PT213

Phosphate, nitrogen and irrigation management in potatoes

Ian McPharlin, M.A. Hegney
Agriculture Western Australia
R.C. Jeffery
Chemistry Centre of WA

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Level 6
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Telephone: (02) 9418 2200
Fax: (02) 9418 1352
E-Mail: hrdc@hrdc.gov.au

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PHOSPHATE, NITROGEN AND IRRIGATION MANAGEMENT OF POTATOES

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1.0 PROJECT EXECUTIVE SUMMARY

In December 1991 we approached the Potato Growing Industry Trust Fund of Western Australia (WA) with a project proposal to investigate the irrigation and fertiliser management of table potatoes in WA over a 3 year period. There were two main issues we considered important to investigate. One was the management of phosphate fertilisers on the heavy soils of the south west (SW) of Western Australia (ie. the Manjimup, Pemberton and Busselton regions). The other was the management of phosphate, nitrogen and irrigation on the sandy soils of the Swan Coastal Plain to minimise leaching of fertilisers and associated water pollution. These soils are noted for their poor retention of nitrogen (across all sands) and phosphorus (especially the pale yellow and grey/white sands). The adjacent water pollution has been attributed to fertiliser leaching from these sandy soils.

In all these studies we used the variety 'Delaware' which is the most important variety for fresh or table consumption in WA.

Phosphorus Management

High P-fixing soils in the south west
Even though fertilisers represent 15 to 20% of the direct costs of production of potatoes, little had been done to assist growers with more profitable use of phosphorus (P) fertilisers on heavy soils in the SW. For example, there was genuine interest in the use of soil testing as part of P fertiliser management programs in the SW and growers regularly tested soils for residual P (ie. 'superbank P') and other nutrients. However, despite the wide range of levels of residual P in soils (from 6 to 220 μg/g bicarbonate extractable, Colwell, P), growers applied similar rates of P across all sites (~ 245 kg/ha). The main reason was that there were no standards, calibrated locally, to determine the amount of P required for maximum yield from soil tests on these soils. In some cases, standards from 'similar soils' in other Australian states, or from overseas, which may not have been appropriate, were used.

Preliminary estimates suggested growers could improve profit by as much as $3000 /ha by not under-fertilising with phosphorus, or save around $400/ha by not over-fertilising. In the project, 36 experiments were conducted on growers properties across the SW with 22 in the Manjimup-Pemberton area. The results showed that the traditional soil test, the Colwell P test, gave an accurate indication of whether a given site would respond to applied P. However, this test could not be used to accurately predict the amount of applied P required to achieve maximum yield on individual sites (ie. only 46% accurate). It was necessary to develop an improved soil test to enable accurate prediction of the quantity of P to apply, based on soil test readings. To achieve this, a measure of the P sorption ability of the soil was used. One test examined was the P adsorption test. This provided reasonably accurate prediction of P required for maximum yield (71% accurate), however, it is tedious and expensive to perform and so is unlikely to be used commercially. A simpler and less expensive test of soil P sorption capacity is the PRI test (= phosphate retention index) which was originally developed for ranking the P sorption capacities of the low P-fixing sands of the Swan coastal plain. We found that, when suitably modified for the higher P-fixing soils of the SW to the PRI(100) test, we could determine P required for maximum yield with 80% accuracy. Further, when this PRI(100) test was combined with the original Colwell test, the overall accuracy in determining P required for maximum yield and profit could be improved to 85%. Consequently, we are recommending that growers use both the Colwell P and PRI(100) tests to help improve P management practices on high P-fixing soils in the south west. Already one laboratory is offering both tests commercially to growers, and others are expected soon.

Preliminary comparative work with two varieties over 6 sites, Delaware, the main table variety, and Russet Burbank, the main processing variety, showed no significant difference in P requirements with soil test. This finding indicates that the soil test procedure outlined above for heavy soils may be quite robust across varieties. This will require further work as results in other states have shown varietal differences in P requirements.

Coastal sands
Soil testing was shown to be a valuable technique for improving the management of P fertilisers on the sands in the environmentally sensitive coastal areas. In contrast to the results on higher P-fixing soils, the Colwell soil P test was successfully correlated with P required for maximum yield on Karrakatta and Spearwood sands. At soil test levels above 50 μg/g Colwell P on Karrakatta sands and 90 μg/g on Spearwood sands, currently-applied P could be reduced to a maintenance level sufficient to replace crop removal (20 to 35 kg P/ha), without reducing yield. This reduction would assist in minimising the impact of applying P fertilisers to potatoes on the water systems of the coastal plain. Adoption of soil testing should also lead to increased profit as growers on the coastal plain normally apply 150 to 300 kg P/ha/crop to potato crops, irrespective of levels of residual P in the soil.

P fertiliser placement
The placement of P fertiliser was also examined on the sandy coastal plain soils as a possible means of improving P fertiliser use efficiency. Broadcasting P at planting was found to be a significantly more efficient method of applying P to potatoes than banding on Karrakatta and Spearwood sands. For example, potato yields were 142% higher (ie. 51 versus 21 t/ha) when P was broadcast compared with banding on a Karrakatta sand, and 27% higher (ie. 61 versus 48 t/ha) on a Spearwood sand. Consequently, banding P fertilisers to potatoes on the coastal sands would result in significant economic loss.

Since most growers on the coastal sands broadcast P fertilisers we will recommend they don't change their fertiliser placement strategies. We will advise those who band-place P fertilisers to potatoes on coastal sands to change to broadcasting.

Nitrogen and Irrigation Management

Research directed at determining the optimum management of irrigation to minimise the leaching of nitrogen fertilisers into the water systems of the coastal plain was conducted at the Medina Research Centre. A specific experimental design, the 'line source design', enabled us initially to examine a large number of combinations of irrigation and nitrogen levels in a reasonably small area (< 1 ha). Results showed that, for summer (February) planted Delaware potatoes, irrigation at 150% of the daily pan evaporation (after crop emergence) and 700 kg of applied N/ha was necessary for maximum total yield. In this work, the nitrogen was applied in 10 equal amounts at weekly intervals beginning at first emergence. At the 700 kg of applied N/ha level only 184 kg of N/ha ,or 26%, of the applied N was used by the crop leaving 74 % as a possible source of leaching. However, further examination of the data suggested that the level of applied N could be reduced to

417 kg/ha without significant economic loss. This would increase the recovery efficiency of applied N by the potato crop to 44%. Surveys of grower fertiliser practices have shown the average rate of applied N to potatoes on the coastal sands was 900 kg/ha/crop with a range of 356-1510 kg N/ha/crop. Therefore, adoption of the N fertiliser management recommendations from this preliminary study could result in significant savings for the growers and reduced environmental impact. An additional benefit is improved cooking quality of potatoes at lower rates of applied N.

In an effort to examine the relative N requirements of winter (July) and summer (February) planted crops, and to assess the possibility of further reducing N application levels by the use of daily rather than weekly applications, more detailed studies were conducted on Spearwood sands. In this work, N was applied in 105 equal daily amounts beginning at first emergence. Frequent measurements (at 10 day intervals) of plant growth and N uptake were made during the two crop growth seasons, in addition to measuring final tuber yield. In terms of gross total amounts of applied N, 556 kg N/ha was found to be necessary for maximum final tuber yield of wintered planted Delaware potatoes. For summer planted crops, 498 kg N/ha was required for maximum yield. However, analysis of the crop growth and N uptake data showed that whole plant and tuber growth reached a maximum before N applications were complete. Therefore, N applications after the time of maximum plant and tuber growth were unnecessary and the final total N application levels were an over-estimation of the actual quantities of N required for maximum yield. From the growth analysis data, it is suggested that, on Spearwood sands, approximately 460 kg N/ha applied up to 12 weeks after emergence is required for maximum yield of winter planted potatoes, and 350 kg N/ha applied up to 10 weeks after emergence for summer planted crops. These N levels were derived from the quantities of N applied right up to the time of maximum plant and tuber growth. Further work may show that the levels can be reduced still further as continued application of N right up to the time of maximum tuber growth is unlikely to be necessary.

At the levels N applied up to the time of maximum plant and tuber growth, in both the winter and summer seasons, an average of 46% of the N applied was removed in tubers. This is very similar to the level of N removal in tubers found in the first 'line source' study (44%) in which N was apply weekly, rather than daily, as in this second study. When considered in addition to the fact that the final critical total applied N level was higher in the summer planting in this second study, compared with that found in the first study (498 cf. 417 kg N/ha), these data suggest that applying N daily, rather than weekly, does not reduce the total quantity of N required for maximum potato yield on Spearwood sands or increase N uptake efficiency.

The data collected during this second study is sufficiently detailed to form the basis of a crop nitrogen demand model for potatoes on the Swan coastal plain. Such a model will now be developed to enable improved prediction of crop N requirements under different climatic conditions.

Extension

Results from this work have been presented to WA growers and the rest of the industry at various field days and seminars. The phosphorus results on sandy soils have been included in an Agriculture WA Bulletin on using soil testing as part of the management of P fertilisers for vegetable crops on the coastal sands. They have also been extended to growers through the *Potato Grower* and *Potato Australia* magazines. The phosphorus, nitrogen and irrigation data from this study is being used by advisers and consultants working with the potato industry, and is being incorporated into codes of best practice and quality assurance programs. Some of the data has already been published in the scientific literature, with the remainder to be published shortly.

2.0 PUBLICATIONS ARISING OUT OF THIS WORK

Research Journals

1. Hegney,M.A.,McPharlin,I.R. and Jeffery,R.C.(1997). Response of winter-grown potatoes (*Solanum tuberosum* L.) to applied and residual phosphorus on a Karrakatta sand. *Australian Journal of Experimental Agriculture* **37**,131-9.
2. Hegney,M.A.,McPharlin,I.R. and Jeffery,R.C.(1997). Using soil testing to determine phosphorus fertiliser requirements of potatoes (*Solanum tuberosum* L) in the Manjimup-Pemberton region of Western Australia. Submitted to *Australian Journal of Experimental Agriculture.*
3. Hegney,M.A and McPharlin,I.R.(1997). Broadcasting phosphate fertilisers produces higher yield of potatoes (*Solanum tuberosum* L) than band-placment on coastal sands in Western Australia. In preparation for *Australian Journal of Experimental Agriculture.*
4. Hegney,M.A and McPharlin,I.R.(1997). The nitrogen requirements of potatoes (*Solanum tuberosum* L.) at different levels of applied water using sprinkler irrigation on a Spearwood sand. In preparation for *Journal of Plant Nutrition.*

Extension Articles

1. Hegney, M.A., McPharlin, I.R., and Jeffery, R.C. (1994). Phosphorus requirements of potatoes under the microscope. *Potato Grower* (January), 4-9.
2. Hegney, M.A. (1994). Phosphorus fertiliser requirements. *Potato Grower* (September-October), 30-31.
3. Hegney,M.A.(1994). Interpreting soil analysis for potatoes on coastal sands. *Potato Grower* (December),19-21.
4. Hegney, M.A. (1994). Phosphorus requirements on sandy soils in WA. *Potato Australia* **5**, 18-19.
5. Dawson, P., Hegney, M., and Mortimore, J. (1995). Soil testing increases profit. *Potato Grower* (March), 12-17.
6. McPharlin,I.R and Hegney,M.A.(1997). Soil testing for vegetable production on the coastal plain. Bulletin No.4328, Agriculture Western Australia.(in press).

3.0 PROJECT STAFF AND COLLABORATORS

Ian McPharlin - Project Principal Investigator and Manager.

Murray Hegney - Project Research Officer.

Bob Jeffery - Project Collaborating Scientist.

Peter Dawson - Vegetable Extension Specialist.

Rani Weissberg and Tony Shimmin - ProjectTechnical Officers.

Jenny Harboard - Project Laboratory Technician - Chemistry Centre of Western Australia.

Gavin D'Adhemar - Technical Officer, Medina Research Centre.

John Doust - Formerly Senior Technical Officer, Manjimup Horticultural Research Centre.

Harald Hoffman - Technical Officer, Manjimup Horticultural Research Centre.

Staff of Medina Research Centre.

Staff of Manjimup Horticultural Research Centre.

Staff of Chemistry Centre of Western Australia.

Using soil testing to determine phosphorus fertiliser requirements of potatoes (*Solanum tuberosum*) in the Manjimup-Pemberton region of Western Australia

M.A. Hegney, I.R. McPharlin and R.C. Jeffery

Summary

Field experiments were conducted over 3 years at 22 sites in the Manjimup-Pemberton area of Western Australia to examine the effects of freshly-applied (current) and previously applied (residual) phosphorus (P) on the yield of potatoes (*Solanum tuberosum* L. cv. Delaware) and petiolar P concentrations, and to calibrate, in terms of total yield, the Colwell soil P test. The P was placed (banded) at planting, 5 cm either side of and below seed planted at 20 cm depth, at levels up to 800 kg P/ha, The relationships between level of current P required for maximum yield, the Colwell soil P test and two P sorption indices (phosphate adsorption (P-adsorb) and phosphate retention index (PRI)) were examined.

Phosphorus application significantly ($P<0.05$) increased total tuber yield at 15 sites. The mean percentage of maximum (relative) yield for these responsive sites was 50.3% (range 10.4 - 85.9%), compared with 97.6% (range 89.2 - 101%) for the non-responsive sites. Marketable tuber yield response paralleled total tuber yield response at all sites. Marketable tuber yields averaged 85% of total tuber yields (range 63-94%).

Across all sites, there was a significant ($P<0.001$) Mitscherlich relationship between yield response to applied P and Colwell soil P test value. The fitted equation accounted for 86% of the variation in relative tuber yield. The soil P test value required for 95% of maximum yield was 147 µg/g, and 174 µg/g for 99% maximum yield.

There was a significant ($P<0.001$) negative linear relationship between Colwell soil P test value and the level of applied P required for 99% of maximum yield (P required or PR). However, the fitted model accounted for only 47% of the variation in PR across individual sites. Significant ($P<0.001$) positive linear relationships were found between P-adsorb and PR, and between a modified PRI (PRI(100)) and PR. These relationships accounted for 71 and 80%, respectively, of the variation in PR, much higher than that accounted for by the Colwell soil P test. However, the most accurate predictions of P Required were achieved by considering together the Colwell soil P test value and PRI(100). The fitted multiple linear regression equation involving these parameters accounted for 85% of the variation in PR.

When tubers were 10 mm long, the total P in petioles of youngest fully expanded leaves which corresponded with 95% of maximum yield was 0.41% (dry weight basis). For 99% it was 0.54%.

These results show that, while the Colwell soil P test is a useful predictor of the responsiveness of potato yield to applied P across a range of soils in the Manjimup-Pemberton region, consideration of both the soil P test level and the P sorption capacity of the soil, as determined here by PRI(100), is required for accurate predictions of the level of P fertiliser required to achieve maximum yields on individual sites.

Introduction

The Manjimup-Pemberton region is the most important potato production area in Western Australia (WA) producing 54% of WAs total production of 106,000 tonnes in 1993/94 (Kelly 1994). This included 35% of the fresh, 92% of the French fry and 45% of the States crisping potatoes.

In recent years, as profit margins have decreased, growers have reviewed fertiliser practices with the aim of reducing input costs. In the past, growers in the Manjimup-Pemberton region have applied phosphorus (P) according to either tradition or general regional recommendations. The regional recommendations were based on experiments which showed potatoes required 250-285 kg P/ha for maximum yield on newly cleared Karri loams in the area (Fallon 1961). A survey of grower fertiliser practices in the area from 1991-1993 showed the mean amount of P applied by 119 growers was 245 kg/ha with a range of 200 to 300 kg P/ha (unpublished data of M.A. Hegney). Of most interest was that growers applied similar amounts of P to soils with very different P fertiliser histories and therefore different soil P test values. These ranged from 6 to 220 µg/g Colwell P (Colwell 1963) in the top 0-15 cm, the standard depth used in WA for horticultural crops. Consequently, growers could be losing money by over or under fertilising depending on the levels of residual P in the soil.

Soil testing has been used to determine optimum amounts of applied P for maximum yield of potatoes over a wide range of soil types. For example, on sandy loams and loams (podzolic soils) in South Australia 30 to 40 µg/g Colwell P was adequate for 95% of maximum yield, whilst for siliceous sands 7.5 µg/g Colwell P was adequate (Maier *et al.* 1989a). In Tasmania, yield responses to applied P were recorded on krasnozem soils with 210 µg/g Colwell P (Sparrow *et al.* 1992). On krasnozems in the Ballarat area of Victoria the amount of applied P required for maximum yield of cv. Kennebec potatoes ranged from 89 kg P/ha at <20 µg/g Olsen P (Olsen *et al.* 1954) to 0 kg P/ha at >66 µg/g (Strange and Marshall 1990). This upper level of 66 µg/g Olsen P equates to 284 µg/g of Colwell P, based on the results of Sparrow *et al.* (1992) from similar soils. The P required for 99% of maximum yield of winter-grown potatoes on a Karrakatta sand in WA ranged from 161 kg P/ha on virgin sites with <10 µg/g Colwell P, to 0 kg P/ha for Colwell P >51 µg/g (Hegney *et al.* 1997). In the latter study, for 95% of maximum yield, 99 kg P/ha was required on virgin sites and 0 kg P/ha for Colwell P >33 µg/g. On high P fixing soils in Idaho, USA, P required for maximum yield varied from 228 kg P/ha on soils with Olsen P <5 µg/g, to 0 kg P/ha at 30 µg/g Olsen P (Tindall *et al.* 1991). In California, USA, 80 µg/g Olsen P was recommended as adequate for maximum yield without additional fertiliser (Tyler *et al.* 1961).

The variability, referred to above, in the soil P test values above which no further response to applied P was recorded indicates that the relationship between yield response to applied P and soil P test value is site and/or soil type specific. In a review of 30 years of soil P testing data for crops and pastures in South Australia, Reuter *et al.* (1995) concluded that the Colwell soil P test was reasonably robust in predicting yield response to applied P across a range of sites and crop species. However, they suggested the sensitivity of soil P tests on a given site could be enhanced by considering other factors such as soil type, surface soil texture or soil P sorption indices. Reuter *et al.*(1995) advocated the use of "additional sites descriptors", such as P buffering capacity (Helyar and Spencer 1977;

Holford 1979, 1980; Holford *et al.* 1985), P sorption indices (Ozanne and Shaw 1967, 1968; Bache and Williams 1971), reactive soil iron and aluminium (e.g. Lewis *et al.* 1981; Maier *et al.* 1989a), or other easily determined surrogate tests to improve the prediction of soil P tests. Colwell P is most commonly used in WA for soil P testing. For horticultural soils, the phosphorus retention index (PRI, Allen and Jeffery 1990) is being offered by commercial laboratories as a measure of the capacity of the soil to sorb P. There are no published data on the relationship between yield responsiveness of potatoes to applied P and Colwell soil P test on soils in the Manjimup-Pemberton region. There is also no information on whether including a measure of P sorption of the soil, such as PRI or P sorption, will improve the prediction of P fertiliser requirements for potatoes in this region over that achieved by the Colwell soil P test alone.

As a check on the adequacy of P fertiliser programs, plant analysis is commonly used to assess the P status of potato crops. Based on sampling petioles of youngest fully expanded leaves (P-YFEL), critical total P concentration ranges have been proposed for different crop growth stages. For example, in South Australia, Maier *et al.* (1989b) proposed a critical total P concentration range of 0.41 - 0.53% (dry weight basis) in P-YFEL sampled when the longest tubers are 5-10 mm long. Roberts and Dow (1982) in California, proposed a critical total P concentration range of 0.38-0.45% in P-YFEL at the 20 mm tuber stage.

The work described in this paper aimed to (1) investigate the relationship between yield response current applied P and Colwell P for potatoes grown in the Manjimup-Pemberton region of WA, (2) assess the ability of the Colwell test to estimate the current P status of the soil and therefore whether it is profitable to use current applied P for the next crop, and (3) to examine whether the prediction of crop P fertiliser requirement at individual sites is improved by consideration of the capacity of the soil to sorb P. The relationship between relative tuber yield and total P concentration in P-YFEL , sampled when the largest tubers were 10-15 mm long, was also examined and a critical concentration range is suggested.

Materials and Methods

Field experiments

Field experiments were conducted on commercial properties in the Manjimup-Pemberton region in the south west of Western Australia over 3 consecutive seasons - 1992/93, 1993/94 and 1994/95. Some of the chemical and physical properties of the soils at each site are given in Table 1. The very high level of Colwell P on site 22 (560 μg/g) was the result of 1450 kg P/ha being applied as double superphosphate and incorporated to a depth of 25 cm with a rotary hoe 2 years before planting. In each year, all experiments were planted during October - November and harvested the following February - March. The experimental design was a randomised block with 4 replications. At sites 1-17 and site 22, 8 levels of phosphorus(P) (sites 1-12: 0, 50, 100, 200, 300, 400, 500 and 600 kg P/ha; sites 13-16: 0, 20, 40, 80, 120, 240, 450 and 600 kg P/ha; sites 17 and 22: 0, 10, 20, 40, 80, 120, 240 and 480 kg P/ha) were applied. At sites 18-21, 6 levels of P (0, 50, 100, 200, 400 and 800 kg P/ha) were applied. For experiments conducted during 1992/93, triple superphosphate (19.7% P) was used as the P source. For later experiments, double superphosphate (17.5% P) was used.

At all sites, basal fertiliser containing nitrogen, as ammonium sulphate, at 75-135 kg N/ha and potassium, as potassium sulphate, at 175-250 kg K/ha was applied depending on soil type, cropping history and the quantities being used by the grower on the surrounding crop. In addition, all sites received magnesium, as $MgSO_4.H_2O$ at 17 kg Mg/ha and 100 kg/ha of a blended trace element mix (Essential Minerals®, W.A. Produce and Agricultural Supplies) containing 12% Mg, 6% Zn, 6% Mn, 2% Fe, 2% Cu, 0.5% B, 6% S and 0.005% Mo.

The field procedure at each site was as follows: (i) after ground preparation, a uniform area (12m x 60m) of land was selected; (ii) a soil sample from the surface 0-15 cm was collected systematically by taking 40, 5 cm diameter cores along a zig-zag course through each trial area. The cores were bulked and sub-sampled for analysis; (iii) cut seed of the cultivar Delaware was planted by machine at the same time as the basal and treatment fertiliser was placed as a double band 5 cm either side of and below the seed pieces using a tractor mounted planter/belt fertiliser applicator; (iv) row spacings varied from 0.76 to 0.8 m depending on grower practice, while in-row seed piece spacing was 0.15 m; (v) plots were 2 rows by 9 m, except at sites 17 and 22 where plots were 3 rows by 10 m; (vi) treatments were directed across rows and replicates down rows; (vii) after natural haulm senescence, tubers from a 7 m section of each row were mechanically lifted onto the soil surface and then picked up by hand. The total tuber yield from each plot was recorded. The yield of marketable tubers (80-450 g) was also recorded.

Cultivation, pest and disease management, irrigation and any post-planting fertiliser applications (minus any P) were carried out by the grower. All crops were sprinkler irrigated.

Soil analysis

Soil samples were air-dried and sieved on a 2 mm screen before chemical analysis. Soils were analysed for extractable phosphorus using the method described by Colwell (1963), hereafter referred to as soil P test. It is the amount of P extracted from the soil when 1 g of soil is equilibrated with 100 mL of 0.5 M $NaHCO_3$ at pH 8.5 on an end over end shaker (10 rpm) for 16 h at 23°C. Soils collected from sites 1-12 and 18-22 were also analysed for extractable phosphorus using the method described by Olsen *et al.* (1954). It is the amount of P extracted from the soil when 1 g of soil is equilibrated with 20 mL of 0.5 M $NaHCO_3$ at pH 8.5 for 30 minutes. Soils were analysed for organic carbon by the procedure of Walkley and Black (1934) and pH in 0.01 M $CaCl_2$ at a soil:solution ratio of 1:5. On samples from sites 1-17, total soil phosphorus was determined on a Kjedahl digest of soil ground to less than 0.15 mm. The P was measured by the method of Murphy and Riley (1962). The phosphorus retention index (PRI) was determined on each sample using the method described by Allen and Jeffery (1990). PRI is calculated by dividing the amount of P sorbed by the soil by the concentration of P measured in the equilibrium solution when the soil is equilibrated with a solution of 10 µg/mL P in 0.02M KCl at 23°C and a soil solution ratio of 1:20. For comparison, an alternative phosphorus retention index (PRI100) was also determined using the method described above, but with a soil solution ratio of 1:100. Phosphate adsorption (P-adsorb) was determined by the method of Ozanne and Shaw (1967). It is the amount of P sorbed by the soil that is in equilibrium with 0.3 µg/mL of P in solution. Particle size was determined using a method adapted from Loveday (1974) using a plummet suspended below an electronic balance.

Petiole phosphorus analysis

Thirty petioles from youngest fully emerged leaves (P-YFEL)(the fourth or fifth from the growing terminal) were collected per plot when the largest tubers were 10-15 mm long. The petiole samples were dried at 70°C in a forced draught oven for 48 h and ground to pass through a 1 mm screen. Subsamples were digested with sulphuric acid and hydrogen peroxide (Yuen and Pollard 1954) and P was measured as the molybdo-vanadate complex by an automated colorimetric process (Varley 1966)

Statistical analysis

For each site, the yield data were analysed by analysis of variance. Linear, Mitscherlich ($y = a\text{-}b\exp(\text{-}cx)$) and spline ($y = a+b(x\text{-}c)$, Bolland *et al.* 1987) models were fitted to mean data for the relationship between yield and the level of current applied P from all sites. The best fitting model was used to estimate maximum yield. Where a linear model was fitted, the yield at 100 kg P/ha, as calculated from the fitted equation, was taken as the maximum yield. Where a Mitscherlich or spline model was fitted, the *a* coefficient was taken as the maximum yield. The relative yield at each site was calculated as 100x(mean yield without P/maximum yield). A Mitscherlich equation was then fitted to the relationship between soil P test and relative yield. For each site, the level of applied P corresponding with 95 and 99% of maximum yield was calculated from the fitted model.

A Mitscherlich equation was also fitted to the combined data on %P in P-YFEL versus relative yield from all sites and %P corresponding with 95 and 99% relative yield was determined.

