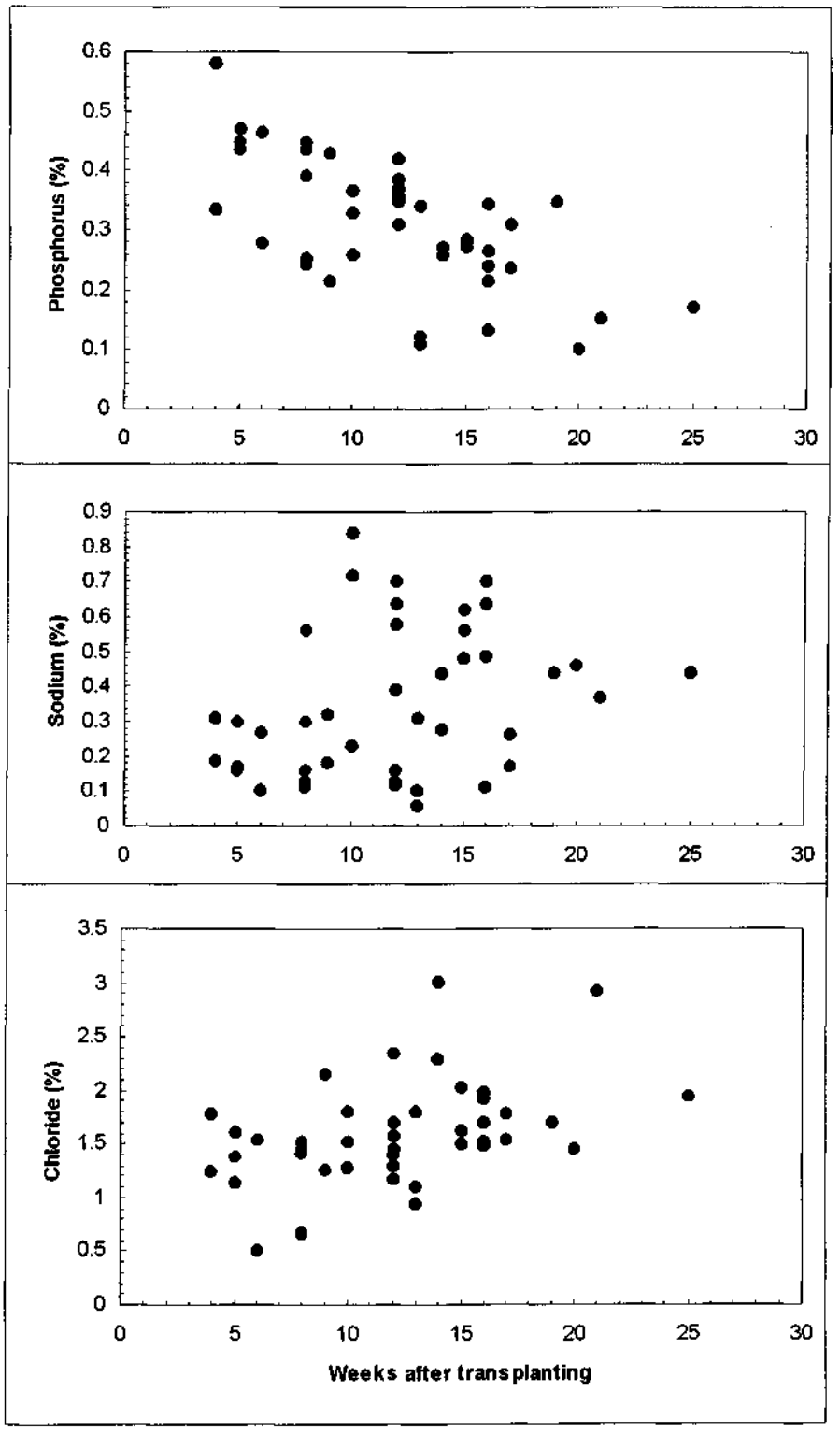

Figure 4. Relationships between phosphorus (top), sodium (centre) and chlorine (bottom) concentrations in dried petioles and sampling time for survey samples from commercial crops of Brussels sprouts from SA, NSW, VIC and TAS.