Table 1. Selected chemical and physical properties (air-dry basis) of surface (0-15 cm) soils for each experimental site.

Site No.	Colwell P (mg/kg)	Olsen P (mg/kg)	Total P (mg/kg)	P-adsorb (mg/kg)	PRI	PRI(100)	pH ($CaCl_2$)	Organic carbon (%)	Particle size distribution (%)			
									stones	sand	silt	clay
1992/93												
1	9	3	340	840	>1000	516	5.8	4.7	20	82.5	12.5	5.0
2	17	5	350	670	>1000	300	6.0	4.2	44	78.5	15.0	6.5
3	35	11	520	460	>1000	137	5.3	2.9	25	83.2	10.5	6.2
4	37	10	590	400	>1000	108	5.4	3.2	33	86.0	10.0	4.0
5	45	10	1000	910	>1000	738	5.5	4.0	27	75.0	19.5	5.5
6	50	15	790	790	>1000	353	5.0	6.2	18	83.0	13.5	3.5
7	54	16	600	500	>1000	202	5.5	3.2	20	83.5	9.0	7.5
8	67	24	440	130	79	32	5.4	2.3	7	91.5	6.5	2.0
9	77	29	560	210	330	58	4.8	2.6	39	84.5	8.0	7.5
10	82	24	940	600	>1000	264	5.2	3.2	30	78.5	12.5	9.0
11	170	66	1000	210	380	57	4.7	2.2	30	85.5	6.0	8.5
12	150	53	840	250	490	60	4.8	2.7	30	82.5	8.2	9.2
1993/94												
13	72	-	470	280	610	88	4.8	3.2	26	85.0	7.5	7.5
14	45	-	550	480	>1000	254	5.1	4.1	8	72.5	18.5	9.0
15	110	-	990	410	>1000	198	4.7	3.7	23	80.5	11.0	8.5
16	48	-	690	770	>1000	589	5.3	4.4	21	80.5	13.0	.5
17	160	-	900	240	410	76	4.7	3.5	23	82.0	9.5	8.5
1994/95												
18	43	11	-	430	>1000	285	5.2	6.9	57	85.0	9.0	6.0
19	165	48	-	270	440	120	5.4	4.1	29	86.0	8.0	6.0
20	150	55	-	139	117	35	4.6	2.8	28	87.0	6.0	7.0
21	50	12	-	620	>1000	445	5.4	3.3	41	77.0	15.0	8.0
22	560	140	-	69	104	16	4.9	3.2	47	79.0	10.0	11.0

Results and Discussion

Soil chemical and physical properties
All of the sites chosen for this study had acid surface (0-15 cm) soils. All 22 soil samples had pH values in the range 4.6-6 (Table 1). The majority of surface soils were gravelly loamy sands, but ranged in texture from gravelly sands (sites 8 and 19) to gravelly sandy loams (sites 5, 14, 21 and 22).

The sandy surface soils had the lowest P-adsorb and PRI values, with the only exception being at site 22 which had an artificially created, very high soil P test level. On sites with P-adsorb values higher than 300, PRI values exceeded 1000, but are reported as >1000. Phosphorus retention index values greater than 1000 are recorded when the equilibrium solution P concentration is less than 0.2 μg/mL. The analytical error associated with measurements of solution P concentrations less than this is considered too great to enable PRI values greater than 1000 to be reported with confidence (Allen and Jeffery 1990). One solution to this problem would be to use the P-adsorb test, rather than the PRI, to distinguish the different P sorption capacities of high P-fixing soils. However, compared to the single point PRI test, the P-adsorb test requires the determination of a P sorption isotherm which involves adding several levels of P to define the sorption curve (Ozanne and Shaw 1967). This is more time consuming and costly and so P-adsorb is not routinely done by commercial laboratories. Modification of the PRI test was considered a more practical solution. One possible modification would have been to start with a higher initial solution P concentration. For example, Bache and Williams (1971) postulated that a more useful P sorption index would be achieved by using a starting P concentration of 77.5 μg/mL, compared with 10 μg/mL for the PRI. The Bache and Williams (1971) P sorption index has been used successfully elsewhere in Australia to distinguish the different P sorption abilities of a range of soil types with varying P-fixing abilities. (eg. Maier *et al.* 1989a; Holford and Cullis 1985).

An alternative to increasing the starting solution P concentration is to reduce the soil:solution ratio. We chose this alternative because Western Australian soil analysis laboratories are currently routinely determining PRIs on samples of sandy soils from the Swan coastal plain. The PRI has proved useful in separating these sandy soils based on their relatively much lower P sorption capacities (eg. McPharlin *et al.* 1990) and hence we see no need to modify the test for these soils. However, for soils with higher P sorption capacities, a modification is required and we consider it would be simpler for commercial laboratories to change the amount of soil used rather than changing the starting solution P concentration. We found that by changing the soil:solution ratio from 5 g soil/100 mL solution, to 1 g/ 100mL it was possible to achieve meaningful measurements of P sorption capacity across all soil samples in our study. We have called this modified test PRI(100) to distinguish it from the standard PRI (Table 1).

Tuber yield
Total tuber yield increased significantly ($P<0.05$) in response to applied P at 15 sites (Table 2). The mean relative yield for these responsive sites was 50.3% (range 10.4 - 85.9%), compared with 97.6% (range 89.2 - 101%) for non-responsive sites.

At sites 13 and 15, a spline equation best described the relationship between applied P and total tuber yield. At all other responsive sites a Mitscherlich equation best described the data. For non-responsive sites, linear equations were fitted, except at site 8 where a Mitscherlich equation better ($P<0.1$) described the data.

At all sites, marketable tuber yield response paralleled total tuber yield response (data not shown). On average, marketable yields were 85% of total tuber yields (range 63 - 94%).

Table 2. Regression equations relating total tuber yield to level of applied phosphorus, together with relative yields and level of applied P (P Required) to achieve given percentages of maximum yield for all sites.

Site No.	Regression equation	R^2	Significance[1]	Relative yield (%)	P Required (kg/ha) 95%	P Required (kg/ha) 99%
1	$Y = 60.4\text{-}53.8\exp(-0.022X)$	0.94	***	10.4	131	210
2	$Y = 57.8\text{-}40.9\exp(-0.022X)$	0.91	***	28.2	120	195
3	$Y = 51.8\text{-}31.9\exp(-0.031X)$	0.97	***	38.2	81	135
4	$Y = 54.5\text{-}34.3\exp(-0.036X)$	0.96	***	36.9	70	113
5	$Y = 61.1\text{-}34.1\exp(-0.01X)$	0.90	***	40.7	241	420
6	$Y = 74.5\text{-}29.3\exp(-0.021X)$	0.95	***	60.2	98	175
7	$Y = 53.8\text{-}24.3\exp(-0.018X)$	0.92	***	55.2	122	210
8	$Y = 59.8\text{-}6.5\exp(-0.108X)$	0.50	ns	89.2	7	22
9	$Y = 44.9\text{-}6.3\exp(-0.108X)$	0.82	***	85.9	10	25
10	$Y = 73.5\text{-}23.1\exp(-0.021X)$	0.85	***	68.4	87	160
11	$Y = 38.0+0.003X$	0.102	ns	99.0	0	0
12	$Y = 69.4+0.0076X$	0.51	*	96.0	0	7
13	$Y = 78.2+0.1552*(X\text{-}132.9)$	0.90	***	75.0	107	128
14	$Y = 84.1\text{-}49.5\exp(-0.0138X)$	0.93	***	39.1	178	290
15	$Y = 62.6+0.097*(X\text{-}144.7)$	0.63	***	79.0	113	138
16	$Y = 89.6\text{-}69.8\exp(-0.0115X)$	0.95	***	21.0	159	380
17	$Y = 78.1+0.008X$	0.081	ns	99.0	0	1
18	$Y = 72.0\text{-}28.8\exp(-0.0175X)$	0.87	***	61.0	119	211
19	$Y = 78.7+0.0093X$	0.66	*	99.0	0	0
20	$Y = 70.95\text{-}0.0034X$	0.07	ns	100.0	0	0
21	$Y = 65.1\text{-}29.0\exp(-0.013X)$	0.98	***	5.0	168	293
22	$Y = 69.0\text{-}0.0095X$	0.105	ns	101.0	0	0

1. *** = $P<0.001$, ** = $P<0.01$, * = $P<0.05$, ns = not significant

Critical soil P test level

When the data from all sites was combined, there was a significant ($P<0.001$) Mitscherlich relationship between relative tuber yield and soil P test level (Figure 1). The fitted equation accounted for 86% of the variance in the data which indicates that Colwell P is a useful predictor of potato yield response to P fertiliser on soils in the Manjimup-Pemberton region. In contrast, Maier *et al* (1989a) found that, compared with the Bray 1 and 2 (Bray and Kurtz, 1945) and Olsen (Watanabe and Olsen, 1965) soil tests, Colwell P was less effective in separating responsive and non-responsive sites for potatoes on loamy sand and sandy clay loam soils in South Australia. Similarly, Holford and Cullis (1985) found that the Colwell soil P test was inferior to other soil tests for predicting the response of wheat to applied P in New South Wales.

From the fitted equation in Figure 1, the soil P test level corresponding with 95% relative yield was 147 µg/g, and for 99% relative yield was 174 µg/g. These critical levels are higher than those found for a range of sandy loams and loams in South Australia (40 µg/g for 95% max. yield, Maier *et al.* 1989a) and for Karrakatta sands in Western Australia (33 μg/g for 95% max. yield and 51 μg/g for 99% max. yield, Hegney *et al.* 1997), but lower than the level at which potato yield responses to applied P have been recorded on the high P fixing krasnozem soils in Tasmania (210 μg/g, Sparrow *et al.* 1992).

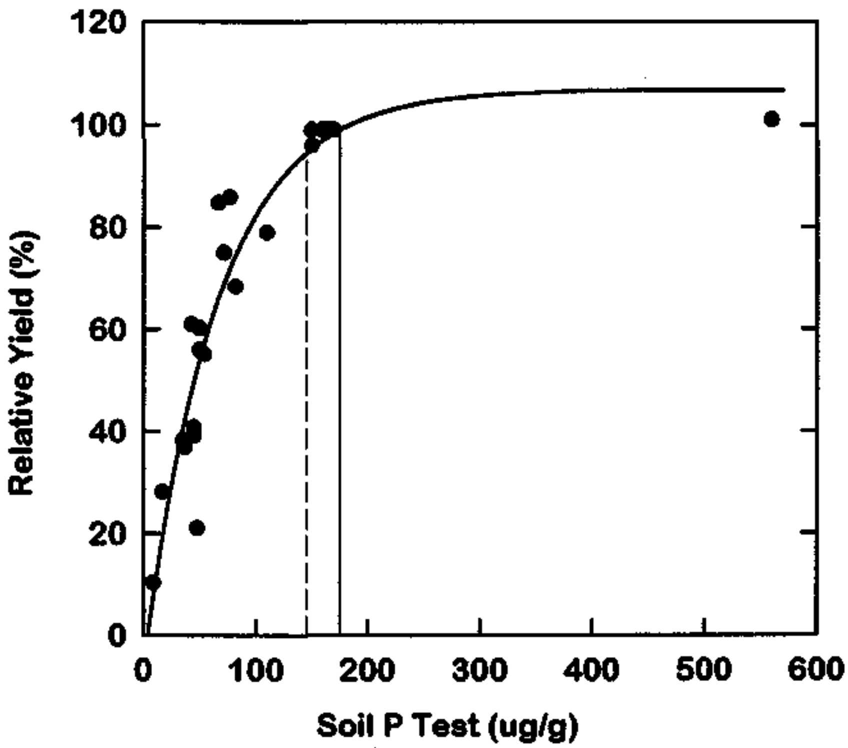

Figure 1. Relative total yield of potatoes in response to soil phosphorus (P) test on all sites. Broken and unbroken lines refer to 95 and 99% of maximum yield respectively. The equation of the fitted line is:

$$Y = 106.8 - 113.4\exp(-0.0153X) \quad (R^2 = 0.86, P<0.001)$$

Predicting P fertiliser requirement

In terms of P fertiliser management, the likely magnitude of potato yield response to applied P on a given site is an important criteria. However, of more practical concern is the amount of P required to obtain that response. In the current study, a significant ($P<0.001$) negative linear relationship was found between the level of applied P required to achieve 99% of maximum yield (P_{opt}) and soil P test level (Figure 2). However, as shown by the R^2 value, the fitted equation accounted for only 47% of the variance in the data. The percent variance accounted for did not improve when a quadratic relationship was fitted to the data, or when the amount of applied P required to achieve 95% of maximum yield was substituted for the amount required to achieve 99% maximum yield (data not shown). This suggests that, for soils in the Manjimup-Pemberton region, while Colwell P is a good predictor of responsiveness of potato yield to applied P on an individual site, it is a poor predictor of the amount of applied P required to achieve a given yield response.

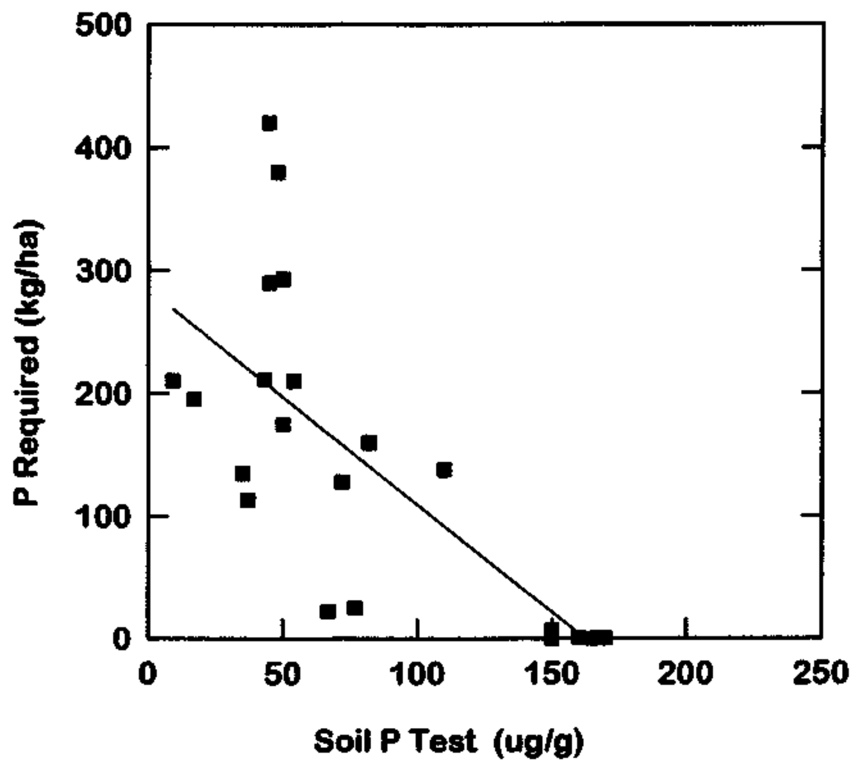

Figure 2. Relationship between level of phosphorus required for 99% of maximum yield (P Required) and soil phosphorus (P) test. The equation of the fitted line is:

$$Y = 284.4 - 1.748X \quad (R^2 = 0.47, P<0.001)$$

A better relationship than that between P_{opt} and soil P test was found between P_{opt} and P adsorb (Figure 3). The significant ($P<0.001$) positive linear relationship between these two variables accounted for 71% of the variance in the data. This supports the data of Ozanne and Shaw (1967) who, in field and pot experiments, found that P-adsorb accounted for over 80% of the variation in P required to achieve 90% of maximum pasture yield on a range of soil types in Western Australia. Together, these results suggest that P-adsorb, on its own, may be an adequate predictor of P fertiliser requirement for a range of crops across different soil types. However, as indicated previously, due to cost, P-adsorb is unlikely to be offered as a routine test by commercial laboratories.

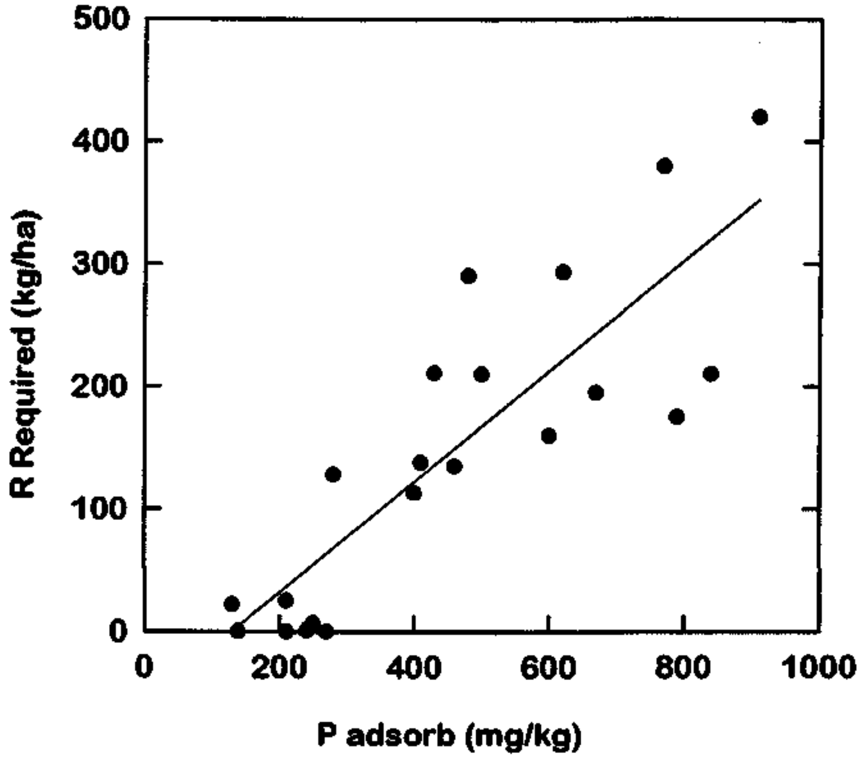

Figure 3. Relationship between level of phosphorus required for 99% of maximum yield (P Required) and phosphate adsorption (P-adsorb) (Ozanne and Shaw 1967). The equation of the fitted line is:

$$Y = -58.3 + 0.451X \quad (R^2 = 0.71, P<0.001)$$

A significant (P<0.001) positive linear relationship was also found between P_{opt} and PRI(100) (Figure 4). This relationship was not only better than that between P_{opt} and soil P test, but accounted for a higher proportion of the variation in P requirement than P-adsorb (80% cf. 71%). The PRI(100) test has the added advantage of being a relatively low cost, and simple test that could be offered routinely by commercial laboratories.

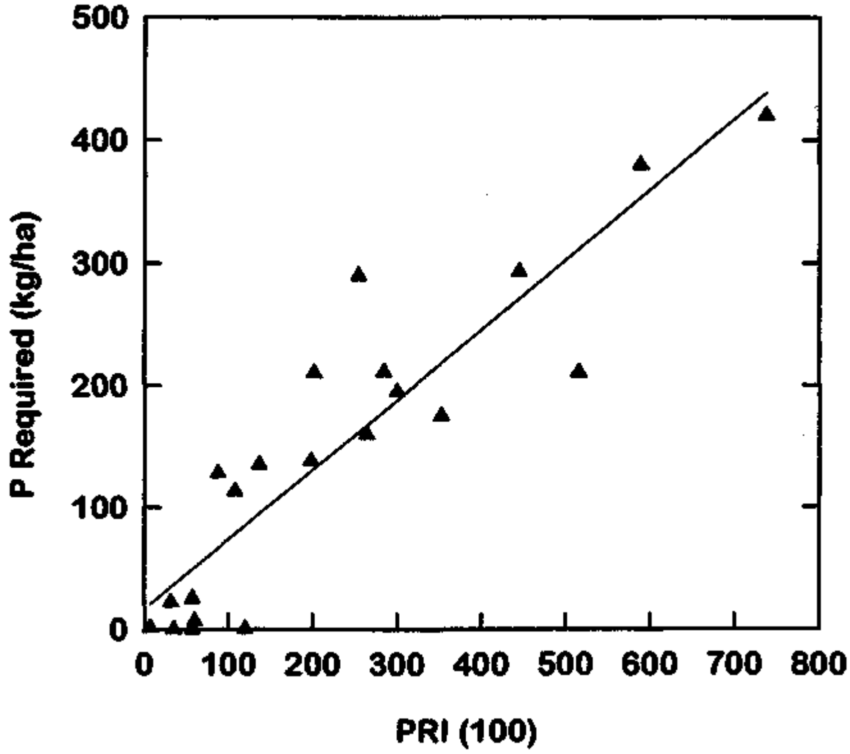

Figure 4. Relationship between level of phosphorus required for 99% of maximum yield (P Required) and PRI(100). The equation of the fitted line is:

$$Y = 16.3 + 0.572X \quad (R^2 = 0.80, P<0.001)$$

Reuter *et al.* (1995) concluded that, while the Colwell soil P test was a reasonably robust predictor of P fertiliser requirements for a range of crop species over a diverse range of soils in South Australia, the predictive efficacy of soil P tests could be improved by consideration of "additional site descriptors", such as a P sorption index. In our study, when added together as part of a multiple linear regression, considering both soil P test value and PRI(100) for predicting P_{opt} was better than either of these measures on their own (R^2=0.85). The response surface of the relationship between P_{opt}, soil P test and PRI(100) is shown in Figure 5. From the fitted response surface, it can be seen that P_{opt} was more responsive to PRI(100) than to soil P test. However, as soil P test level contributed significantly (P<0.001) to the fitted relationship, we suggest that both PRI(100) and soil P test level should be considered together when determining the P fertiliser requirements of potatoes on the soils in the Manjimup-Pemberton region of Western Australia. A similar conclusion was reached by Holford and Cullis (1985) after analysing data from 39 P fertiliser field experiments with wheat in NSW. They found that taking into account soil P sorptivity as well as extractable P level gave substantial improvements in their predictive model of P fertiliser requirement.

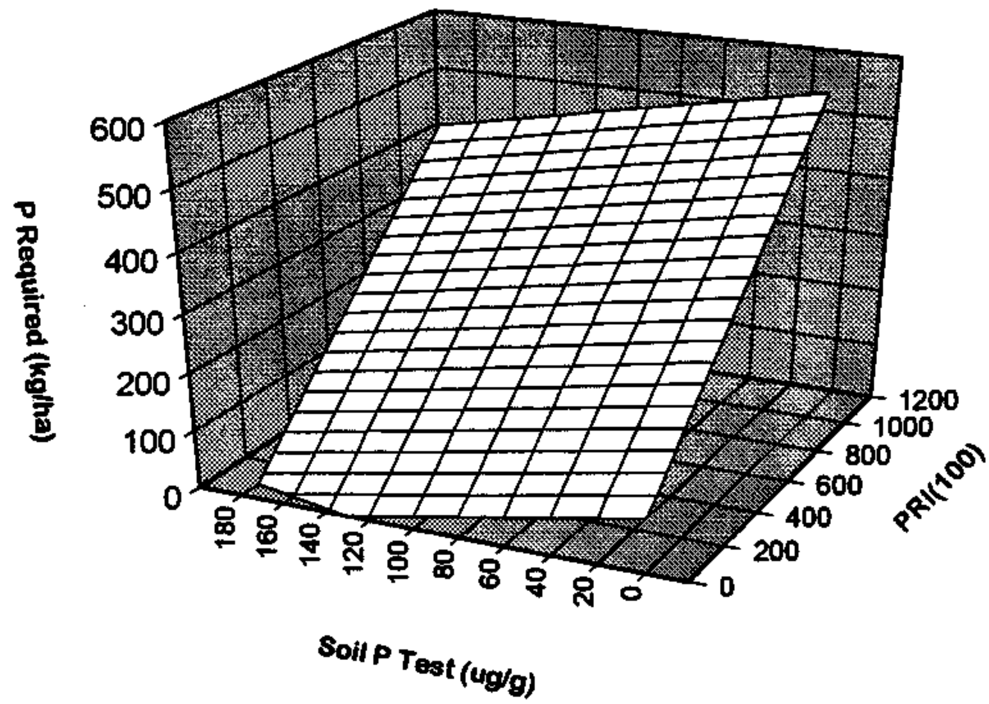

Figure 5. Level of phosphorus required for 99% of maximum yield (P Required) in response to soil phosphorus (P) test and PRI(100). The equation of the fitted surface is:

$$P\ Required\ (kg/ha) = 92.3 + 0.474 PRI(100) - 0.706 Soil\ P\ Test \quad (R^2 = 0.85, P<0.001)$$

Petiole phosphorus

The relationship between relative tuber yield and %P in P-YFEL at the 10 mm tuber stage is given in Figure 6. From the fitted Mitscherlich equation, the %P corresponding with 95% maximum yield was 0.41, and for 99% maximum yield was 0.54. These petiole P concentrations are similar to critical levels reported previously for potatoes. For example, at a similar tuber growth stage, Sparrow *et al.* (1992) found that, for 95% of maximum yield of potatoes grown on high P-fixing krasnozems in Tasmania, petiole P concentrations were in the range 0.36-0.4%. From studies on sandy loam and loam soils in South Australia, Maier *et al.* (1989b) suggested a critical petiole P concentration range of 0.41 to 0.53% which corresponded with 90% of maximum yield. In our work, from the relationship in Figure 6, the percentage P required for 90% of maximum yield was 0.34. This difference in critical petiole P concentration for 90% maximum yield may reflect the higher P-fixing capacity of our soils.

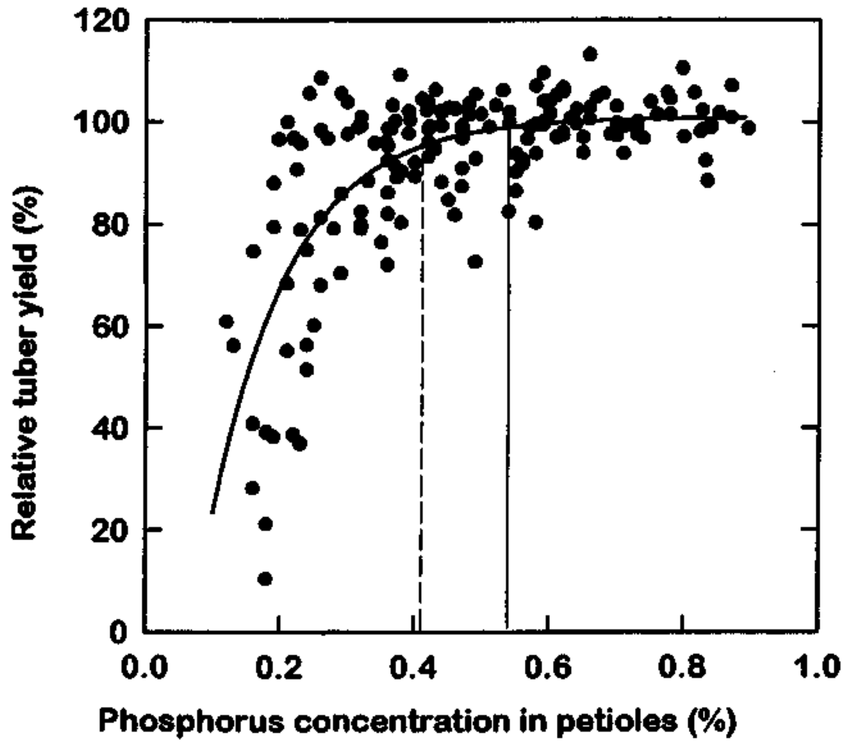

Figure 6. Relative tuber yield in relation to phosphorus (P) concentration in petioles of youngest fully expanded leaves (P-YFEL) at the 10 mm tuber stage. Broken and unbroken lines refer to 95 and 99% maximum yield respectively. The equation of the fitted line is:

$$Y = 100.86-180.9\exp(-8.48X)\ (R^2 = 0.50, P<0.001)$$

The possibility that the capacity of the soil to sorb P may have an affect on critical petiole P concentrations is supported by contrasting the critical concentrations found in the present study with those of Hegney *et al.* (1997) for potatoes grown on low P-fixing Karrakatta sands. Using the same cultivar as that used in this study (cv. Delaware), they found petiole P concentrations corresponding with 95 and 99% maximum yield of 0.7 and 0.87%, respectively. These levels are considerably higher than the critical levels found here.

Conclusions

The results of this study show that P sorption capacity is a major soil characteristic determining the level of P fertiliser required to achieve maximum potato yields on individual sites in the Manjimup-Pemberton region of Western Australia. The Colwell soil P test, which is the most widely used soil test in Australia, proved to be a good predictor of potato yield response to applied P, but was a relatively poor predictor of the level of fertiliser P required to achieve maximum yield. For accurate predictions of P fertiliser requirement on individual sites, the P sorption capacity of the soil, as measured here using the PRI(100) test, must be considered together with the Colwell soil P test. The combination of these tests, both of which are relatively inexpensive and can be performed routinely by commercial laboratories, will enable potato growers in the Manjimup-Pemberton region of Western Australia to closely match P fertiliser applications with crop requirements, thus maximising yields while minimising fertiliser costs.

Further work is required to examine the possible influence of soil P sorption capacity on critical petiole P levels for potatoes.

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Response of winter-grown potatoes (*Solanum tuberosum*) to applied and residual phosphorus on a Karrakatta sand.

M.A. Hegney, I.R. McPharlin and R.C. Jeffery

Summary

The response of winter grown potatoes (*Solanum tuberosum* L. cv. Delaware), as determined by yield, to applied (broadcast) phosphorus (P) (0-480 kg/ha) and to residual P was measured on an acutely P deficient, newly cleared Karrakatta sand in experiments over two years.

Tuber yield responded significantly ($P<0.001$) to level of applied P. Phosphorus at 162 kg/ha was necessary for 99% of maximum total yield, which corresponded with maximum economic yield. For 95% of maximum yield 99 kg/ha was necessary. Phosphorus recovery efficiency by tubers (P uptake tubers / P applied, both in kg/ha) decreased from 0.14 at 30 kg P/ha to 0.04 at 480 kg P/ha.

Bicarbonate soluble P (soil test P) extracted from the top 15 cm of soil was determined on residual P sites in each experiment to which P was applied (as superphosphate) from 0 to 800 kg/ha 9months earlier. These soil test P levels were related ($R^2 = 0.91$) to total tuber yield. The soil test P level required for 95% of maximum total yield was 33 μg/g and for 99% was 51 μg/g.

When tubers were 10 mm long, the total P in petioles of youngest fully expanded leaves which corresponded with 95% of maximum yield was 0.7% (dry weight basis), and for 99% was 0.87%.

These results are important in improving the phosphorus management of potatoes on the sandy soils of the Swan coastal plain.

Introduction

The importance of the sandy soils of the Swan coastal plain in Western Australia for vegetable production has been discussed previously (McPharlin *et al.* 1992). Similarly the very low P sorption capacity of these sandy soils and the associated problem of P leaching from horticultural properties located on them has been the subject of extensive discussion and research (e.g. Sharma *et al.* 1991; McPharlin *et al.* 1990; McPharlin *et al.* 1994). This problem represents a significant threat to the sustainability of horticultural production on the coastal plain. Efforts are being made to monitor current pollution levels and assist growers to adopt more efficient fertiliser practices (Paulin *et al.* 1995).

Potatoes are the second most extensively grown vegetable on the Swan coastal plain (Anon 1993). Phosphorus fertilisers applied to potatoes on the coastal plain are commonly broadcast before planting in both organic and inorganic forms at rates from 125 to 300 kg P/ha (P. Dawson, personal communication). These rates are higher than reported elsewhere for maximum yield of potatoes grown on a range of soil types. For example in South Australia, recommended rates for 95% of maximum yield on P deficient sites varied between 27 kg P/ha on coarse-grain sandy soils to 73 kg P/ha on loamy sands and sandy clay loams (Maier *et al.* 1989a). Strange and Marshall (1990) found that 89 kg P/ha was sufficient for maximum marketable yield of potatoes on P deficient krasnozem soils near Ballarat, Victoria. In the United States of America (USA) recommended rates for maximum yield vary from 87 kg/ha for soils of low fertility in Massachusetts (Lorenz and Maynard 1988) to 105 kg/ha for soils with low P fixing ability in Idaho (Tindall *et al.* 1991). Only on soils with very high P fixing abilities are recommended rates similar to those presently used on the Swan coastal plain (e.g. 228 kg/ha on high fixing soils in Idaho, Tindall *et al.* 1991; >150 kg/ha on high fixing soils in Tasmania, Sparrow *et al.* 1992).

Soil testing of residual P has been used to improve P fertiliser management of potatoes in a number of countries. For example in California, USA, Tyler *et al.* (1961) suggested that potatoes grown on soils with more than 80 μg/g of Olsen P (Olsen *et al.* 1954) would not respond to phosphorus fertilisation. In Idaho, USA, recommended rates of P for maximum yield varied between 228 kg/ha for high fixing soils with <5 μg/g Olsen P to 0 for the same soils with 30 μg/g Olsen P (Tindall *et al.* 1991). On low P fixing soils, Tindall *et al.* (1991) recommended 0 kg P/ha for soils with ≥15 μg/g Olsen P. On coarse-grain sand surface soils in South Australia, Maier *et al.* (1989a) suggested that potatoes would not respond to phosphorus when the soil test P (Colwell 1963) was greater than 7.5 μg/g, whereas on loamy sands and sandy clay loams, no response would be expected at soil test P levels >30-40 μg/g. There are no published data for the relationship between soil test P and yield of potatoes on coastal sands in Western Australia.

Soil testing has already been shown to be useful in improving the P management of vegetable crops grown on Karrakatta sand on the Swan coastal plain (McPharlin *et al.* 1994; 1995). This work is enabling growers to reduce rates of currently applied P without impacting on crop yield potential, while reducing the leaching of P into water systems.

As a supplement to soil testing, plant analysis has been shown to be useful in determining the adequacy of phosphorus fertiliser programs for irrigated potatoes. If a phosphorus deficiency is detected early enough, it may be possible, particularly on the low P fixing soils of the Swan coastal plain, to treat the deficiency during the current season. Based on sampling petioles of youngest fully expanded leaves (P-YFEL) when the largest tubers are 5-10 mm long, Maier *et al.* (1989b), in South Australia, proposed a critical total phosphorus concentration range of 0.41-0.53% (dry weight basis). If total phosphorus concentrations were below this range, tuber yield was significantly reduced. Roberts and Dow (1982) in California, proposed a critical total phosphorus concentration range of 0.38-0.45% in P-YFEL at the 20 mm tuber stage. There are no published critical petiole phosphorus concentration ranges for irrigated potatoes grown in Western Australia.

The aim of the work reported here was to correlate soil test P levels with yield of potatoes grown on Karrakatta sand. The relationship established was used to determine optimum soil test levels for 95 and 99% of maximum yield. The relationships between soil test levels and the rate of freshly-applied P required for 95 and 99% of maximum yield, together with the corresponding critical petiole P levels were also determined.

Materials and methods

Site characteristics

Two experiments were conducted in consecutive years on previously uncropped sites at Medina Research Station (32°S, 116°W), 35 km south of Perth. The soil was a yellow Karrakatta sand (Uc 4.22, Northcote 1979). Prior to the application of any fertilisers, fourty soil samples were collected from each experimental site, using 0-15 cm soils samplers (2.2 cm diameter), and the samples were bulked. The results of textural and chemical analyses conducted on these samples are shown in Table 1.

Experimental design

The design was a completely randomised block with 2 times of P application (immediately before planting (freshly-applied P) and 9 months before planting (residual P)) and 6 levels of P application. There were 4 replications. Each plot was 3 rows by 10 m with 0.75 m between row centres. Each experiment was on a different site of the same soil type. To create the residual P treatments, P was applied to half of the plots (randomly distributed) in each

Table 1. Soil texture and chemical characteristics of experimental sites.

	% sand (0.02 - 2.0 mm)	% silt (0.002 - 0.02 mm)	% clay (<0.002 mm)	pH (1:5 $CaCl_2$)	Total P[a] (µg/g)	Soil test P[b] (µg/g)	PRI[c] (mL/g)
Expt. 1	97.4	1.2	1.4	6.1	75	7	4.2
Expt. 2	97.7	1.1	1.2	5.8	35	2	1.7

[a] Allen and Jeffery (1990)

[b] Colwell (1963)

[c] Phosphorus retention index, Allen and Jeffery (1990)

experiment 9 months before planting at 0, 50, 100, 200, 400 and 800 kg/ha. The P was applied to the soil surface and incorporated into the top 20 to 25 cm using a rotary hoe. A period of 9 months was considered adequate to allow P concentrations to equilibrate on this soil type. Our experience has shown that P concentrations equilibrate within 6 months after P application on yellow Karrakatta sands, and that long term P reactions are less significant than on other WA soils (McPharlin *et al.*, unpublished). Also, when used in commercial production, 2 vegetable crops per year are grown on this soil type, so that the period between fresh applications of P fertiliser is commonly less than 6 months. Further, to ensure that the equilibration reactions continued between the time of application of P to residual P plots and the time of preparation for planting, the sites were allowed to return to native pasture and were lightly watered twice per week. On the remaining plots, 2 days before planting, P was applied at 0, 25, 50, 100, 200 and 400 kg/ha (Exp. 1) or 0, 30, 60, 120, 240 and 480 kg P/ha (Exp. 2). These were the freshly-applied P plots. Again, the P was applied to the soil surface and incorporated as for the residual P plots. Single superphosphate (9.1% P) was used as the P source in all treatments.

Crop management
Certified seed of the *Solanum tuberosum* cv. Delaware was used in each experiment. Experiment 1 was planted on 14 May 1993 and experiment 2 on 26 May 1994. Hand cut seed pieces (50 g), which were dusted with toloclofos-methyl (2 kg Rizolex®/t) to control tuber borne Rhizoctonia, were planted at an in-row spacing of 0.15 m (88,888 plants/ha) using a single row tractor-mounted planter. All plots were machine moulded immediately after planting. Paraquat + diquat (2 L SpraySeed®/ha) was applied 2-3 days before emergence for control of weeds which had emerged since planting. Linuron (1.0 kg Afalon®/ha) was applied at emergence for residual weed control. Full emergence (100%) was recorded on 18 June 1993 and 27 June 1994 in experiments 1 and 2, respectively. Chlorothalonil (2 L Bravo®/ha) and iprodione (2 L Rovral®/ha) were applied periodically for control of early leaf blight. Methamidophos (0.7 L Nitofol®/ha) was applied for control of potato tuber moth and aphids. Both crops were irrigated using mini-sprinklers (Lego® 170 L/h, experiment 1 and Eindor® 300 L/h, experiment 2). For the first six weeks after planting, the crops were irrigated on a daily or twice daily basis at a rate equivalent to 100% of long term average pan evaporation. Thereafter, the irrigation rate was increased to 150% of long term average pan evaporation. At all times, daily irrigation amounts were adjusted for any rainfall received. 567 mm and 607 mm of rain were received between planting and 50% senescence in experiments 1 and 2 respectively.

Fertiliser applications
A complete trace element mix containing $MnSO_4.H_2O$ (50.4 kg/ha), $MgSO_4.7H_2O$ (100), borax (33.6), $FeSO_4.7H_2O$ (33.6), $CuSO_4.5H_2O$ (33.6), $ZnSO_4.H_2O$ (28.0) and $Na_2MnO_4.2H_2O$ (2.24) plus K (165 kg K/ha as K_2SO_4) was hand broadcast on all plots 2 days before planting. At the same time, P fertiliser was hand broadcast on to the fresh P plots. The whole site was then rotary hoed to 20-25 cm.

All post-planting fertilisers were injected via the irrigation system (TMB® injector). NH_4NO_3 (Agran 34-0®,34% N) and K_2SO_4 (Haisol-K®, 42% K) were applied on a daily basis for 105 days, beginning 14 days after planting, at 16.8 and 8.84 kg/ha.day, respectively, to a total of 600 kg N/ha and 390 kg K/ha. In addition, 25 kg $MgSO_4.7H_20$/ha was applied between days 50 and 57 and again between days 70 and 77 after planting.

Measurements and analysis
Soil phosphorus. Soil samples were collected for P analyses 3 days before planting by taking 30 cores (2.2 cm diameter) to a depth of 15 cm from all residual P plots. Cores from each plot were bulked, dried at a maximum of 40°C in a forced draught oven and thoroughly mixed. Samples were sieved (<2 mm) prior to analysis for bicarbonate-extractable P (Colwell 1963), hereafter referred to as soil test P.

Petiole nutrients. Thirty petioles from youngest fully emerged leaves (P-YFEL)(the fourth or fifth from the growing terminal) were collected per plot when the largest tubers were 10 mm long. The petiole samples were dried at 70°C in a forced draught oven for 48 h and ground to pass through a 1 mm screen. Sub-samples were digested with sulphuric acid and hydrogen peroxide (Yuen and Pollard 1954) and P was measured as the molybdo-vanadate complex by an automated colorimetric process (Anon 1977).

Given that single superphosphate, the P source used in these experiments, also contains both calcium (Ca, 18-22%) and sulphur (S, 14-18%), petiole concentrations of these nutrients were measured to ensure that responses to applied superphosphate were due to increased levels of P and not limited by low levels of Ca or S. Using separate sub-samples, Ca and S concentrations were determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES) after digestion with nitric/perchloric acids (McQuaker *et al.*, 1979).

Harvest. All plots were allowed to fully senescence naturally. All tubers from an 8 m section of the middle row in each plot were dug mechanically on 25 October 1993 in experiment 1 and on 7 November 1994 in experiment 2. Total yield of fresh tubers for each plot was recorded. Marketable tuber yield was also recorded as the yield of blemish free tubers weighing between 50 and 450 g. For tuber analysis, in experiment 2, 20 tubers of marketable size were randomly sampled from each plot. The tubers were cut in half longitudinally and visually assessed for any internal defects. A 5 mm thick slice was then removed from a cut half of each tuber. The slices were then diced and the total fresh weight of all slices from each plot recorded. The samples were then dried, dry weights recorded and analysed for total phosphorus as for petiole samples.

Analysis of data

Analysis of variance was carried out on the level of applied P and total and marketable yield from the freshly-applied P plots. Similarly, analysis of variance was carried out on the soil test P and total and marketable yield from the residual P plots. For each experiment, mean data for the relationship between level of applied P and yield from freshly-applied P plots, and soil test P and yield from residual P plots were fitted to a Mitscherlich equation: $y = a - b\exp(-cx)$. Relative yields were then calculated by expressing absolute yield as a percentage of predicted maximum yield (i.e. the a coefficients). The data from both experiments were combined and Mitscherlich equations fitted to relative yield versus level of freshly-applied P, and relative yield versus soil test P. The levels of freshly-applied P and soil test P corresponding with 95 and 99% of predicted maximum yield were then determined. For increasing increments of soil test P, the equivalent value of freshly-applied P was determined by equating the relative yield data from the freshly-applied P and soil test P versus relative yield relationships. The level of freshly-applied P required for 95 and 99% of maximum yield at each soil test level was then calculated by subtracting these values from the level of freshly-applied P required for 95 and 99% of maximum yield on a previously uncropped site.

The P required for 99% of maximum yield was chosen as the critical concentration between deficiency and sufficiency based on an analysis of the P levels required to give maximum profit. This analysis was carried out using a fertiliser economics program, Yield Fit (Barreto and Westermann 1985).

Using data from experiment 2 only, a Mitscherlich equation was fitted to level of freshly-applied P versus P removed in tubers. The amount of phosphorus removed in tubers (kg/ha) at freshly-applied P levels corresponding to 95 and 99% of maximum yield was then determined. Phosphorus removal in tubers on 0 kg P/ha plots was deducted from P removal at other freshly-applied P levels to account for non-fertiliser sources of P. Phosphorus recovery efficiency (RE) by tubers [i.e. fertiliser P uptake by tubers/P applied both in kg/ha (Novoa and Loomis, 1981)] was calculated.

A Mitscherlich equation was fitted to the combined data on %P in P-YFEL versus soil test P from both experiments and %P corresponding with soil test P required for 95 and 99% of maximum yield was determined. For comparison, a Mitscherlich equation was also fitted to %P in P-YFEL versus relative tuber yield and %P corresponding with 95 and 99% relative yield was determined.

Results and Discussion

Freshly applied P

Total and marketable yield responded significantly (P<0.001) to level of freshly-applied P in both experiments (Table 2). A severe outbreak of early leaf blight late in the life of experiment 2 reduced its growing period resulting in lower yields. There was no significant difference in relative yield response to level of freshly-applied P between the 2 experiments, so the data for

Table 2. Effect of level of freshly-applied phosphorus on total and marketable yield (t/ha) of potatoes grown on a virgin Karrakatta sand.

Level of freshly applied P (kg/ha)	Experiment 1		Experiment 2	
	Total	Marketable (50-450g)	Total	Marketable (50-450g)
0	23.6	14.9	17.9	11.5
25	44.2	39.1	-	-
30	-	-	39.6	32.8
50	51.0	46.2	-	-
60	-	-	41.1	35.6
100	58.0	53.2	-	-
120	-	-	53.6	48.6
200	61.0	55.4	-	-
240	-	-	51.6	49.9
400	64.4	59.7	-	-
480	-	-	53.2	51.5
l.s.d. (P = 0.05)	5.4	5.4	8.8	5.8

both were combined. The level of freshly-applied P required for 95% of maximum total yield was 99 kg P/ha and for 99% was 162 kg P/ha (Fig. 1). The levels required for 95 and 99% of maximum marketable yield were 105 and 166 kg P/ha, respectively. The levels are similar to those recommended for P deficient, low P fixing soils in the United States of America (Lorenz and Maynard, 1988; Tindall *et al.* 1991). However, they are higher than the level required for 95% of maximum yield on a site with P deficient, coarse-grain sand surface soil in South Australia (59.3 kg P/ha, site 26, Maier *et al.* 1989a). Comparison of the chemical characteristics of the soil at this site suggest that it is very similar to the virgin Karrakatta sand used in our study. The difference between our data and that of Maier *et al.* (1989a) may, in part, be due to different methods of fertiliser application - P fertilisers were banded in the South Australian work compared with broadcast application in our work. However, while banding of P has been shown to be a more efficient method of P fertiliser placement than broadcasting for a range of crops, particularly on high fixing soils (DeWit 1953), McPharlin *et al.* (1995) reported no effect of placement on the response of cauliflowers to freshly-applied P on a Karrakatta sand. The higher P levels required for maximum yield found in our work, compared to the South Australian work, may also be due to different seasonal conditions. Our data are from crops grown during winter (May planting) when temperatures were low and heavy rain may have resulted in some leaching of phosphorus, whereas in the work of Maier *et al.* (1989a) all crops were grown over spring and summer (October to December planting).

A third possible explanation for the different response to freshly-applied P in our work compared with that of Maier *et al.* (1989a) may be the different cultivars used in the two studies (Delaware cf. Kennebec). It is possible that Delaware is less P efficient than Kennebec. Freeman *et al.* (1994) showed that Kennebec was more P efficient than Russet Burbank.

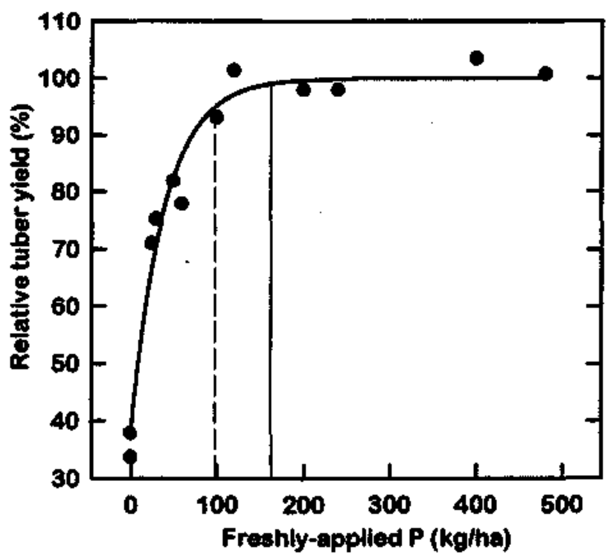

Fig. 1. Relative total yield of potatoes in response to level of freshly-applied P. Broken and unbroken lines refer to 95 and 99% of maximum yield respectively. Data points are means of 4 replicates of 6 P levels from 2 experiments. The equation of the fitted line is:

$$Y = 99.98 - 63.03\exp(-0.026X) \quad (R^2 = 0.97, P<0.001)$$

The levels of freshly-applied P required for 95 and 99% of maximum yield of potatoes were similar to the equivalent rates for carrots (McPharlin *et al.* 1994) and cauliflower (McPharlin *et al.* 1995) on virgin Karrakatta sand.

Soil test P and potato yield

Total and marketable yields also increased significantly ($P<0.001$) in response to increasing soil test P levels, with the maximum yields being similar to the maximum yields recorded in the freshly-applied P treatments (Table 3).

The relationship between relative yield and soil test P was adequately described by a Mitscherlich equation ($P<0.001$) in both experiments. The combined data from both experiments is shown in Figure 2. The soil test P level required for 95% of maximum yield was 33 µg/g and for 99% was 51 µg/g. From data across 7 sites with coarse-grain sand surface soils in South Australia, Maier *et al.* (1989a) suggested a critical soil test P level of 7.5 µg/g. This level corresponded with 90% of maximum yield. The soil test P level required for 90% of maximum yield in our work was 26 µg/g, which is three times the South Australian level. As with the response to rate of freshly-applied P, the different seasons of production used in the two studies may explain some of this difference in required soil P levels. Also, 6 out of the 7 coarse-grain surface soil sites studied by Maier *et al.* (1989a) had lower P sorption capacities than the Karrakatta sand used in our work. In contrast, for loamy sand and sandy clay loam surface soils with higher P sorption levels, Maier *et al.* (1989a) suggested a critical soil P concentration range of 30-40 µg/g for 90% of maximum yield. Economic yield responses to applied P were recorded on high P fixing krasnozems with soil test levels as high as 210 µg/g in Tasmania (Sparrow *et al.* 1992)

Table 3. Effect of level of P applied 9 months before planting (residual P treatments) on the soil test P (Colwell P) level at planting, and on total and marketable (50-450g tubers) yield (t/ha) of potatoes grown on a Karrakatta sand.

Level of	Experiment 1			Experiment 2		
applied P (kg/ha)	Soil test P (µg/g) (±s.e.)	Total yield	Marketable yield	Soil test P (µg/g) (±s.e.)	Total yield	Marketable yield
0	6.8 (±1.0)	23.6	14.9	5.0 (±1.2)	17.9	11.5
50	19.8 (±4.1)	46.1	38.2	12.5 (±1.6)	43.2	41.2
100	37.5 (±5.2)	51.9	46.4	20.5 (±1.8)	47.4	45.3
200	52.8 (±7.6)	62.3	59.1	33.0 (±3.5)	55.6	53.8
400	122.5 (±18.0)	63.2	57.2	50.0 (±1.6)	55.0	53.0
800	170.0 (±31.9)	65.2	61.2	107.5 (±14.9)	56.9	54.8
l.s.d. (P=0.05)		6.3	8.2		7.0	6.7

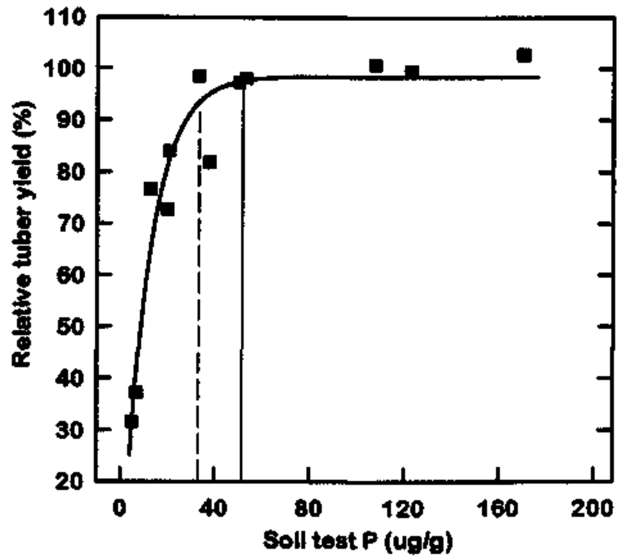

Fig. 2. **Relative total yield of potatoes in response to soil test P on a Karrakatta sand. Broken and unbroken lines refer to 95 and 99% of maximum yield respectively. Data points are means of 4 replicates of 6 residual P treatments from 2 experiments. The equation of the fitted line is:**

$$Y = 98.5\text{-}105.6\exp(-0.092X) \quad (R^2 = 0.91, P<0.001)$$

The soil test P levels required for 99% of maximum yield found here for potatoes was very similar to that for cauliflowers (55 μg/g, McPharlin *et al.* 1995) and slightly lower than for carrots (60 μg/g, McPharlin *et al.* 1994) on a Karrakatta sand.

P removal

P uptake by tubers increased significantly (P<0.001) with level of applied P and the relationship was adequately described by a Mitscherlich equation (P<0.001) (Fig. 3). P removal in tubers increased from 5.4 kg P/ha at 0 kg applied P/ha to 26.4 at 480 kg P/ha. Removal of P by tubers in this work was similar to that reported (21 kg/ha) by Lorenz and Maynard (1988) based on a 50t/ha crop of tubers, but lower than similar data (28 kg P/ha) presented by Maier *et al.* (1989a).

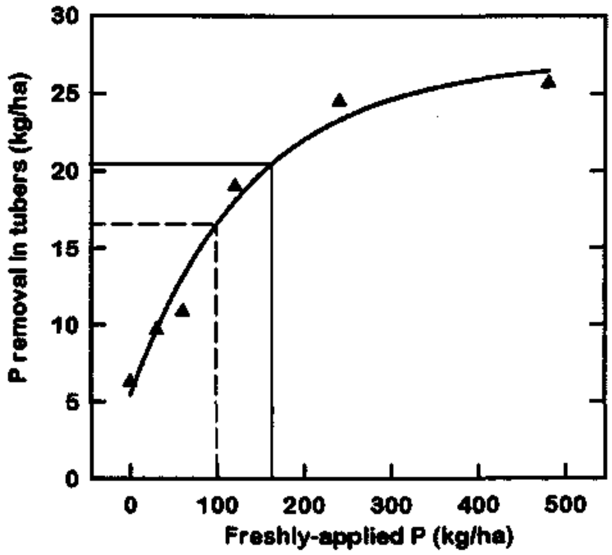

Fig. 3. **P removal in tubers with level of freshly-applied P. Data points are means of 4 replicates of 6 levels of freshly-applied P in experiment 2. Broken and unbroken lines refer to P uptake at 95 and 99% of maximum yield respectively. The equation of the fitted line is:**

$$Y = 27.1 - 21.7\exp(-0.0073X) \quad (R^2 = 0.96, P<0.001)$$

P uptake by tubers was 16.6 kg/ha at 95% maximum yield and 20.4 kg /ha at 99% maximum yield. When the amount of P taken up in the nil P treatments was subtracted, the corresponding values were 11.2 and 15.0 kg P/ha. The P recovery efficiency (RE) by tubers decreased from 0.14 at 30 kg P/ha to 0.04 at 480 kg P/ha. At levels of freshly-applied P necessary for 95 and 99% of maximum yield, the RE were 0.11 and 0.09, respectively. These recovery efficiencies are lower than those reported (0.16 and 0.12 for 95 and 99% of max. yield) for cauliflower curds on a Karrakatta sand (McPharlin *et al.* 1995). However, as with cauliflowers, reducing levels of currently applied P could significantly increase phosphorus RE and reduce the impact of potato production on the P pollution of water systems on the Swan coastal plain.

Fertiliser P requirement
The level of P required for 95 and 99% of maximum yield decreased from 99 and 162 kg P/ha, respectively, at ≤10 µg/g soil test P to 0 at the soil test P levels required to achieve these yield percentages (Table 4). Maier *et al.* (1989a) found that on soils with similar P fixing ability to the Karrakatta sand used here (sites 24 and 25), at a soil test P level of 31-33 µg/g, 13 kg P/ha was required for 95% of maximum yield. This compares well with our data for Karrakatta sand, where at soil test P levels between 30 and 35 µg/g we found 12 kg P/ha was required for 95% of maximum yield. These levels are lower than levels

currently used commercially on developed sites on the Swan coastal plain (125 - 300 kg P/ha, P. Dawson, personal communication). Based on the amount of phosphorus removed in tubers calculated above, we suggest that at least 20 kg P/ha be applied when the soil test P levels are >30 µg/g for 95% or >45 µg/g for 99% of maximum yield in order to maintain soil P levels adequate for these yield levels.

Table 4. Rate of freshly-applied P (kg/ha) required for either 95 or 99% of maximum yield of potatoes according to soil test values (µg/g) on a Karrakatta sand. Soil test is bicarbonate extractable P after Colwell (1963).

Soil test (µg/g)	Freshly-applied P (kg/ha) % Maximum Yield 95 (%)	99 (%)
0-10	99	162
10-15	84	147
15-20	66	130
20-25	48	111
25-30	30	93
30-35	12	75
35-40	0	57
40-45	0	40
45-50	0	22
50-55	0	4
> 55	0	0

Petiole P, Ca and S

The %P in P-YFEL at the 10 mm tuber stage increased significantly ($P<0.001$) in response to both residual and freshly-applied P. Percent P in P-YFEL was correlated with relative tuber yield (Fig. 4) and with soil test P level (Fig. 5). From both relationships, the %P corresponding with 95% maximum yield was similar at 0.75 and 0.70, respectively. However, from the %P versus relative tuber yield relationship, the %P required for 99% of maximum yield was 1.09, compared with 0.87 suggested by the %P versus soil test P relationship.

Percent P in petioles was better correlated with soil test P than relative yield ($R^2 = 0.95$ versus 0.74) an gives critical levels which are more comparable to published data. For this reason the %P versus soil test P relationship is preferred.

Whichever relationship is used, the petiole P levels are higher than critical levels previously reported for potatoes. For example, at a similar tuber growth stage, Maier *et al.* (1989b) suggested a critical range of 0.41 to 0.53% P in P-YFEL. However, these levels corresponded with only 90% of maximum relative yield. In our work, from the relationships in both Fig. 4 and Fig. 5, the %P required for 90% of maximum yield (26 μg/g soil test P) was 0.6, which is much closer to the upper level suggested by Maier *et al.*(1989b). Roberts and Dow (1982) established a critical petiole P range of 0.38 to 0.45% (95 to 100% maximum yield). However, these levels were derived from petioles sampled at a later tuber growth stage (20 mm tuber stage) than in our work. As shown in data presented by Roberts and Dow (1982), petiole phosphorus concentrations decrease with plant age. Maier *et al.* (1989b) discussed the importance of defining sampling times to ensure the correct interpretation of petiole nutrient analyses.

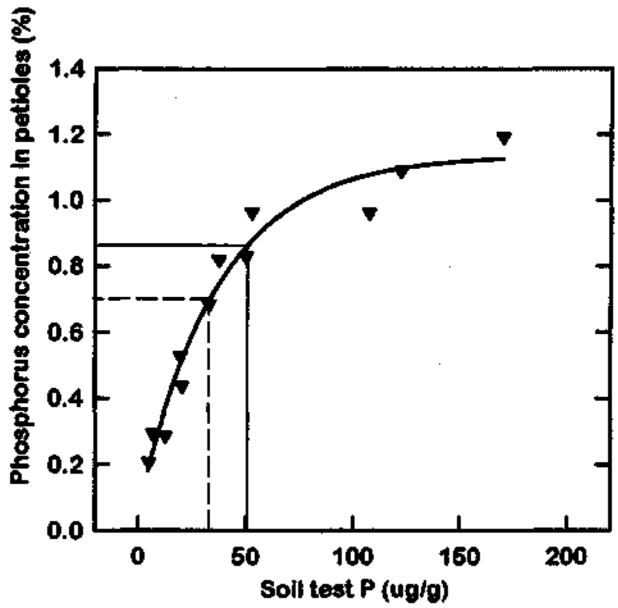

Fig. 4. Phosphorus concentration in petioles of youngest fully emerged leaves (P-YFEL) at the 10mm tuber stage in relation to soil test P. Broken and unbroken lines indicate the soil test P levels corresponding with 95 and 99% of maximum yield. Data points are means of 4 replicates of 6 residual P treatments from 2 experiments. The equation of the fitted line is:

$$Y = 1.14\text{-}1.08\exp(-0.027X) \quad (R^2 = 0.95, P<0.001)$$

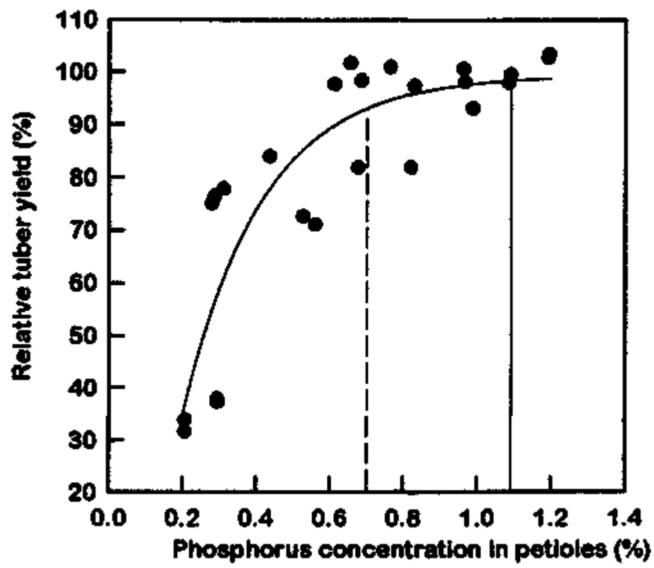

Fig. 5. **Relative tuber yield in relation to %P in petioles of youngest fully emerged leaves (P-YFEL) at the 10mm tuber stage. Broken and unbroken lines indicate 95 and 99% relative yield, respectively. Data points are means of 4 replicates of 6 residual P treatments from 2 experiments. The equation of the fitted line is:**

$$Y = 99.39 - 162.1\exp(-4.63X) \quad (R^2 = 0.74, P<0.001)$$

Different potato varieties may have different critical petiole P concentrations. For example, Maier *et al.* (1994) reported that total P concentrations in P-YFEL of Kennebec were significantly higher than Atlantic at each of three different experimental sites. However, there is no published evidence that Delaware, the variety used in our work, has a higher critical petiole P concentration than other common varieties. Tyler *et al.* (1961) stated that in their work, the yield and petiole P concentration response of White Rose (of which Delaware is a clone) to applied P was comparable to the responses of Russet Burbank, Pontiac and Kennebec varieties.

The very low P retention capacity of the Karrakatta sand may also have contributed to the higher petiole P levels in this work compared to studies conducted on more highly P "fixing" soils. Sparrow *et al.* (1992) suggested that the higher P sorption capacity of the krasnozems in Tasmania may have contributed to the lower petiole P levels required for 95% of maximum yield in their work (0.36 - 0.4%) compared with the critical petiole P range suggested by Maier *et al.* (1989b).

In both experiments and in all treatments, the %Ca and %S in P-YFEL at the 10 mm tuber stage was greater than 1.5% and 0.25%, respectively. These levels of Ca and S fall within or above the concentration ranges suggested by Maier *et al.* (1987) as being adequate for irrigated potatoes (i.e. 0.4-1.4% Ca and 0.2-0.4% S). Therefore, yield responses to applied P shown in this work were not limited by inadequate levels of Ca or S.

Conclusion

In this work, yield of potatoes responded significantly to freshly-applied P on previously uncropped Karrakatta sand. The retention of P in the soil over 9 months was adequate to derive a relationship between soil test P values and yield. We suggest therefore, that soil testing can be used on Karrakatta sands to determine optimum levels of P application for potatoes, and that reductions in P application levels will be possible at high soil test P values. Reduced P application, combined with increased P recovery efficiency at low P application levels, will lead to reduced leaching of P into water systems on the Swan coastal plain. However, before being used in commercial practice, the critical soil test P levels found in this work need to be confirmed over a larger range of sites.

The higher critical petiole P levels found in our study, compared with previously published data, suggest that further work is also required to quantify possible differences in critical levels between potato varieties. Also, the possible influence of soil P retention capacity on critical petiole P levels warrants further study.

In addition, further work is required to investigate the P fertiliser requirements of potatoes on soils with low P retention capacity when the fertiliser is banded compared with broadcasting.

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Broadcasting phosphate fertilisers produces higher yields of potatoes *(Solanum tuberosum* L.) than band-placement on coastal sands

M.A. Hegney and I.R. McPharlin

Summary

The relative effectiveness of broadcasting compared with band placement of phosphorus (P) fertilisers was compared using potatoes grown on sandy soils over two seasons in Western Australia.

The maximum yield of potatoes when the P was banded was 30 and 13 t/ha lower than when broadcast in 1993 and 1996, respectively. However, higher rates of applied P were required to reach 99% of maximum yield on the broadcast compared with the banded plots in both years (i.e. 174 versus 134 kg/ha in experiment 1, and 279 versus 125 kg/ha in experiment 2). Despite these higher requirements for applied P, banding of P fertilisers for potatoes grown on Karrakatta and Spearwood sands would result in significant economic loss.

The higher yield on the broadcast treatment corresponded with higher P concentrations (about two times) in petioles of youngest fully expanded leaves from 56 to 131 days after sowing. The petiole P concentrations required for 95% and 99% of maximum yield at the 10 mm tuber stage were 1.13 and 1.28% in experiment 1, and 0.95 and 1.11% in experiment 2.

Phosphorus uptake by tubers was significantly ($P<0.001$) higher (about two times) when P was broadcast rather than banded, especially at high rates of applied P, as was recovery efficiency (RE; P uptake/applied P) of fertiliser P.

Introduction

The management of phosphate fertilisers on sands must be improved to reduce the impact of vegetable growing on the water systems of the Swan coastal plain (McPharlin *et al.* 1992, Paulin *et al.* 1995). These soils are important for the expected growth in production of high quality horticultural export crops. Potatoes are the second most important vegetable crop on an area basis on the Swan Coastal Plain (Anon. 1993). Two techniques have been investigated to improve the sustainability of potato production on these soils: P soil testing (Hegney *et al.* 1997) and Alkaloam amendment (Robertson *et al.* 1997). Recovery efficiency of fertiliser P by potatoes can be increased significantly if rates are reduced at high (ie. > 51 µg/g Colwell P) soil test levels (Hegney *et al.* 1997). This would reduce impact on water systems by reducing the amount of residual P in the soil after cropping. Amendment with freshly-applied Alkaloam (60 to 120 t/ha) caused yield reductions (7 to 10%) in potatoes apparently due to induced potassium deficiency (Robertson *et al.* 1997). Residual Alkaloam only reduced yield (12%) at high rates ie. 240 t/ha.

More efficient use of P fertiliser may be achieved through more accurate placement (i.e. banding rather than broadcasting). Banding has been shown to be more efficient (i.e. less applied P required for an equivalent yield) than broadcasting for a range of crops particularly on high P-fixing soils (Dewit 1953). For example, banding P fertiliser resulted in significantly higher yields (8 to 18%) of Russet Burbank potatoes than broadcasting on high P-fixing krasnozems in Tasmania (Sparrow *et al.* 1992). These higher yields were associated with higher (22 to 26%) levels of petiole P in plants from the banded plots. There is little information on the response of potatoes to P fertiliser placement on low P-fixing sandy soils. With other vegetable crops, the response to P fertiliser placement was variable. For example, there was no significant response in the yield of cauliflowers (McPharlin *et al.* 1994) or lettuce (McPharlin *et al.* 1997) to broadcasting versus banding of P fertilisers on Karrakatta sands. By contrast, the agronomic efficiency of P fertiliser use (yield of crop/P applied) by onions was increased by banding versus broadcasting (McPharlin and Robertson unpublished data). Sanchez *et al.* (1990) found that, on a Histosol in Florida, USA, the optimum rate of applied P required for maximum yield of lettuce when the fertiliser was banded was one-third that when broadcast.

The purpose of this work was to test the hypothesis that banding would result in increased agronomic efficiency of P fertiliser use by potatoes and a reduced quantity of applied P required for maximum yield.

Materials and methods

Site characteristics

The experiments were conducted on a previously uncropped site at Medina Research Station, 35 km south of Perth (32°S, 116°F). The soil was a yellow Karrakatta sand (Uc 4.22, Northcote 1979) in experiment 1 (1993) and a Spearwood sand (Uc 1.22) in experiment 2 (1996). Chemical characteristics of the soil used in both experiments is given in Table 1. Textural characteristics have been reported previously (Hegney *et al.* 1997).

Experimental design

The design was a two (methods of P application, banded or broadcast) by six (levels of P application) treatment combination in a randomised block with four replications. Each plot was 3 rows by 10 m, with a row spacing of 0.75 m. The levels of applied P were 0, 30, 60, 120, 240 and 480 kg/ha. Ordinary superphosphate (9.1% P) was used as the P source in all treatments. On the broadcast plots, P was hand broadcast and incorporated to 20-25 cm using a rotary hoe on the day before planting. On the banded plots, P was banded in two rows to the side of and below the seed pieces at planting.

Crop management

Certified seed of the cultivar Delaware was used. The experiments were planted on 19 May 1993 (experiment 1) and 15 May 1996 (experiment 2). Hand cut seed pieces (50 g), which were dusted with toloclofos-methyl (2 kg Rizolex/t), were planted at an in-row spacing of 0.15 m (88,888 plants/ha) using a single row tractor mounted planter. All plots were machine moulded immediately after planting. Paraquat + diquat (2 L Sprayseed/ha) was applied 2-3 days before emergence for control of weeds which had emerged since planting. The date of crop emergence (100%) was recorded for both experiments. Linuron (1.0 kg Afalon/ha) was applied at emergence for residual weed control. Chlorothalonil (2 L Bravo/ha) and iprodione (2 L Rovral/ha) were applied periodically for control of early leaf blight. Methamidophos (0.7 L Nitofol/ha) was applied for control of potato tuber moth and aphids.

The crop was irrigated using mini-sprinklers (Lego® 170 L/h, experiment 1 and Eindor® 300 L/h, experiment 2). For the first six weeks after planting, the crop was irrigated on a daily or twice daily basis at a rate equivalent to 100% of long term average pan evaporation. Thereafter, the irrigation rate was increased to 150% of long term average pan evaporation. At all times, daily irrigation amounts were adjusted for any rainfall received.

Fertiliser applications

A complete trace element mix containing (kg/ha) $MnSO_4.H_2O$ (50), $MgSO_4.7H_2O$ (100), borax (33.6), $FeSO_4.7H_2O$ (33.6), $CuSO_4.5H_2O$ (33.6), $ZnSO_4.H_2O$ (28.0) and $Na_2MoO_4.2H_2O$ (2.24) plus K (165 kg K/ha as K_2SO_4) was hand broadcast on all plots one day before planting. At the same time, P fertiliser was hand broadcast on to the broadcast P plots. The whole site was then rotary hoed to 20-25 cm.

All post-planting fertilisers were injected via the irrigation system (TMB® injector). NH_4NO_3 (Agran 34-0®, 34% N) and K_2SO_4 (Haisol-K®, 42% K) were applied on a daily basis for 105 days, beginning 14 days after planting, at 16.8 and 8.84 kg/ha/day, respectively, to a total of 600 kg N/ha and 390 kg K/ha. In addition, 25 kg $MgSO_4.7H_2O$/ha was applied between days 50 and 57 and again between days 70 and 77 after planting.

Measurements and analysis

Petiole nutrients. Thirty petioles from youngest fully expanded leaves (P-YFEL) (the fourth or fifth from the growing terminal) were collected per plot when the largest tubers were 10 mm long 63 days after sowing (DAS) in experiment 1 and 56 DAS in experiment 2. Three more samples were collected 77, 91 and 117 DAS, respectively, in experiment 1 and five additional samples, 75, 91, 105, 118 and 131 DAS, in experiment 2. The petiole samples were dried at 70°C in a forced draught oven for 48 h and ground to pass through a 1 mm screen. Sub-samples were digested with sulphuric acid and hydrogen peroxide (Yuen and Pollard 1954) and P was measured as the molybdo-vanadate complex by an automated colorimetric process (Varley 1966).

Given that single superphosphate, the P source used in these experiments, also contains both calcium (Ca, 18-22%) and sulphur (S, 14-18%), petiole concentrations of these nutrients were measured to ensure that responses to applied superphosphate were due to increased levels of P and not limited by low levels of Ca or S. Using separate sub-samples, Ca and S concentrations were determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES) after digestion with nitric/perchloric acids (McQuaker *et al.*, 1979).

Harvest. After haulm senescence, tubers from an 8 m section of the middle row in each plot were dug mechanically on 15 November 1993 and 14 November 1996 and the total yield of fresh tubers for each plot was recorded. After counting and weighing reject tubers (greens, rots, knobs) all remaining tubers were graded into the following size categories: 0-30 g, 30-80 g, 80-250 g, 250-450 g and > 450 g. Marketable tuber yield was also recorded as the yield of blemish free tubers weighing between 30 and 450 g. For tuber analysis, in experiment 2, 20 tubers of marketable size were randomly sampled from each plot. The tubers were cut in half longitudinally. A 5 mm thick slice was then removed from a cut half of each tuber. These slices were diced and the total fresh weight of all slices from each plot recorded. Samples were then dried, dry weights recorded and analysed for total P as for petiole samples.

Analysis of data

Analysis of variance was carried out on total and marketable yield, and the yield of tuber size categories versus level of freshly-applied P and P application method. Separate Mitscherlich equations ($y = a\text{-}b\exp(-cx)$) curves were fitted to level of freshly-applied P versus yield and P application method. From the fitted Mitscherlich equations the level of freshly-applied P required for 95 and 99% of maximum yield (i.e. of the a or maximum values in each relationship) were determined for each application method. With the cheapest forms of P (ie. superphosphate (9.1% P), double super (17.5% P) or triple super (19.7% P) and high product price, 99% of maximum yield closely approximates maximum economic yield (ie. profit) whereas 95% is more appropriate for more expensive forms of P such as in compound NPK fertilisers and when the produce price is low. The 95% response level may also be more appropriate where environmental considerations are important, as on the Swan coastal plain.

The % P in P-YFEL was plotted (Mitscherlich relationships) against rate of applied P for each time (days after sowing) of petiole sampling. From this relationship the % P corresponding to the level of applied P necessary for 95 or 99% of maximum yield (determined above) was determined.

The P uptake (kg/ha) by tubers was calculated from the % P and dry weight of the tubers. This was plotted against rate of applied P for both banded and broadcast treatments.

Recovery efficiency (RE, P uptake by tubers/P applied both in kg/ha) of fertiliser P by tubers, from 30 to 480 kg applied P/ha, was determined after deducting P uptake by tubers on 0 applied P plots.

Table 1. Some chemical characteristics of soil (0-15 cm) used in P placement experiments

	pH (1:5 $CaCl_2$)	Total P[(a)] (μg/g)	Colwell P[(b)] (μg/g)	PRI[(c)] (mL/g)
Experiment 1	5.8	35	2	1.7
Experiment 2	5.4	94	9	5.2

a Allen and Jeffery (1990).

b Colwell (1963).

c Phosphorus retention index, Allen and Jeffery (1990).

Results and discussion

Yield and response to level of applied P and method of application

Both total and marketable yield increased significantly ($P < 0.001$) with level of applied P in both experiments (Table 2). The yield responses were due to a reduction in the yield of tubers in the 0-30 g category and an increase in yield in the 30-250 g category.

Table 2a. Total, marketable and reject yield and yield of tuber weight categories in response to level of applied P for broadcast and banded application methods - Experiment 1

P level (kg/ha)	Total yield (t/ha)	Marketable yield (t/ha)	Tuber weight category (t/ha)				
			0-30 g	31-80 g	81-250 g	251-450 g	Rejects
				Broadcast			
0	10.9	7.2	3.6	6.3	0.8	0	0.2
30	30.9	28.4	2.4	16.6	11.8	0	0.1
60	39.7	37.7	1.7	14.5	23.0	0.1	0.3
120	47.6	46.0	1.4	12.5	33.2	0.3	0.2
240	51.1	49.4	1.4	11.3	37.1	0.9	0.3
480	45.8	44.1	1.3	11.5	31.8	0.8	0.4
				Banded			
0	13.7	9.8	3.9	8.8	0.9	0	0.1
30	24.2	21.9	2.2	14.8	7.0	0	0.2
60	34.1	31.8	2.1	17.2	14.6	0	0.1
120	34.6	32.2	2.1	15.6	16.6	0	0.3
240	35.0	32.5	1.8	15.2	17.3	0	0.6
480	33.7	31.5	1.9	14.9	16.6	0	0.3
lsd ($P < 0.05$)	7.2	7.1	0.8	2.3	6.3	ns	ns
P level	***	***	***	***	***	ns	ns
Method	***	***	*	***	***	*	ns
P level x Method	**	**	ns	*	***	ns	ns

* = $P < 0.05$, ** = $P < 0.01$, *** = $P < 0.001$, ns = not significant.

Table 2b. Total, marketable and reject yield and yield of tuber weight categories in response to level of applied P for broadcast and banded application methods - Experiment 2

P level (kg/ha)	Total yield (t/ha)	Marketable yield (t/ha)	Tuber weight category (t/ha)				
			0-30 g	30-80 g	80-250 g	250-450 g	Rejects
				Broadcast			
0	27.00	26.46	1.7	7.95	16.21	0.93	0.21
30	40.27	39.48	1.19	7.3	29.08	2.02	0.68
60	46.48	45.69	0.66	5.14	37.6	2.68	0.40
120	55.84	55.12	0.44	5.19	40.51	9.04	0.66
240	58.11	56.52	0.74	4.99	39.74	11.06	1.58
480	62.91	59.88	0.78	4.33	42.80	12.75	2.25
				Banded			
0	24.77	22.79	1.78	7.44	14.16	1.19	0.29
30	39.22	37.86	1.19	7.86	29.52	0.48	0.17
60	44.80	43.36	1.27	5.88	35.16	2.32	0.17
120	45.20	43.13	1.45	7.1	32.83	3.2	0.62
240	48.07	45.95	1.71	5	38.72	2.23	0.41
480	49.83	47.22	1.55	6.66	38.23	2.33	1.06
lsd ($p < 0.05$)	9.54	9.9	0.68	2.24	8.4	3.55	0.63
P level	***	***	*	**	***	***	**
Method	**	*	***	ns	*	***	*
P level x Method	ns	ns	ns	ns	ns	***	ns

* = $P < 0.05$, ** = $P < 0.01$, *** = $P < 0.001$, ns = not significant.

Total and marketable yield was significantly higher in the broadcast compared with the banded treatments in both experiment 1 ($P < 0.001$) and experiment 2 ($P < 0.01$, $P < 0.05$). Banding gave higher yields in the smaller weight grades (0-80 g) and lower yields in the larger (80-250 g) weight grades compared with broadcasting. The interaction between P level and method of application was significant ($P < 0.05$) for total and marketable yield in experiment 1 but not significant in experiment 2. These results contrast with those of Sparrow *et al.* (1992) who found that banding P gave higher (8 to 18%) yields than broadcasting in Russet Burbank crops on krasnozems in Tasmania. This would reflect the higher P-fixing capacity of the krasnozems compared with the sands used here. Banding is likely to be increasingly more efficient (higher yield per unit of applied P) than broadcasting as the P-fixing capacity of the soil increases (De Wit 1953).

The relationship between level of applied P and yield was exponential (Mitscherlich) for both banded and broadcast treatments in both experiments (Figure 1). The rate of applied P required for 95% and 99% of maximum yield from these relationships were 110 and 174 kg/ha for broadcasting and 82 and 134 kg/ha for branding in experiment 1 (Figure 1a). In experiment 2 the rate of applied P required for 95 and 99% of maximum yield was 73 and

125 kg P/ha for the banded and 167 and 279 kg P/ha for the broadcast treatment (Figure 1b).

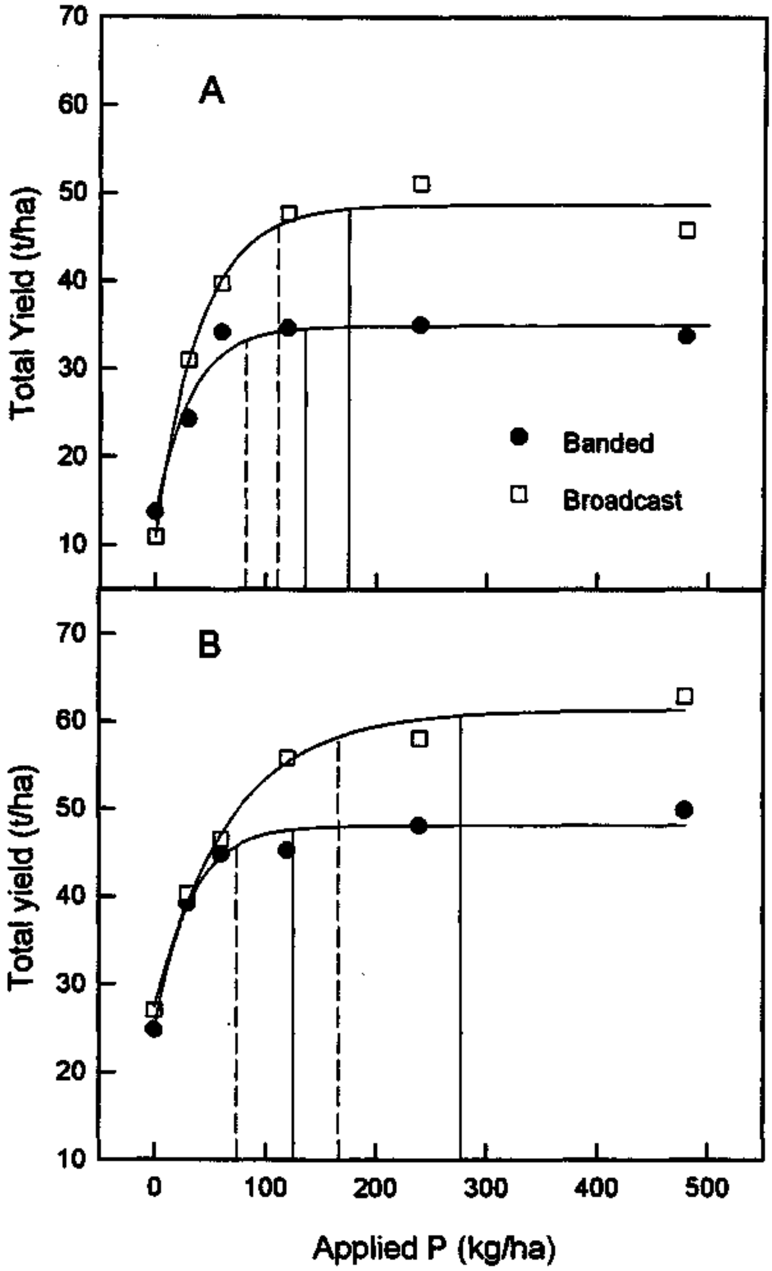

Figure 1. **Yield of potatoes in response to level of applied P and P fertilisers placement in experiments 1 and 2. (A = Exp.1, Karrakatta sand, B = Exp. 2, Spearwood sand). Broken and unbroken lines correspond with 95 and 99% of maximum yield for each fitted relationship. The equations of the fitted relationships are:**

A	**Broadcast**	**$Y = 51.90 - 44.49\exp(-0.003X)$ (R^2=0.99)**
	Banded	**$Y = 21.43 - 14.165\exp(-0.0144X)$ (R^2=0.98)**
B	**Broadcast**	**$Y = 61.32 - 33.91\exp(-0.0144X)$ (R^2=0.98)**
	Banded	**$Y = 48.08 - 23.19\exp(-0.0309X)$ (R^2=0.97)**

These rates of applied P required for 95 or 99% of maximum yield in experiment 1 are comparable to those reported by Hegney *et al.* (1977) (100-160 kg P/ha) for P broadcast before planting to potatoes on a Karrakatta sand. However, the rates required for 95 and 99% of maximum yield in the broadcast treatment plots in experiment 2 are higher than those reported by Hegney *et al.* (1997). This could be due to the higher P retention capacity of the Spearwood sand used in experiment 2 compared with the Karrakatta sand in experiment 1 (ie. PRI 5.2 cf. 1.7) (Table 1).

The most important finding from this work is that banding P fertiliser limits the yield potential of potatoes on Karrakatta and Spearwood sands. For example, the maximum (predicted) yields on the banded treatments were 30 t/ha (51 versus 21, Exp. 1) and 13 t/ha (61 versus 48 t/ha, Exp. 2) lower than the corresponding broadcast plots. Thus banding P fertilisers on sands would result in significant economic loss (up to $10,000/ha) in potato crops despite the lower rates of applied P required to optimise yield.

Petiole phosphorus, calcium and sulphur

The % P in P-YFEL increased significantly ($P < 0.001$) with level of applied P for both broadcast and banded treatments in both experiments (Table 3). The petiole P concentration was significantly higher ($P < 0.001$) in the broadcast compared with the banded treatments at all sampling times after sowing (Table 3) in both experiments. By contrast, the petiole P concentration in Russet Burbank potatoes was 22-26% higher in banded plots compared with broadcast plots on krasnozem soils in Tasmania (Sparrow *et al.* 1992).

The P concentration in wrapper leaves of spring-planted lettuce, at early heading, was on average 12% higher when P fertilisers were broadcast compared with banded treatments on a Karrakatta sand (McPharlin and Robertson 1997). However, there was no significant increase in yield in the broadcast treatment.

The petiole P concentrations required for 95 or 99% of maximum yield in the broadcast treatment declined linearly with time (days after sowing) in both experiments (Figure 2). For example, the petiole P concentration required for 95 and 99% of maximum yield declined from 1.13 and 1.28% (experiment 1) and 0.95 and 1.11% (experiment 2) at 63 and 56 days after sowing (i.e. 10 mm tuber stage) to 0.17 and 0.22% (experiment 1) and 0.24 and 0.38% (experiment 2) 117 and 131 days after sowing (Table 4). The equations for the Mitschlerlich relationship between petiole P concentration and applied P corresponding to 95% or 99% of maximum yield at each sampling time in experiments 1 and 2 are shown in Table 5. The first sampling time in each experiment corresponded to the 10 mm tuber stage.

These critical petiole P concentrations at the 10 mm tuber stage are higher than those reported necessary for 95 and 99% of maximum yield of potatoes on a Karrakatta sand by Hegney *et al.* (1997) (0.70 to 0.87%), but similar to those reported by Robertson *et al.* (1997) (1.2%) on unamended Karrakatta sands.

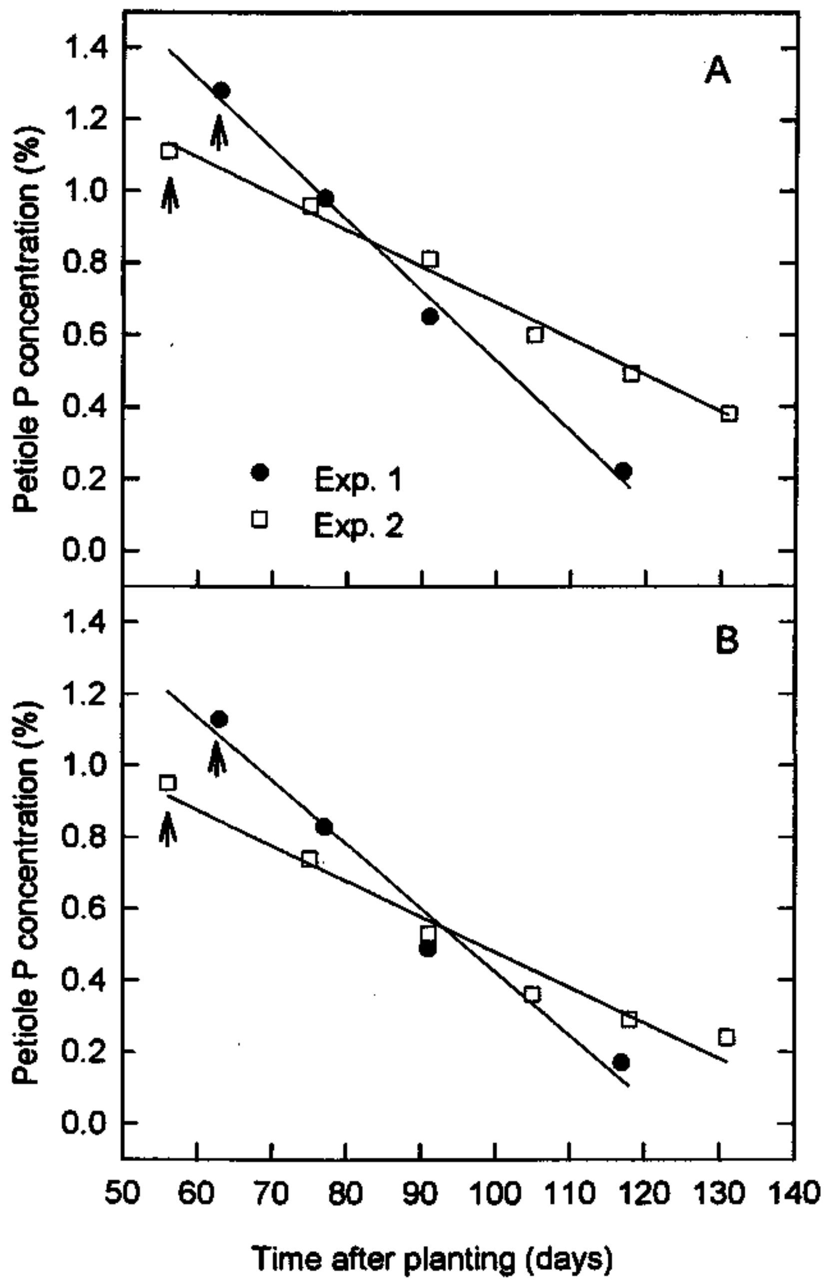

Figure 2. Phosphorus concentration (% dry basis) in P-YFEL required for 99% (A) and 95% (B) of maximum yield with time after planting in experiments 1 (Karrakatta sand) and 2 (Spearwood sand). Arrows refer to 10 mm tuber stage. Equations of the fitted lines are:

A	**Exp. 1**	$Y = 1.70\text{-}0.01X$	$(R^2=0.99)$
	Exp. 2	$Y = 2.49\text{-}0.02X$	$(R^2=0.99)$
B	**Exp. 1**	$Y = 2.20\text{-}0.02X$	$(R^2=0.97)$
	Exp. 2	$Y = 1.47\text{-}0.01X$	$(R^2=0.97)$

Table 3. P (%) in petioles for broadcast and banded P with time (days after sowing) and level of applied P

Experiment 1

Treatment	kg P/ha	Time (days after sowing)			
		63	77	91	117
Broadcast	0	0.220	0.248	0.120	0.102
	30	0.460	0.330	0.142	0.130
	60	0.887	0.562	0.265	0.115
	120	1.217	0.970	0.605	0.185
	240	1.355	1.055	0.750	0.278
	480	1.360	1.163	1.092	0.723
Banded	0	0.195	0.142	0.102	0.105
	30	0.412	0.188	0.120	0.120
	60	0.505	0.183	0.140	0.125
	120	0.635	0.232	0.172	0.138
	240	0.680	0.298	0.192	0.188
	480	0.623	0.335	0.260	0.188
lsd ($p < 0.05$)	Treatment	0.065	0.056	0.047	0.038
lsd ($p < 0.05$)	P level	0.113	0.098	0.081	0.067

Experiment 2

Treatment	kg P/ha	Time (days after sowing)					
		56	75	91	105	118	131
Broadcast	0	0.295	0.215	0.135	0.12	0.125	0.158
	30	0.41	0.377	0.174	0.12	0.127	0.153
	60	0.61	0.357	0.175	0.123	0.128	0.133
	120	0.853	0.62	0.275	0.16	0.173	0.153
	240	1.072	0.928	0.798	0.613	0.445	0.36
	480	1.21	1.177	1.24	1.065	1.095	0.978
Banded	0	0.313	0.3	0.13	0.11	0.115	0.153
	30	0.415	0.237	0.138	0.125	0.125	0.148
	60	0.585	0.43	0.17	0.13	0.15	0.158
	120	0.585	0.32	0.195	0.165	0.173	0.223
	240	0.508	0.302	0.203	0.165	0.16	0.203
	480	0.525	0.393	0.185	0.165	0.18	0.195
lsd ($p < 0.05$)	Treatment	0.047	0.077	0.041	0.028	0.055	0.038
lsd ($p < 0.05$)	P level	0.08	0.13	0.071	0.048	0.095	0.065

Similar declines in petiole P concentration with time have been reported for cv. Pontiac grown in pots (Maier unpublished data).

Table 4. Regression equations for the relationships between petiole P concentration (% dry basis) and level of applied P (kg/ha), together with the petiole P concentrations corresponding with 95% (P_{95}) and 95% (P_{99}) of maximum yield at each sampling time (days after sowing, DAS) in broadcast P treatments in experiments 1 and 2

DAS+	Exp. No.	Regression equation	P_{95}(%)	P_{99}(%)
63++	1	$Y = 1.3961 - 1.228\exp(-0.0136X)$, ($R^2 = 0.97$)	1.13	1.28
77	1	$Y = 1.187 - 1.005\exp(-0.0093X)$, ($R^2 = 0.94$)	0.83	0.98
91	1	$Y = 1.297 - 1.233\exp(-0.0037X)$, ($R^2 = 0.96$)	0.49	0.65
117	1	$Y = -0.0148 + 0.1187\exp(+0.0038X)$, ($R^2 = 0.99$)	0.17	0.22
56++	2	$Y = 1.247 - 0.97\exp(-0.00714X)$, ($R^2 = 0.99$)	0.95	1.11
75	2	$Y = 1.414 - 1.206\exp(-0.00349X)$, ($R^2 = 0.98$)	0.74	0.96
91	2	$Y = 8.4 - 8.3\exp(-0.00032X)$, ($R^2 = 0.95$)	0.53	0.81
105	2	$Y = -2.08 + 2.13\exp(+0.00082X)$, ($R^2 = 0.94$)	0.36	0.6
118	2	$Y = -0.185 + 0.277\exp(+0.0032X)$, ($R^2 = 0.99$)	0.29	0.49
131	2	$Y = 0.0301 + 0.956\exp(+0.0047X)$, ($R^2 = 0.98$)	0.24	0.38

\+ Days after sowing.

++ Days corresponding to 10 mm tuber stage.

The slower rate of decline of petiole P concentration with time in experiment 2 versus experiment 1 may reflect the higher P fixing capacity (i.e. less P leaching) of the soil in experiment 2. There is no published information on petiole P concentrations with time comparing different soil types.

In both experiments and in all treatments, the %Ca and %S in P-YFEL at the 10 mm tuber stage was greater than 1.5% and 0.25%, respectively. These levels of Ca and S fall within or above the concentration ranges suggested by Maier *et al.* (1987) as being adequate for irrigated potatoes (i.e. 0.4-1.4% Ca and 0.2-0.4% S). Therefore, yield responses to applied P shown in this work were not limited by inadequate levels of Ca or S.

P uptake by tubers

P uptake by tubers increased significantly ($P < 0.001$) with level of applied P in both broadcast and banded treatments (Figure 3). P uptake by tubers in the broadcast treatments was significantly ($P < 0.001$) higher than in the banded treatments. For example, P uptake by tubers increased from 7.6 kg P/ha at 0 kg/ha applied P in broadcast plots to 41.5 kg P/ha at 480 kg P/ha. By contrast, in banded plots, P uptake increased from 7.42 to only 21.92 kg/ha over the same range of applied P. These uptake values for broadcast plots are similar to those reported by Hegney *et al.* (1997) for cv. Delaware on Karrakatta sands and for potatoes on a range of soils in the USA (Lorenz and Maynard 1988). Recovery efficiency (RE) of fertiliser P was higher in the broadcast compared with the banded treatment. This difference was more pronounced at high rates of applied P. For example, RE decreased from 0.15 at 30 to 0.03 at 480 kg P/ha in the banded treatment.

On the broadcast treatment, RE decreased from 0.13 to 0.07 at the same rates of applied P. These recovery efficiencies are similar to those reported by Hegney *et al.* (1997) for broadcast application of P.

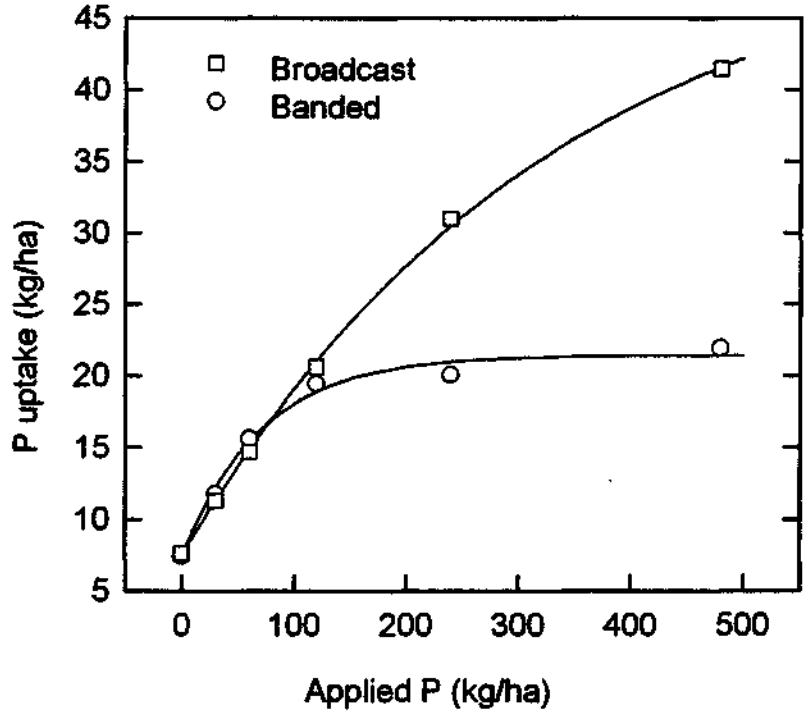

Figure 3. **Phosphorus uptake (kg/ha) by tubers with level of applied P and P fertiliser placement (banded vs broadcasting).**

Conclusions

In this study, for both broadcast and banded methods of application, potato yield responded significantly to applied P on virgin Karrakatta and Spearwood sands. Higher rates of applied P were required to achieve maximum yield in the broadcast compared with the banded method of application. However, maximum yield was between 13 and 30 t/ha higher when the P was broadcast compared with banded. Thus, despite the lower rates of applied P required to optimise yield, banding P fertilisers on sandy soils with low P sorption capacities will result in significant economic loss.

This higher yield potential in the broadcast compared with the banded P application method was associated with significantly higher petiole P concentrations. To develop an understanding of the mechanisms controlling P uptake on sandy soils, factors such as root distribution in relation to P fertiliser placement and soil moisture require further investigation. Also, the possible toxic affects of high rates of P fertiliser banded close to the potato seed piece at planting is worthy of further investigation.

In terms of the potential yield of potatoes, differences between broadcast and banded methods of P application are likely to decrease as soil P sorption capacity increases. There is a need to examine the yield response of potatoes to banded and broadcast P on a range of soils with varying P sorption abilities.

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Response of summer-planted potatoes (*Solanum tuberosum* L.) to level of applied nitrogen and water under sprinkler irrigation on a Spearwood sand

M.A. Hegney, I.R. McPharlin and R.C. Jeffery

Summary

The irrigation and N requirements of potatoes (cv. Delaware) were determined using sprinklers in a line-source design on a Spearwood sand. There was a significant yield (total and marketable) response to irrigation ($P < 0.001$) applied at 73 to 244% of the daily pan evaporation (Epan A) and N ($P < 0.001$) applied at 0 to 800 kg N/ha (total applied) as NH_4NO_3 in 10 applications post-planting. The interaction between irrigation and N was also significant ($P < 0.001$). There was no significant yield response to irrigation above 149% of Epan (i.e. I3 to I6 treatment). Irrigation at 125 to 150% Epan and N at 417 to 700 kg/ha (average of I3 to I6 irrigation levels) was required for 95 or 99% of maximum yield respectively from the Mitscherlich relationships. Total N and nitrate-N concentrations in petioles (% dry weight) at the 10 mm tuber stage required for 95 and 99% of maximum yields were 1.78, 2.11, 0.25 and 0.80% respectively from the quadratic relationships.

There was a significant ($P < 0.001$) increase in N uptake by tubers with level of applied N (Mitscherlich relationship) from 57 to 190 kg/ha at 0 and 800 kg applied N/ha (average of I3 to I6 treatments). After accounting for N uptake from soil reserves (57 kg N/ha), recovery efficiency of fertiliser N by tubers (fertiliser N uptake/fertiliser N applied) declined from 0.28 at 100 to 0.17 at 800 kg N/ha.

There was a linear increase in both after cooking darkening and sloughing of tubers with increasing level of applied N. Rate of irrigation had little effect on after cooking darkening or sloughing.

Introduction

The sandy soils of the Swan Coastal Plain of Western Australia have low nutrient (Weaver *et al.* 1988) and water holding (Luke, 1987, McPharlin and Luke, 1989) capacities. Leaching of nitrogen fertilisers applied to vegetable crops has been identified as one of the contributors to the pollution of ground water bodies on the Coastal Plain (Cargeeg *et al.* 1987; Pionke *et al.* 1990). Consequently, growers have been advised to improve the management of irrigation and nitrogen to reduce these off-site effects (McPharlin and Luke, 1989).

In 1991/92, approximately 1000 ha of potatoes, representing 40% of the total Western Australian crop was produced on the Swan Coastal Plain. 60% of this area is planted in January-February and 40% in July-August. Due to the high value of potatoes, these crops are managed for maximum yield using high rates of nitrogen and irrigation.

Irrigation amounts applied to potatoes and other vegetable crops on the Coastal Plain are based on grower experience and are generally in excess of crop requirements. Sharma *et al.* (1991) measured water and nutrient leaching below commercial vegetable crops produced on sands of the Cottesloe (Spearwood series) and Bassendean associations. They showed that for a range of vegetable crops, including potatoes, between 35% (Spearwood) and 50% (Bassendean) of the irrigation water applied leached below the crop root zone to recharge groundwater aquifers. Studies with summer planted crops of cabbage, lettuce and tomato on the Coastal Plain have shown that the daily replacement of between 100 and 150% of pan evaporation is required for maximum yields (Cripps *et al.* 1982; Cripps, pers. comm.). For potatoes planted in July-August, daily replacement of 120% of pan evaporation is currently recommended (Floyd, 1984). No data is available on optimum irrigation amounts for potatoes planted in January-February.

A survey of potato crops produced on the Coastal Plain has shown that nitrogen rates up to 1510 kg/ha/crop are being used (range 356-1510 kg/ha, average 990 kg/ha) (M. Graham, Agriculture Western Australia, unpublished data). These rates are high compared to the measured nitrogen requirements of potatoes grown on sandy soils elsewhere (Saffigna *et al.* 1977; Lauer, 1985). There are no published studies of potato nitrogen requirements on the sandy soils of the Swan Coastal Plain.

Consideration of the interaction between irrigation management and nitrogen is critical when defining crop nitrogen and irrigation requirements on sandy soils. Increased fertiliser nitrogen efficiency in potatoes can be achieved by reducing preplant applications and then frequently applying small amounts during the growing season (Roberts *et al.* 1982). Applying irrigation in small frequent amounts has also been shown to reduce nitrogen and irrigation rates required for maximum yields on sandy soils (Saffigna and Keeney, 1977).

Aim

The aim of the work reported here was to simultaneously define the optimum irrigation and nitrogen rates for potatoes planted in January-February on a Spearwood sand, based on a regime of irrigating twice daily and applying nitrogen in ten equal applications post-planting.

Materials and Methods

Site details

The experiments were located at the Medina Research Centre, 35 km south of Perth (lat. 32°13' S, long. 115°48' E) on a Spearwood sand (Cottesloe Association, Spearwood series as defined by McArthur and Bettenay, 1960) or Uc 1.22 (Northcote, 1979).

Experimental design and treatments

Differential irrigation treatments were imposed from the time of 100% emergence using a single line-source sprinkler arrangement as described by Hanks *et al.* (1976). The sprinkler line, with sprinklers 6.0 m apart, was placed parallel to the row direction in the middle of the field. Each sprinkler head (Pope Premier®), with 4.8 x 2.4 mm nozzle combination, was operated at 275 kPa (40 psi) of pressure. The water application rate was uniform down each row, but decreased almost linearly across the field, from 16 mm/hr at the sprinkler line to a negligible amount at the edge of the experimental area, about 13 m from the line-source.

Fifteen rows of potatoes, 0.8 m apart, were planted on each side of the line-source. Six rows on each side were selected as irrigation treatment locations (row numbers 3, 5, 7, 9, 11 and 13 from the line-source, with the highest irrigation level being received at row 3). Hereafter, these row numbers will be called I6, I5, I4, I3, I2 and I1 respectively.

Six nitrogen rates (0, 100, 200, 400, 600 and 800 kg N/ha) were imposed in 7.0 m wide strips perpendicular to the line-source. The nitrogen treatments were randomised within four replications, two on each side of the line-source. The design was considered a split-block with the nitrogen treatments as main plots, the irrigation treatments as sub-plots and each half of the line source as sub-plots (Hanks *et al.* 1980). Sub-plots were one row wide by 7.0 m long. The nitrogen was applied as urea in ten equal sidedressings at weekly intervals beginning two weeks after planting through a drip irrigation system. A single drip irrigation line with an emitter spacing of 0.2 m, was placed on the top of each row after planting. The required amount of nitrogen was dissolved in a stock solution each week and delivered, via an injector, through the drip lines separately to each treatment in a total 2.8 mm of water. Application uniformity through the drip system was consistently high (coefficient of uniformity ≥ 87%, Christiansen 1942).

Site preparation
An unfertilised oat crop was grown on the site prior to the experiment. Also, the site received a total of 1050 mm of water in rainfall and irrigation prior to the experiment, which provided considerable leaching.

Four weeks before planting, all plant material was mown, raked and removed from the experimental site. Two weeks before planting, the site was deep ripped. Metham sodium (500 L/ha Vapam®) was then applied and incorporated by rotary hoe to a depth of 0.2 m for control of soil insect pests and diseases. A fertiliser mix containing 700 kg/ha double super (17.5% P), 200 kg/ha K_2SO_4, 56 kg/ha $MgSO_4$, 34 kg/ha $CuSO_4$, 28 kg/ha $ZnSO_4$, 50 kg/ha $MnSO_4$, 34 kg/ha $FeSO_4$ and 34 kg/ha Borax was broadcast and incorporated with a rotary hoe 3 days before planting.

Crop management
Whole, pre-sprouted seed tubers, of cultivar Delaware, weighing between 50 and 80 g were dusted with toloclofos-methyl fungicide (2 kg/t Rizolex®) and machine planted at an in row spacing of 0.15 m on 3 February 1993. All plot rows were hilled two days after planting. 100% emergence was recorded on 19 February 1993.

Linuron (2.5 kg/ha Afalon®) was applied 10 days after planting for general weed control. Regular sprays of chlorothalonil (2 L/ha Bravo®) and iprodione (2 L/ha Rovral®) were applied to control early blight (*Alternaria solani*), together with methamidophos (700 mL/ha Nitofol® (or permethrin (150 mL/ha Ambush®)) for control of potato tuber moth, aphids and caterpillars.

K was applied at 40 kg/ha/week using K_2SO_4 for nine out of 10 weeks to a total of 792 kg/ha. KCl was used for the remaining week. In each experiment $MgSO_4$ was applied at 50 kg/ha in weeks 6 and 9 after planting.

Measurements and analysis

Soil

Soil samples were collected for chemical analysis three days before planting by taking 20 cores (2.2 cm diameter) to seven depths (0-15, 15-30, 30-45, 45-60, 60-75, 75-90 and 90-105 cm) at 12 sites corresponding to each irrigation rate on each side of the sprinkler line. Cores from each site were bulked, dried at 40°C in a forced draught oven and thoroughly mixed. Samples were sieved (< 2 mm) and then analysed for extractable nitrate-N, ammonium-N, total N (Best 1976 and Reardon *et al.* 1966) bicarbonate extractable P and K (Colwell 1963) and pH (Table 1). Sub-samples were also collected for textural analysis (Table 2).

Table 1. Chemical characteristics of Spearwood sand (0-15 cm)

	Parameter						
Depth (cm)	pH (H_2O)	pH ($CaCl_2$)	Organic C[1] (%)	Ammonium -N[2] (ug/g)	Nitrate -N[3] (ug/g)	Bicarbonate P[4] (ug/g)	Bicarbonate K[4] (ug/g)
0- 15	7.69	6.86	0.69	1	3	118	44
15- 30	-	-	-	2	6	-	-
30- 45	-	-	-	< 1	3	-	-
45- 60	-	-	-	< 1	3	-	-
60- 75	-	-	-	< 1	2	-	-
75- 90	-	-	-	< 1	2	-	-
90-105	-	-	-	< 1	3	-	-

1 Walkley and Black (1934)
2 Reardon *et al.* (1966)
3 Best (1976)
4 Colwell (1963)

Table 2. Physical characteristics of Spearwood sand (0-45 cm)

	Depth (cm)		
Fraction (%)	0-15	15-30	30-45
[1]Coarse sand	87	87	87
[2]Fine sand	9	9	9
[3]Silt	1.5	1.5	1.0
[4]Clay	2.5	2.5	3.0

1 2.0 to 0.2 mm
2 0.2 to 0.02 mm
3 0.02 to 0.002 mm
4 < 0.002 mm

Evaporation and irrigation

The net evaporation (mm) was recorded on a daily basis from a class A pan located adjacent (25 m south west) to the site from planting to harvest. Rainfall plus irrigation was recorded using rain gauges located in each of the six irrigation treatments on each half of the experimental area. Water applied during fertigation was added to the total amount of precipitation. The amount of water applied (irrigation plus rainfall) was expressed as a percentage of pan evaporation (total water applied/pan evaporation x 100%) for each irrigation treatment from 100% emergence to harvest (Table 3).

Table 3. Level of total precipitation (irrigation water applied plus rainfall) in each treatment expressed as either mm or percentage of pan evaporation

Treatment	Proportion	
	Water applied[1] (mm)	% of Epan[2] (%)
I1	444	73
I2	561	109
I3	694	149
I4	827	189
I5	948	226
I6	1008	244

[1] Irrigation plus rainfall.
[2] % of evaporation from a Class A pan from 100% emergence to harvest.

Plant
Thirty petioles from the youngest fully expanded leaves (P-YFEL; the fourth or fifth from the growing terminal) were collected from the middle 5 m of each plot when the largest tubers were 10 mm long on 9 March 1993, and 14 days later on 23 March 1993. These samples were collected between 900 and 1200 h on each sampling date. The petiole samples were dried at 70°C in a forced draught oven for 48 h and ground to pass through a 1 mm screen. Sub-samples were digested with sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2) (Yuen and Pollard 1954) and total N and nitrate-N determined by automated colorimetry using the endophenol blue method (Anon. 1977).

Harvest
All plots were allowed to fully senesce naturally. All tubers from a 5 m section of both rows in each plot were dug mechanically on 29 June 1993. Total fresh yield and the fresh weight of tubers in six weight categories (< 30 g, 31-80 g, 81-150 g, 151-350 g, 351-450 g and > 450 g) were recorded for each plot. Twenty tubers from each plot, weighing between 80 and 450 g, were cut in half longitudinally and visually assessed for any internal defects. Ten tubers from each plot, weighing between 150 and 450 g, were washed free of soil and blotted dry. The fresh weight of these tubers was recorded and they were then diced and dried at 70°C for 48 hours, their dry weight recorded and then analysed for total and nitrate-N as for the petioles. Cooking tests were carried out on 10 tubers weighing between 80 and 350 g from each plot. The tubers were peeled and then boiled until they could be easily skewered with a fork. Immediately after boiling, the tubers were rated for level of disintegration and sloughing on a scale of 1 to 5, 1 = nil, smooth surface and translucent, 2 = slight, surface dull but mainly intact, 3 = moderate, major part of surface sloughed off but mainly intact, 4 = severe, floury mass, 5 = severe, soupy. The tubers were then left on a bench top for 12 hours after which they were assessed for the level of after cooking darkening, again on a scale of 1 to 5, 1 = nil, 2 = slightly grey, 3 = moderate, greyish black, 4 = marked darkening around eyes and/or stem end, 5 = general blackening.

Analyses of data
Analysis of variance was carried out on level of applied N, irrigation water and total and marketable yield. Similarly analyses of variance were carried out on total and nitrate-nitrogen in petioles and tubers and specific gravity and cooking score in tubers.

Mitscherlich equations ($y = a-b \times \exp(-cx)$) were fitted to the relationship between level of applied N, at each irrigation rate, and conversely between level of irrigation and yield at each level of applied N. As there was no significant difference (P>0.05) between the curvature coefficients (ie. *c* values) of any of the Mitscherlich curves, for either the applied N or applied irrigation relationships, the same value was used in each equation for each set of curves in determining the optimum levels of N or irrigation required for 95 and 99% of maximum yield. The other parameters of the Mitscherlich relationships (ie. maximum yield '*a*', and the responsiveness coefficient '*b*') were significantly different (P<0.05).

The rate of applied irrigation or nitrogen required for 99% of maximum yield was chosen as the critical level based on analysis of profit from a profit optimisation program (Barreto and Westermann 1985). A Mitscherlich equation was fitted to the relationship between average yield for the I3 to I6 treatments and %N in P-YFEL at the 10 mm tuber stage (9 March) and at the 10 mm + 14 days stage. Quadratic equations were fitted to the relationship between percent nitrate-N in P-YFEL and yield at the two sampling times. In all cases the %N or nitrate-N in the P-YFEL corresponding to 95 or 99% of maximum yield was determined.

Mitscherlich equations were fitted to uptake of N by tubers versus level of applied N for each irrigation level. The N uptake corresponding to the level of applied N required for 95 or 99% of maximum yield at I1 and the average of I3-I6 treatments and the fertiliser N recovery efficiency (RE = fertiliser N uptake/level of applied N, both in kg/ha; Novoa and Loomis 1981) was determined.

Linear equations were fitted to the relationship between after cooking darkening rating (ACD) index) and a disintegration rating (after boiling) versus rate of applied N level, applied water or %N in tubers.

Results and Discussion

Response to applied irrigation and nitrogen

There was a significant yield response (marketable and total) of potatoes to level of applied irrigation water ($P < 0.01$) and N ($P < 0.001$). There was also a significant ($P < 0.001$) positive interaction between irrigation and nitrogen (Table 4). The level of applied irrigation required for 95 or 99% of maximum yield from the Mitscherlich relationship was 125 and 150% of pan evaporation (planting to harvest) respectively on average across all rates of applied N (Figure 1). This optimum level for 95 and 99% of maximum yield corresponded closely with the I3 irrigation treatment (Table 3). There was no significant effect on yield with level of irrigation above the I3 treatment (i.e. the Mitscherlich relationships were not significantly different). Consequently the yield data for the I3 to I6 treatments were combined to determine the optimum levels of applied N. The level of applied N required for 95 and 99% of maximum total yield from the Mitscherlich relationship for the combined I3 to I6 irrigation treatments was 417 and 703 kg N/ha, respectively (Figure 2). Similarly, the level of applied N required for 95 and 99% of maximum marketable yield was 339 and 577 kg N/ha. respectively (fitted relationships not shown).

Table 4. Yield (total and marketable) of potatoes with level of irrigation (I1 to I6) and N (0-800 kg/ha)

(a) Total*

	Applied N (kg/ha)					
Irrigation (I)	0	100	200	400	600	800
I1	23.66	31.82	40.80	40.55	42.56	44.73
I2	31.34	42.79	59.81	61.13	69.33	69.36
I3	34.61	49.55	65.76	67.23	72.07	70.90
I4	33.87	49.25	63.87	67.48	71.39	70.24
I5	35.27	47.75	62.85	66.02	75.42	74.41
I6	37.13	49.78	64.26	67.90	74.63	74.66

Lsd ($P < 0.05$) for I = 1.96, N = 3.9 and I*N = 5.6.

(b) Marketable*

	Applied N (kg/ha)					
Irrigation (I)	0	100	200	400	600	800
I1	20.15	28.29	37.43	36.42	38.12	39.61
I2	28.85	40.13	56.62	56.74	62.68	62.83
I3	32.66	47.16	61.99	62.51	64.75	62.64
I4	32.20	45.83	59.37	61.21	61.01	62.73
I5	33.18	44.87	57.78	59.08	68.36	65.58
I6	35.23	47.06	59.82	62.12	66.17	66.85

* Lsd ($P < 0.05$) for I = 1.5, N = 3.4 and I*N = 5.2.

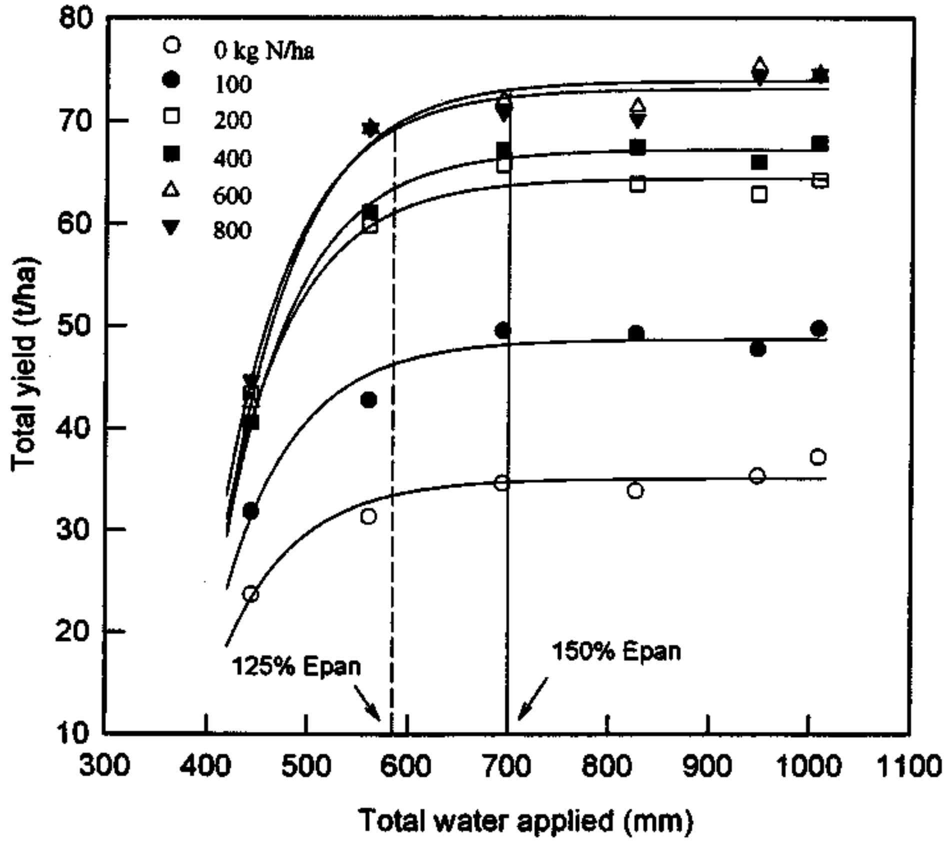

Figure 1. **Total yield response to level of water applied (irrigation + rainfall) at different levels of applied N. Broken and unbroken lines refer to 95 and 99% of maximum yield. The equations of the fitted lines are (note: all are significant at P<0.001):**

kg N/ha		
	0	$Y = 35.04\text{-}5883\exp(-0.014X)$
	100	$Y = 48.71\text{-}8748\exp(-0.014X)$
	200	$Y = 64.38\text{-}11870\exp(-0.014X)$
	400	$Y = 67.21\text{-}13532\exp(-0.014X)$
	600	$Y = 73.95\text{-}15724\exp(-0.014X)$
	800	$Y = 73.15\text{-}14210\exp(-0.014X)$

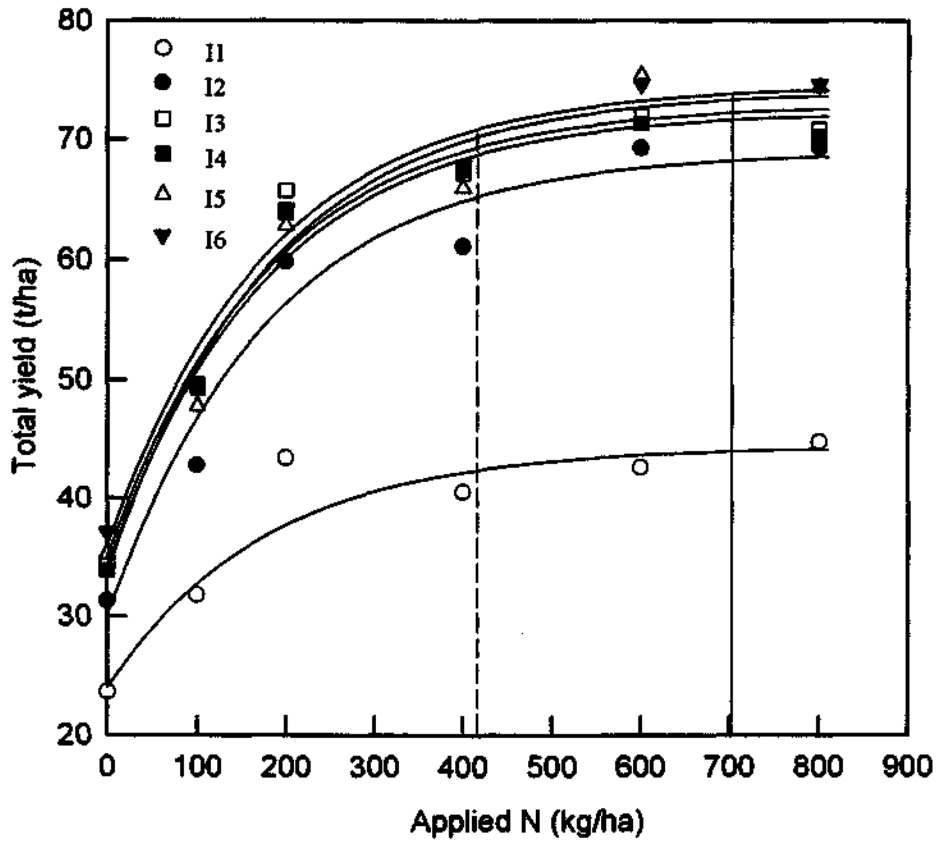

Figure 2. **Total yield response to level of applied N (kg/ha) for each irrigation treatment. Broken and unbroken lines refer to 95 and 99% of maximum yield. The equations of the fitted lines are (note: all are significant at P<0.001):**

Irrigation Treatment	**I1**	$Y = 44.31 - 20.30\exp(-0.0056X)$
	I2	$Y = 68.99 - 38.99\exp(-0.0056X)$
	I3	$Y = 73.00 - 37.87\exp(-0.0056X)$
	I4	$Y = 72.40 - 38.08\exp(-0.0056X)$
	I5	$Y = 74.11 - 40.35\exp(-0.0056X)$
	I6	$Y = 74.58 - 38.49\exp(-0.0056X)$

The rate of applied irrigation required for 99% of maximum yield in the work is similar to that recommended for summer planted cabbage, lettuce and tomato (Cripps *et al.* 1982). Floyd (1984) reported that 120% of Epan was adequate irrigation for winter-planted potatoes on sandy soils in Western Australia. This level is similar to that required for 95% of maximum yield in this work (i.e. 125% of Epan).

The rate of N required for 99% of maximum yield (703 kg/ha) is higher than that recommended for sandy textured soils elsewhere. For example 340 kg N/ha was considered optimum for Russet Burbank potatoes on a Quincy sand/loamy sand in Washington State, USA (Lauer 1985). This is lower but similar to that required for 95% of maximum yield (417 kg/ha) here and may reflect higher N leaching losses due to lower N retention ability of Spearwood sand compared with sands in other work. However, reducing applied N from 703 to 417 kg/ha is unlikely to result in significant economic loss for potatoes on Spearwood sands. Nitrogen requirements for potatoes on heavier textured soils are usually lower than coarse textured soils. For example, levels of N above 224 kg/ha caused yield reductions in Russet Burbank potatoes grown on a Millville silt loam in Utah, USA (Westermann *et al.* 1994).

N and nitrate-N in petioles

The %N in the P-YFEL required for 95% of maximum yield was 1.78%, and for 99% of maximum yield was 2.11%, from the Mitscherlich relationships at the 10 mm tuber stage (9 March)(Figure 3). At the 10 mm + 14 day stage (23 March), the %N required for 95 and 99% of maximum yield was 2.37 and 2.98%, respectively. The percent NO_3-N in the P-YFEL required for 95 or 99% of maximum yield was 0.25 and 0.80% respectively from the quadratic relationships at the 10 mm tuber stage (9 March) (Figure 4a) and 0.84 and 1.68% at the 10 mm + 14 days stage (Figure 4b).

The %N and NO_3-N in P-YFEL required for 99% of maximum yield in this work is lower than that reported as adequate for Atlantic, Coliban and Kennebec potatoes at the 10 mm tuber stage (3.5% N, 2.8% NO_3-N) grown across a range of soils in South Australia (Maier *et al.* 1990, Williams and Maier 1990). These differences may reflect varietal differences in internal N requirements or the timing of N application. In the South Australian work all post-plant N was applied in one application when the plants were 5-10 cm high compared with 10 weekly post-planting applications used here. This is likely to result in higher petiole levels of N at earlier growth stages (ie. 10 mm tuber stage) and therefore higher critical %N and NO_3-N levels in the South Australian work. By contrast, 1.6 to 1.7% NO_3-N in petioles (50 days after planting) was considered adequate for Shepody and Russet Burbank potatoes grown on a gravelly loam soil in Maine, USA, with all the N applied at planting (Parker and Sisson 1991). These levels are similar to the level reported here for 95% of maximum yield at the 10 mm + 14 days stage (42 days after planting) (1.68% NO_3-N). Similar levels of NO_3-N in petioles at mid tuberisation (1.5%) were considered adequate for Russet Burbank potatoes on a Portneuf silt loam in Idaho, USA (Westermann and Kleinkopf 1985). In the Idaho work, N was applied up to four times post-planting with the highest rate of 387 kg N/ha.

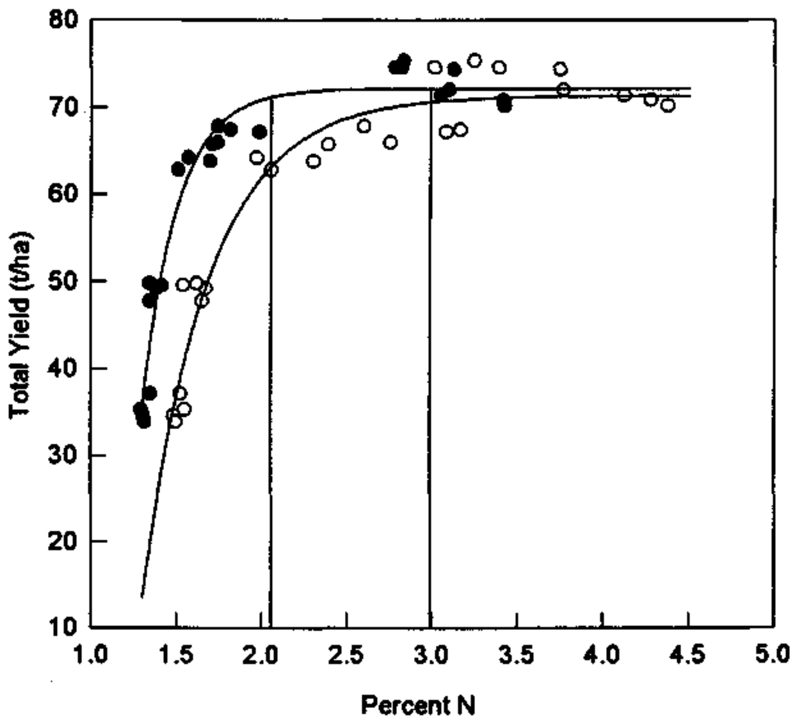

Figure 3. **Total yield response to percent total nitrogen (N) in petioles of youngest fully emerged leaves at the 10 mm (filled circles) and 10 mm + 14 day (open circles) stages. Vertical lines correspond to 99% of maximum yield at each sampling time. The equations of the fitted curves are:**

10 mm stage	$Y = 72.18\text{-}19941\exp(-4.85X)$	(R^2=0.95)
10 mm + 14 day stage	$Y = 71.37\text{-}1706\exp(-2.6X)$	(R^2=0.94)

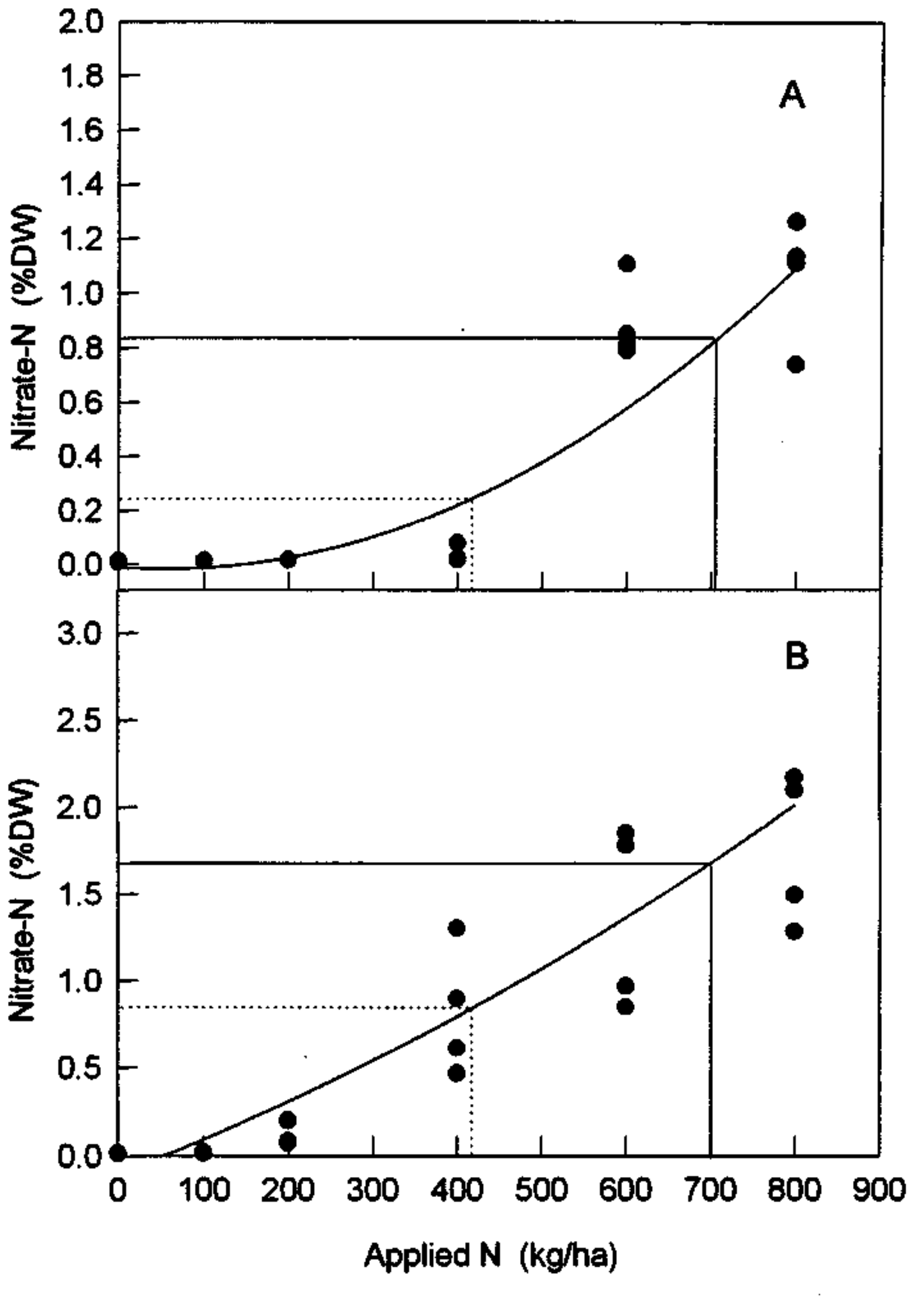

Figure 4. **Nitrate-N in P-YFEL (%DW) with level of applied N (kg/ha) at the 10 mm tuber stage (A) and the 10 mm + 14 day stage (B). Data points are replicate averages from 4 irrigation treatments (I3 to I6). Broken and unbroken lines correspond with levels of applied N required for 95 and 99% of maximum yield. Equations of the fitted lines are:**

A	$Y = -0.01094 - 0.00022X + 0.000002X^2$ ($R^2 = 0.86$)
B	$Y = -0.1016 + 0.00185X + 0.000001X^2$ ($R^2 = 0.84$)

N uptake and N fertiliser recovery efficiency (RE) by tubers

N uptake by tubers increased significantly ($P < 0.001$) with a level of applied N at all irrigation levels. The Mitscherlich equations for the relationship between level of applied N and N uptake by tubers is shown in Table 5. For the combined data of the I3 to I6 irrigation levels N uptake by tubers increased from 57.1 at 0 kg/ha applied N to 190.2 kg/ha at the highest level of applied N (800 kg/ha) (Figure 5). At the level of applied N corresponding to 95 and 99% of maximum yield, i.e. 417 and 703 kg N/ha, N uptake by tubers was 154 and 184 kg N/ha respectively. RE of fertiliser N declined on average, across all irrigation treatments, from 0.27 at 100 kg applied N/ha, to 0.16 at 800 kg N/ha. RE, on the average of the I3 to I6 treatments, declined from 0.28 at 100 kg applied N/ha to 0.17 at 800 kg/ha. At 417 and 703 kg N/ha (applied N levels for 95 and 99% of maximum yield) RE was 0.23 and 0.18 on the average of the I3 to I6 treatments.

Table 5. Regression equations for relationship between N uptake by tubers (*Y*) and applied N (*X*, kg/ha) at each irrigation level.

Irrigation level	Regression equation
I1	$Y = 154.8 - 116.62\exp(-0.00313X)$ ($R^2 = 0.99$)
I2	$Y = 263.0 - 214.42\exp(-0.00150X)$ ($R^2 = 0.92$)
I3	$Y = 207.2 - 153.6\exp(-0.00304X)$ ($R^2 = 0.96$)
I4	$Y = 253.4 - 197.8\exp(-0.00159X)$ ($R^2 = 0.95$)
I5	$Yy = 216.1 - 158.2\exp(-0.00219X)$ $R^2 = 0.97$)
I6	$Y = 213.4 - 150.9\exp(-0.00273X)$ ($R^2 = 0.94$)
I3 to I6 (mean)	$Y = 219.4 = 162.0\exp(-0.00219X)$ ($R^2 = 0.97$)

These levels of N uptake are similar to those reported for Russet Burbank (115-250 kg N/ha) grown on a Quincy sand in Washington with N applied at 150 to 610 kg/ha (Lauer 1985).

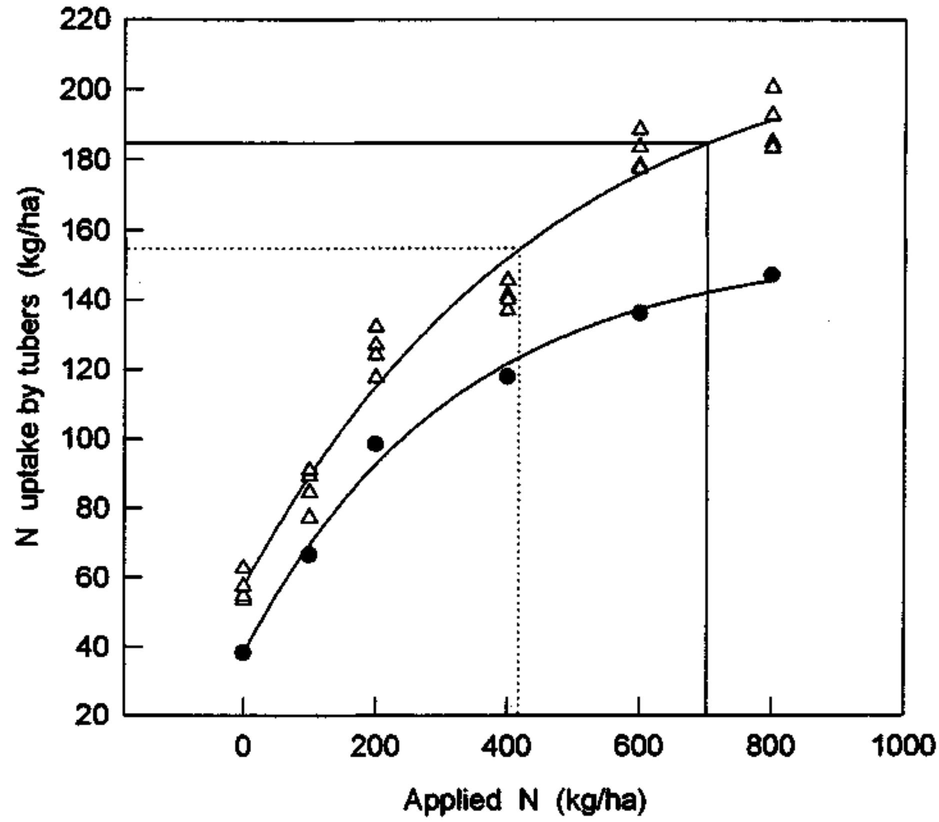

Figure 5. Nitrogen uptake by tubers (kg/ha) with level of applied nitrogen (kg/ha) at the I1 irrigation level (filled circles) and the combined I3-I6 irrigation level (open triangles). Broken and unbroken lines correspond with the levels of applied N required for 95 and 99% of maximum yield, respectively. The equations of the fitted lines are:

I1	$Y = 154.8\text{-}116.62\exp(-0.00313X)$	**(R^2=0.99)**
I3-I6	$Y = 219.4\text{-}162\exp(-0.00219X)$	**(R^2=0.97)**

Tuber quality

There was a linear (R^2=0.97) increase in after cooking darkening (ACD index) with applied N (averaged across all irrigation treatments) from 1.2 at 0 kg N/ha, to 2.3 at 800 kg N/ha (Figure 6a). ACD index increased in a similar linear fashion (R^2=0.97) with %N in tubers from 1.2 at 0.94 to 2.3 at 2.12 %N in tubers (Figure 6b). Disintegration (sloughing) after boiling decreased in a linearly divided by linear fashion with level of applied N (Figure 7a, R^2=0.96) and in a linear fashion with %N in tubers (Figure 7b, R^2=0.80).

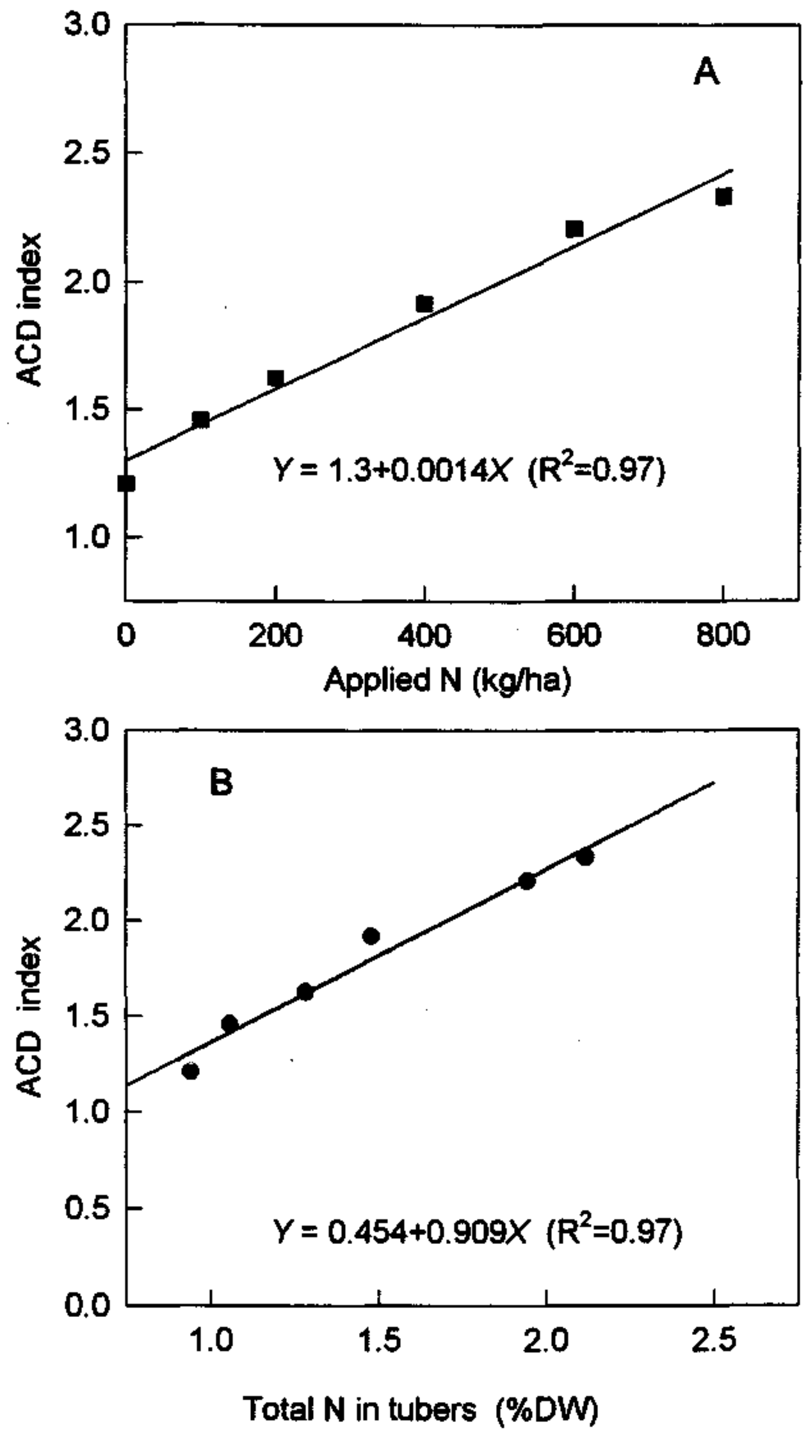

Figure 6. After cooking darkening (ACD index) with level of applied N (A) and percent N in tuber (B). Data points are means of 4 replicates of 6 irrigation treatments.

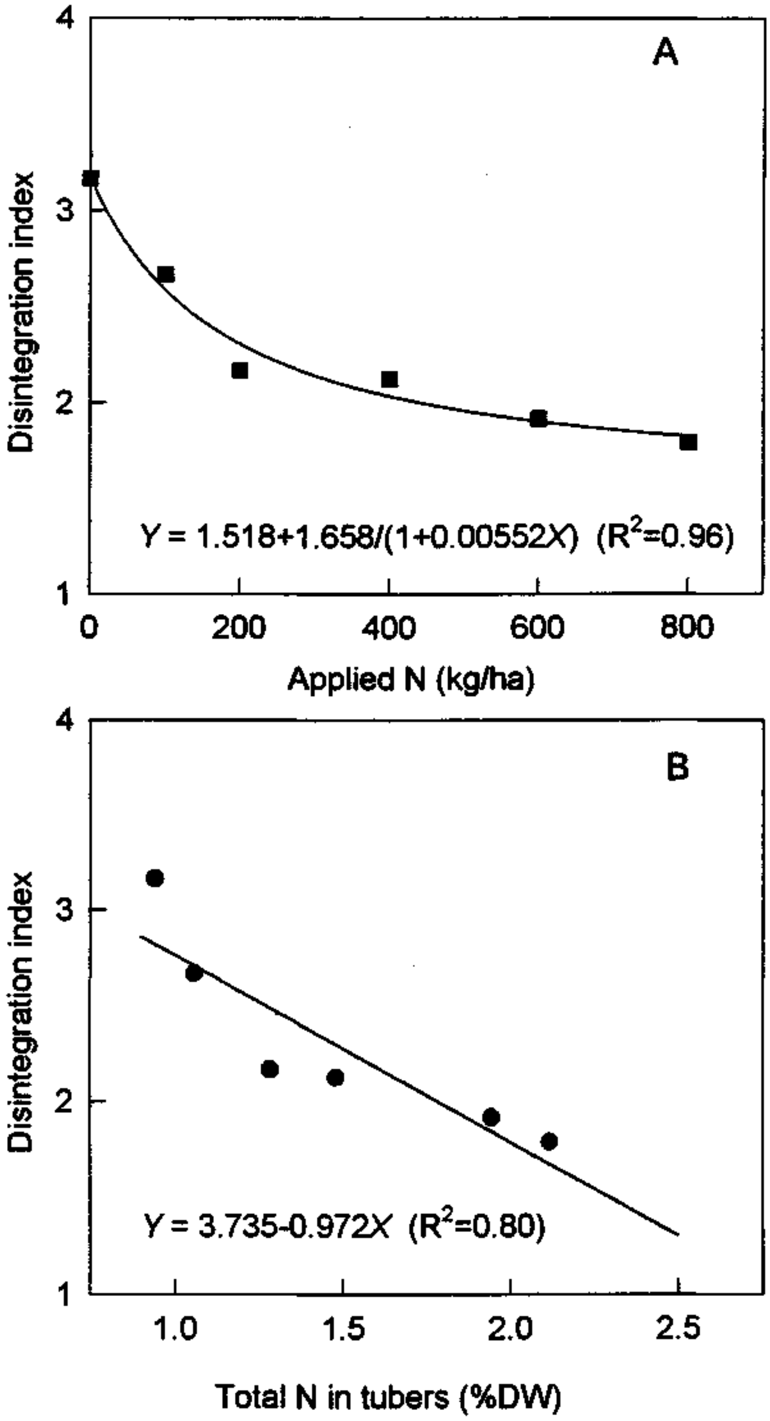

Figure 7. **Disintegration index with level of applied N (A) and percent N in tuber (B). Data points are means of 4 replicates of 6 irrigation treatments.**

There was little effect of rate of irrigation on either after cooking darkening or disintegration.

High rates of N have been reported to increase crisp colour of Kennebec potatoes grown in South Australia (Dahlenberg *et al.* 1989). For example applied N in excess of that required for maximum yield (80-120 kg N/ha) resulted in significantly darker crisps. However the time in storage had a greater influence on crisp colour than applied N. Applied N (> 80 kg/ha) had a significantly greater effect on SG than other quality parameters. SG is not important in this work as Delaware are marketed as table potatoes for processing. However the effect of high rates of N on disintegration of tubers after boiling is of concern.

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Defining the nitrogen requirements of potatoes (*Solanum tuberosum* L.) produced in different seasons on sandy soils.

M.A. Hegney and I.R. McPharlin

Summary

The effect of applying nitrogen (N) fertiliser in 105 equal daily amounts post-planting, to total levels of between 0 and 1000 kg N/ha, on the tuber yield, growth and N uptake of potatoes was studied in winter (July 1994) and summer (February 1995) planted crops on a Spearwood sand. Total and marketable tuber yield responded significantly ($P<0.001$) to level of total applied N in both seasons. In the winter season, the level of total applied N required for 95% of maximum total and marketable yield was 556 and 577 kg N/ha, respectively. For 99% of maximum total and marketable yield, the required levels of applied N were 882 and 910 kg N/ha, respectively. In the summer season, the level of total applied N required for 95% of maximum total and marketable yield was 498 and 272 kg N/ha, respectively. For 99% of maximum total and marketable yield in the summer season, the required level was 790 and 431 kg N/ha, respectively. As N application at the level required for 95% rather than 99% maximum yield is unlikely to have a negative impact on the economics of potato production on Spearwood sands, based on environmental considerations, we suggest that the levels required for 95% be recommended.

In both winter and summer seasons, N uptake in all measured plant components increased significantly ($P<0.001$) as level of applied N increased. At the high levels of N application (1000 kg/ha in winter; 750 and 1000 kg N/ha in summer) the crops took up more N than was needed to satisfy their immediate requirements for growth. The extra N was partitioned to the canopy rather than the tubers, and resulted in unnecessary extra canopy growth as well as excessive canopy N concentrations. More so in the summer than in the winter planting, this extra canopy growth occurred at the expense of tuber growth. In the summer planting, tuber growth was delayed significantly ($P<0.001$) in the 750 and 1000 kg N/ha treatments. Maximum tuber dry matter production was similar for the 250, 500, 750 and 1000 kg N/ha treatments (11.3 - 12.3 t/ha). However, compared with the 250 and 500 kg N/ha treatments, the 750 and 1000 kg N/ha treatments took between 40 and 50 days longer to achieve these maximum tuber dry matter levels. This effect was not as marked in the winter planting, where tuber dry matter production occurred at similar rates in the 500, 750 and 1000 kg N/ha treatments.

In both seasons, total plant and tuber growth reached a maximum before N applications were complete. In the winter season, N applications continued until 105 days after emergence (DAE), however, plant and tuber growth reached a maximum at 84 DAE. At 84 DAE, a total of 405 and 607 kg N/ha had been applied in the 500 and 750 kg N/ha treatments, respectively. This lead to the conclusion that the final total amounts of applied N were an overestimation of the levels of N required to reached maximum yield in each treatment. Similarly, in the summer season, N applications continued until 101 DAE, but plant and tuber growth reached a maximum at 70 DAE in the 250, 500 and 750 kg N/ha treatments. At 70 DAE in the summer

planting, 176, 352 and 529 kg N/ha had been applied in the 250, 500 and 750 kg N/ha treatments. When considered in relation to the levels of total applied N required for 95% of maximum yield, these data suggest that, on Spearwood sands, approximately 460 kg N/ha applied up to 12 weeks after emergence is required for maximum yield of winter planted potatoes, and 350 kg N/ha applied up to 10 weeks after emergence for summer planted crops.

Based on the total treatment N application levels, percent applied N recovered in tubers decreased as N application level increased from 46% at 250 kg applied N/ha to 29% at 1000 kg applied N/ha in the winter season, and from 47% at 250 kg applied N/ha to 27% at 1000 kg applied N/ha in the summer season.

In both season, soil N levels at harvest increased as total N application level increased, though the effects were more marked in the winter than in the summer season.

Introduction

The sandy (Karrakatta, Bassendean, Cottesloe Association) soils of the Swan coastal plain have low nutrient (Weaver *et al.* 1988) and water holding (Luke 1987, McPharlin and Luke 1989) capacities. Leaching of nitrogen (N) and phosphorus fertilisers from vegetable crops grown on these sands has been implicated as one of the contributors to the pollution of both ground and surface water bodies on the coastal plain (Cargeeg *et al.* 1987, Kinhill Engineers 1987).

In Western Australia, potatoes are the most extensively cultivated horticultural crop. In 1989/90, 35% of the State's potato crop was produced on the sandy soils of the Swan coastal plain (ABS). On an area basis, potatoes represent 17% of the total horticultural production on the coastal plain.

The levels of N being applied to commercial potato crops grown on sandy soils are known to be well in excess of crop requirements. In a W.A. Department of Agriculture survey of seventeen commercial crops produced on the Perth metropolitan sands (Graham 1990, unpublished), total N application levels were found to be as high as 1510 kg/ha/crop (range 356 - 1510 kg/ha, mean 990 kg/ha). Hegney and McPharlin (unpublished data) found that 703 kg N/ha and 417 kg N/ha was sufficient for 99% and 95% of maximum yield of potatoes, respectively, on a Spearwood sand. These N application levels are higher than previous estimates of N levels required for maximum yield. For example, on course grain sandy textured soils in South Australia, William and Maier (1990) found that 220 to 260 kg N/ha was sufficient for maximum yield of potatoes. Lauer (1986) found that 340 kg N/ha was sufficient for maximum yield of potatoes on a deep Quincy sand in Washington State, USA.

Requirements for high levels of N fertiliser application to achieve maximum yields on sandy soils may be related to excessive water applications. On the coastal plain, vegetable crops are frequently irrigated in excess of crop requirements (Luke 1987). As N fertilisers are highly soluble, excess irrigation can lead to N leaching. Current recommendations for irrigation of potatoes grown on the coastal plain are for replacement of between 120% (Floyd 1984) and

150% (unpublished data of M.A. Hegney and I.R. McPharlin) of pan evaporation. These rates are higher than those published elsewhere (e.g. Jensen and Middleton 1970 - 100%; Doorenbos and Pruitt 1997 - 85%;). There is considerable scope, therefore, to improve both nitrogen and irrigation management of potatoes grown on the coastal sands.

The most common approach to reducing nutrient leaching losses and increasing uptake efficiencies has been to increase irrigation frequency and minimise the use of the soil as a reservoir for water and nutrients (Phene and Beale 1976; Saffigna *et al.* 1977; Papadopoulos 1988). This approach involves combining irrigation and fertilisation (usually through a sprinkler or micro-irrigation system) and applying both in small, frequent amounts (Phene *et al.* 1979) (i.e. 'fertigation'). Small, frequent applications of soluble nutrients reduces the quantity of nutrient in the soil at any point in time and so reduces potential leaching by heavy rainfall events, compared with less frequent applications. Also, by applying fertiliser with the irrigation water, nutrients are placed in the soil volume in which the roots are most active (Bar-Yosef and Sheikhoslami 1976). Rolston *et al.* (1979) observed that high frequency applications of N with trickle irrigation improved the efficiency of fertiliser use by potatoes more than two fold over conventional fertiliser methods.

Effective use of this fertigation approach requires a knowledge of plant nutrient demand at each growth stage. Westermann and Kleinkopf (1985) reported that for spring planted potatoes, a constant rate of nitrogen uptake was required during tuber growth in order to achieve maximum yield. However, the rate of nitrogen uptake has been shown to vary between growth stages (Kleinkopf *et al.* 1981), suggesting that crop nitrogen use efficiency could be improved by changing nitrogen application regimes to match crop demand.

Crop nitrogen demand is directly affected by crop growth rates which in turn are influenced by climatic factors. For example, in spring and summer planted crops, the rate of nitrogen uptake has been shown to decline towards the end of the rapid tuber growth period (Kleinkopf *et al.* 1981; Millard *et al.* 1989) when solar radiation levels and possibly temperatures were declining. In a situation where these levels increased continuously over the growth period, Huett and Dettmann (1992) found that nitrogen uptake rate continued to increase during tuber growth. On the Swan coastal plain, two crops are planted each year - one in the summer and one in the winter. Summer planted crops grow from a period of long days with high temperatures and solar radiation levels into progressively shorter days with decreasing mean daily temperature and radiation levels. The opposite is the case for winter planted crops. It is possible that the pattern of nitrogen demand will be different for the two planting times.

In addition to climatic factors, patterns of crop nitrogen demand may also be influenced by nitrogen application timing. Where all nitrogen fertiliser has been applied at or shortly after planting, supra-optimal N concentrations have been measured in plants, particularly in the crop canopy (Millar and MacKerron, 1986). Part of the extra N is then available for redistribution to lateral branches and tubers when N availability and hence crop uptake slows towards the end of the season. Such supra-optimal accumulation of N may not occur when the crop nitrogen allocation is spread over a larger proportion of the growing season.

Aims

The objectives of this study were to define the effect of N application level and season of production on potato plant growth, including various growth parameters and radiation use efficiency, and N uptake. Also, the effect of applying nitrogen in small daily doses over an extended part of the crop growth period on the level of nitrogen required for maximum yield was examined.

Materials and Methods

Site characteristics

Two experiments were conducted on adjacent sites at the Medina Research Station, 35 km south of Perth (32°S, 116°W). The sites had not been cropped in the previous 5 years. The soil was a Spearwood sand (Uc 1.22, Northcote 1979). Some chemical characteristics of the soils at each site are given in Table 1.

Table 1. Chemical characteristics of Spearwood sand (0-15 and 15-30 cm) at each experimental site.

	pH (H_2O)	P[a] (μg/g)	K[a] (μg/g)	Total N[b] (% db)	NO_3-N[c] (μg/g)	NH_4-N[c] (μg/g)	EC (1:5) (mS/m)	Organic C[d] (%)
Exp. 1								
0-15 cm	7.7	58	15	0.038	1.0	5.0	5.5	0.70
15-30 cm	7.2	53	17	0.032	1.0	2.0	4.8	0.63
Exp. 2								
0-15 cm	7.5	65	30	0.041	15.0	1.0	16.0	0.78
15-30 cm	7.3	49	27	0.037	11.7	1.0	8.5	0.73

a. Extractable in 0.5M $NaHCO_3$ (Colwell 1963).
b. Reardon *et al.* (1966).
c. Best (1976).
d. Walkley and Black (1934)

Experimental design

The design of each experiment was a randomised block with 5 nitrogen levels (0, 250, 500, 750 and 1000 kg N/ha) and 4 replications. Experiment 1 was planted on 14 July 1994 (winter) and experiment 2 on 2 February 1995 (summer). Figure 1 shows the temperature and rainfall profiles for the two experimental periods. The two experiments were separated by a 20 m buffer area. Each plot was 8 rows by 12 m, with a row spacing of 0.75 m. Plots were separated on all sides by a 1.5 m buffer area.

Crop management

Certified seed of the cultivar Delaware was used in each experiment. Whole seed tubers (40-70g), which were dusted with tolociofos-methyl (2kg Rizolex/t), were planted at an in-row spacing of 0.15m (88,888 plants/ha) using a single row tractor mounted planter. All plots were machine moulded immediately after planting. Paraquat + diquat (2L Sprayseed/ha) was applied 2-3 days before emergence for control of weeds which had emerged since planting. Linuron (1.0kg Afalon/ha) was applied at emergence for residual weed control. First emergence (first stems breaking through the soil surface) was recorded on 11 August 1994 in experiment 1 and on 20 February 1995 in experiment 2. These dates were set as the emergence dates. Full emergence (100%) was recorded on 28 August 1994 and 1 March 1995 in experiments 1 and 2, respectively. Chlorothalonil (2L Bravo/ha) and iprodione (2L Rovral/ha) were applied periodically for control of early leaf blight. Methamidophos (0.7L Nitofol/ha) was applied for control of potato tuber moth and aphids.

Fertiliser applications
A complete trace element mix containing (kg/ha) $MnSO_4.H_2O$ (50.4), $MgSO_4.7H_2O$ (100), borax (33.6), $FeSO_4.7H_2O$ (33.6), $CuSO_4.5H_2O$ (33.6), $ZnSO_4.H_2O$ (28.0) and $Na_2MoO_4.2H_2O$ (2.24) plus P (87.5kg P/ha as double superphosphate, 17.5% P) and K (95 kg K/ha as K_2SO_4) was hand broadcast on all plots 2 days before planting. The whole site was then rotary hoed to 20-25 cm.

All post-planting fertilisers were injected via a trickle irrigation system. The system consisted of a single pumping facility simultaneously supplying tap water to 5 separate mainlines, one for each nitrogen level. Separate nutrient stock solution tanks and injectors (TMB®) were connected to each mainline. Within each plot, the fertiliser solutions were delivered via T-Tape® (2 L/h, 20cm between emitters) with one row of trickle line along the top of each potato ridge. This system was operated once per day for 105 days (15 weeks), beginning 11 August 1994 (28 days after planting, DAP) in experiment 1, and 16 February 1995 (14 DAP) in experiment 2. The equivalent of 1.8 mm of fertiliser solution was delivered through the system each day. For each treatment, the total quantity of nitrogen to be applied was divided by 105 and this amount was applied each day. Potassium was applied at the same time in equal daily amounts to a total of 800 kg K/ha. NH_4NO_3 (Agran 34-0®,34% N) was used as the N source and K_2SO_4 (Haisol-K®, 49% K) as the K sources in both experiments. In addition, 50 kg $MgSO_4.7H_2O$/ha was injected in equal daily amounts between 50 and 85 DAP in each experiment to a total of 5 kg Mg/ha.

Irrigation
Both crops were irrigated using mini-sprinklers (Lego® 170L/h). Between planting and emergence the crops were irrigated once (Exp. 1) or twice (Exp. 2) per day at a rate equivalent to 100% of long term average pan evaporation (Epan). Mini-sprinkler irrigation amounts were adjusted to take account of the water applied through the trickle fertiliser application system and any rainfall. For the first 3 weeks after emergence (WAE), daily irrigation amounts were equivalent to 130% Epan in 2-3 equal applications. Between 3 and 12 WAE, the daily irrigation amount was increased to 180% Epan, while for the periods - 12 to 15 WAE and 15 WAE to top kill - daily Epan replacement rates were 130 and 100%, respectively. Total rainfall received between planting and top kill was 269mm in experiment 1 and 248mm in experiment 2.

Measurements and analysis

Soil samples. Soil samples, consisting of two 50 mm cores were taken from each plot, to a depth of 100 cm (Exp. 1) or 150 cm (Exp.2) in 25 cm increments, prior to the addition of any pre-planting fertilisers and again immediately prior to harvest. These samples were air dried at 35°C for 48 hours. Prior to analysis, soil samples were ground to <2 mm. Samples were then extracted with 1 mol/L KCl (60 minutes, soil solution ratio 6 g:30 mL), centrifuged and the clear supernatant analysed for NH_4^+ and NO_3^- by automated colorimetry; NH_4^+ by saliculate-chlorine (Reardon *et al.* 1966) and NO_3^- by reduction diazotisation and coupling with N-1-naphthyl ethylenediamine dihydrochloride (Best 1976).

Plant samples. Whole plant samples (0.6-1.05 m segments of row, or 4-7 plants) were taken randomly from one of two designated sample rows in each plot at 10-12 day intervals from 13 days after emergence (DAE) in experiment 1 and 7 DAE in experiment 2. To avoid any possible affects of the gaps left by harvested plants on subsequent samples, sample rows were separated by a buffer row and individual samples within a row were separated by a minimum of 4 plants. Each sample consisted of all above ground foliage, below ground stems, tubers (defined as swellings greater than twice the diameter of the stolon) and as much root material as could be recovered by digging with a shovel. After washing to remove all traces of soil and blotting dry, samples were separated into green leaves (including petioles), senescing or dead leaves, above ground stems, below ground stems+stolons+roots, and tubers. Tuber fresh weight was recorded and all tubers were then diced. After removing a sub-sample of 20 green leaves (representing a range of leaf sizes), all samples were dried in a fan-forced oven at 70°C for 48 hours and then weighed for dry matter determination. The green leaf sub-sample was placed in a plastic bag and stored at 2-4°C for 24 hours after which the area of these leaves was measured using a Li-Cor Leaf Area meter (model 3100). Total green leaf area for the whole sample was determined using the relationship between the dry weight of this sub-sample and the total green leaf dry weight.

Plant samples were ground to <1 mm before analysis. After digestion with sulphuric acid and hydrogen peroxide (Yuen and Pollard 1954), total nitrogen was determined by automated colorimetry using the indophenol blue method (Varley 1966).

Climatic data. Total daily solar radiation and photosynthetically active radiation (PAR) (400-700 nm), daily maximum and minimum temperatures and daily rainfall were recorded from an automated weather station (Monitor Sensors, Caboolture, Queensland, Australia) located within 50 m of the experiment sites.

Harvest. After haulm senescence, tubers from a 7 m section of 2 harvest rows in each plot were dug mechanically and the total yield of fresh tubers for each plot was recorded. Marketable tuber yield was also recorded as the yield of blemish free tubers weighing between 50 and 450 g.

Data analysis.

Analysis of variance was carried out on level of total applied N and final total and marketable yield. Similarly, analysis of variance was carried out on level of applied N and dry weight and

N uptake for each plant component at each sampling time. A Mitscherlich equation ($y = a - b\exp(-cx)$) was fitted to the relationship between level of total applied N and final total and marketable tuber yield. The level of N corresponding to 95 and 99% of maximum yield was determined from each fitted relationship.

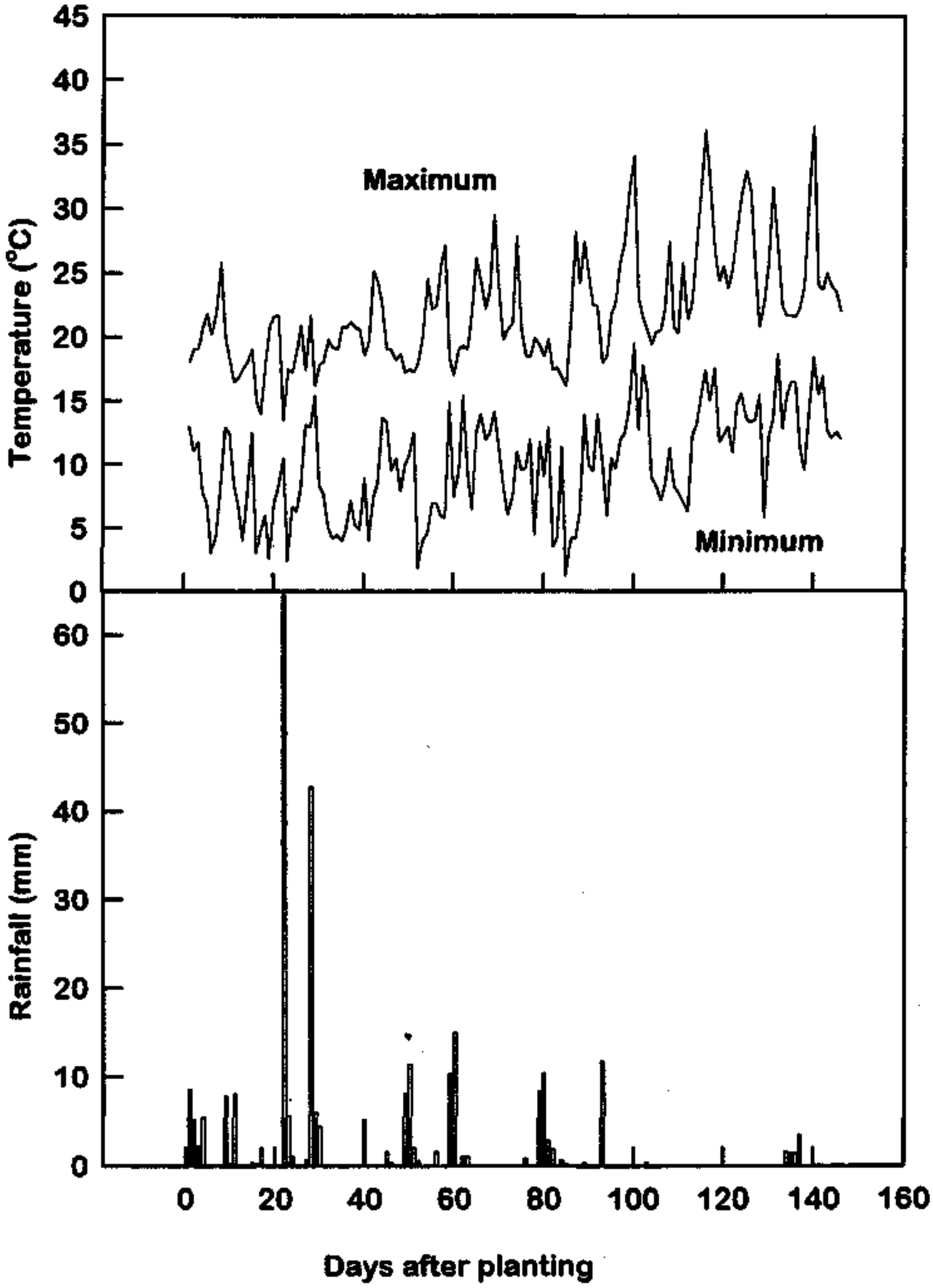

Figure 1A. Daily maximum and minimum temperatures and rainfall received during Experiment 1 (winter planting).

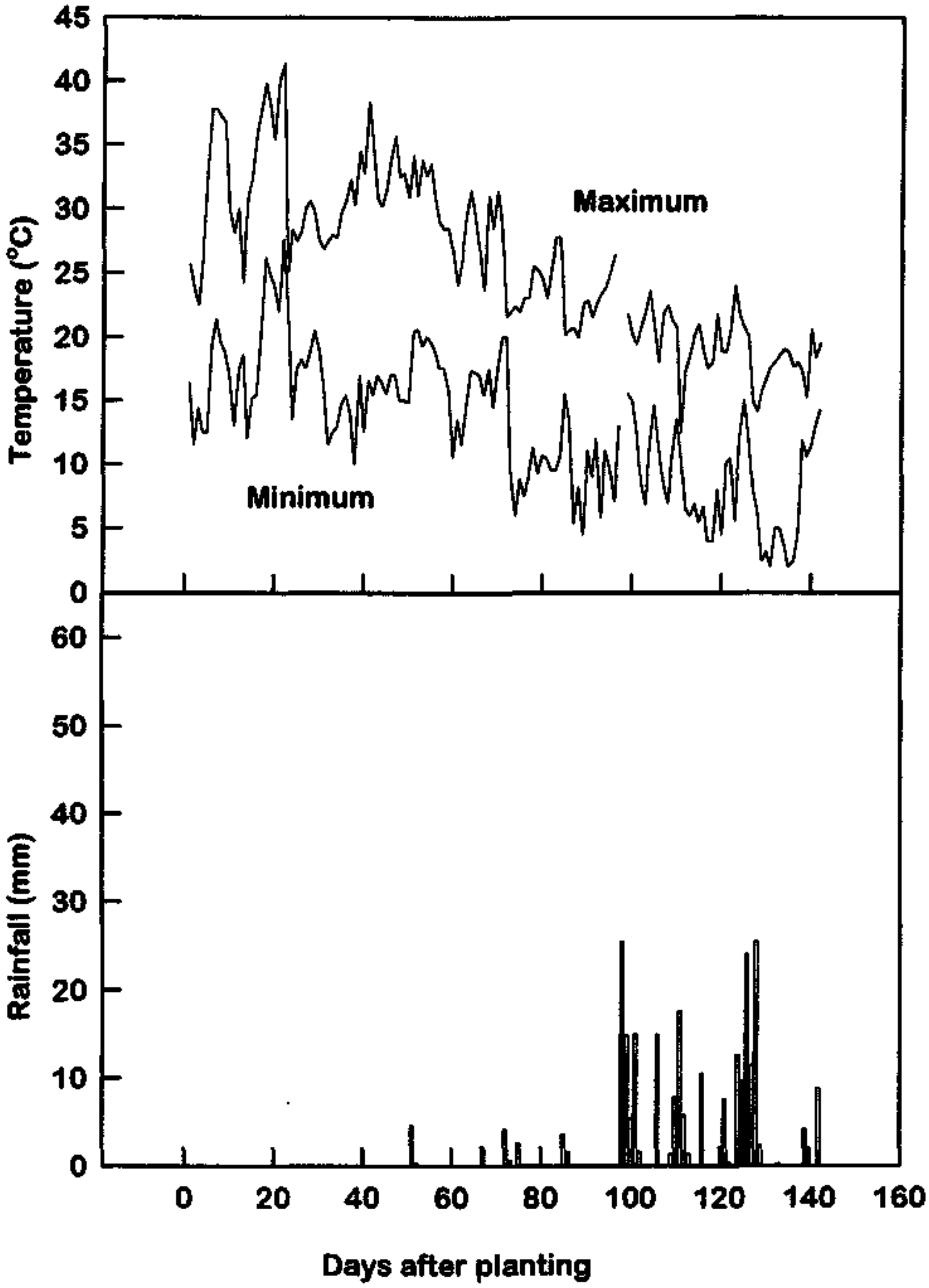

Figure 1B. **Daily maximum and minimum temperatures and rainfall received during Experiment 2 (summer planting).**

Results and Discussion

Yield response to level of total applied nitrogen

Total and marketable tuber yield responded significantly ($P<0.001$) to level of total applied N in both seasons. In the winter season, the level of applied N required for 95 and 99% of maximum total yield from the fitted Mitscherlich relationship was 556 kg/ha and 882 kg/ha, respectively (Figure 2a). Similar levels of applied N were required for 95 and 99% of maximum marketable yield, 577 kg/ha and 910 kg/ha, respectively (Figure 2b). In the summer season, the levels of applied N required for maximum total and marketable yield were lower than in winter. The levels of N required for 95 and 99% of maximum total yield in the summer planting were 498 and 790 kg/ha, respectively, and for 95 and 99% of maximum marketable yield were lower at 272 and 431 kg/ha, respectively (Figure 3a & b). The higher rates of N required for maximum yield in the winter compared with the summer season may, in part, be due to the greater amount of rain received, and hence N leaching losses, during the winter season, particularly during the middle part of the crop growth period (Figures 1a & b).

Applying N at levels required for 95% of maximum yield, rather than 99%, is unlikely to result in significant economic loss for potatoes on Spearwood sands in either winter or summer plantings. For this reason, and to reduce the potential environmental impact of N leaching on coastal sandy soils, we suggest that recommendations be based on the 95%, rather than the 99% yield level.

The level of N required for 95% of maximum total yield found here in the summer planting is slightly higher than that found previously by Hegney and McPharlin (unpublished) for summer planted potatoes on a Spearwood sand (417 kg N/ha). In contrast, the level of N required for 95% of maximum marketable yield in the present study is slightly lower than that found in the previous study (339 kg N/ha). Depending on whether total or marketable yield is used as the indicator, these results suggest that, under the conditions prevailing during the growth of summer planted crops on Spearwood sands, applying N fertilisers daily rather than weekly, does not result in a marked reduction in the total rate of N required for maximum yield.

The levels of N required for maximum yield found in this study are higher than that recommended for sandy textured soils elsewhere. For example, Lauer (1985) found that 340 kg N/ha was sufficient for maximum yield of potatoes (cv. Russet Burbank) on a Quincy sand/loamy sand in Washington State, USA.

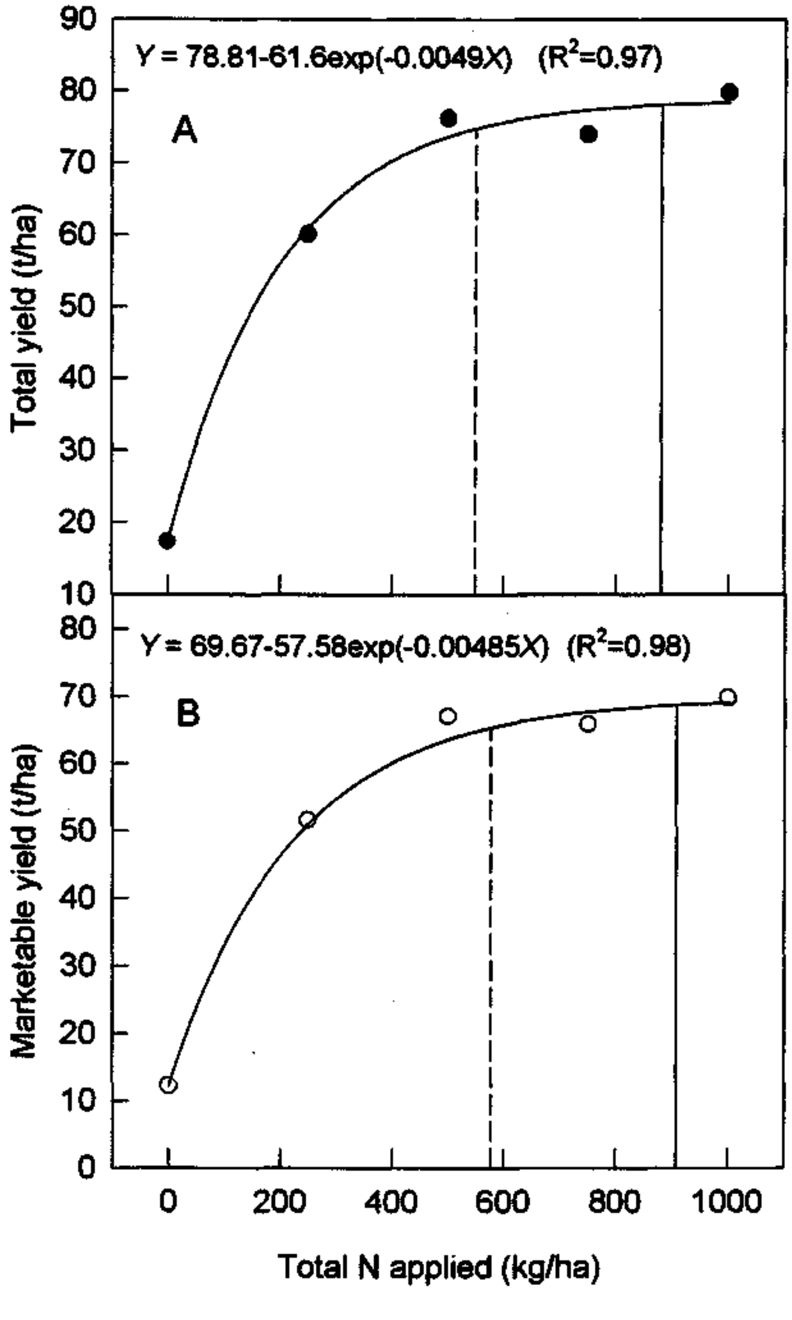

Figure 2. Total (A) and marketable (B) tuber yield in response to level of total applied N for winter planted potatoes on a Spearwood sand. Broken and Unbroken lines correspond with N levels required for 95 and 99% of maximum yield, respectively.

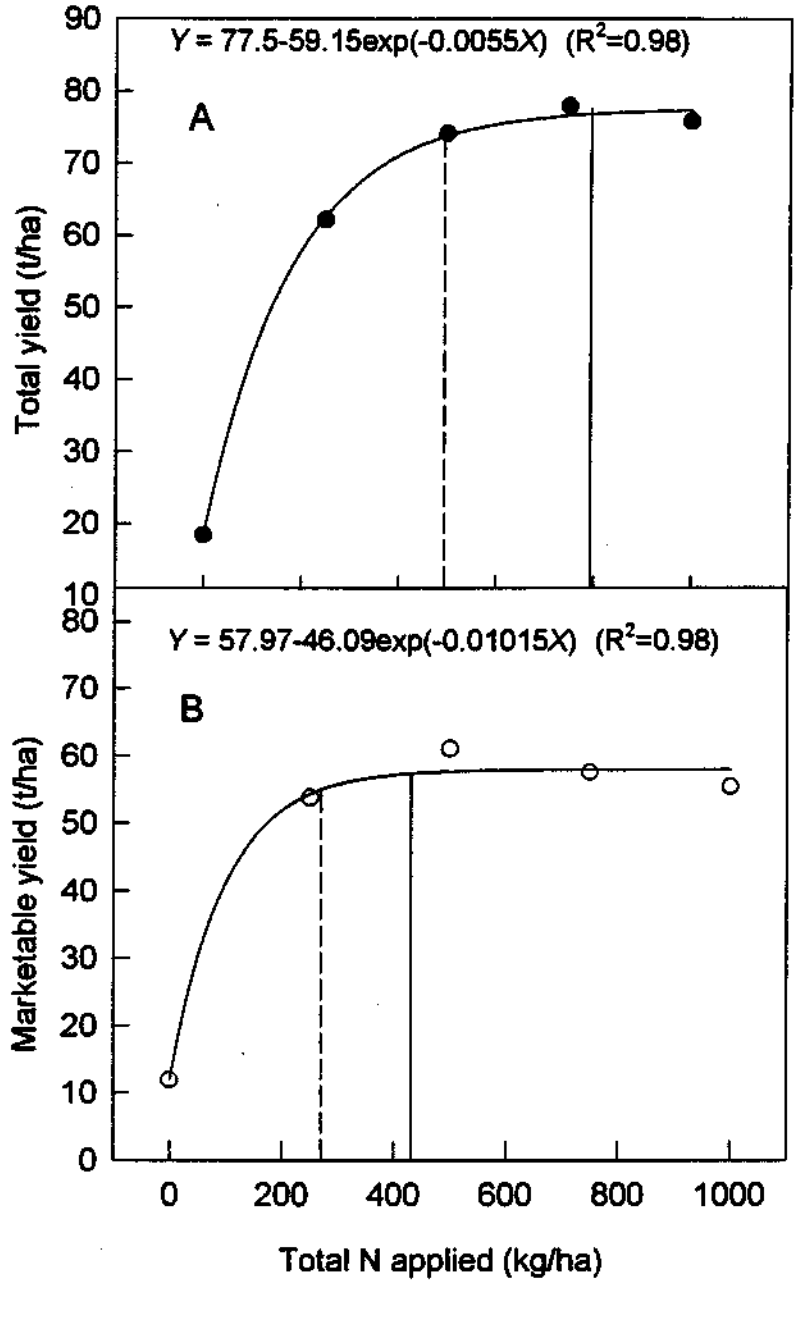

Figure 3. Total (A) and marketable (B) tuber yield in response to level of total applied N for winter planted potatoes on a Spearwood sand. Broken and Unbroken lines correspond with N levels required for 95 and 99% of maximum yield, respectively.

Nitrogen uptake and crop growth

In both the winter and summer planted crops, increased N applications resulted in increased N uptake and dry matter production of the whole crop, the crop canopy and of tubers (Figures 4 & 5). For each plant component, differences in N uptake between treatments tended to be greater than the differences in component dry weights. This indicates that, for each plant component, increased N uptake in response to N applications was the result of both increased dry matter production and increased N concentration.

Winter season

In the winter planted crop, the nitrogen content of the canopy and canopy dry weight reached a maximum between 42 and 52 days after emergence (DAE) in all treatments (Figures 4a & 5a). By this time, increased N applications had significantly ($P<0.001$) increased canopy N uptake and dry weight, though the magnitude of treatment differences in canopy N uptake were greater than the differences in dry weight. The highest canopy N uptake levels and dry weights were recorded in the 1000 kg N/ha treatment. At each sampling time, there was no significant ($P>0.05$) difference in canopy N uptake or dry weight between the 500 and 750 kg N/ha treatments. Both canopy N uptake and canopy dry weight remained fairly constant in all treatments after the respective maximum levels were reached.

From 22 DAE, N uptake by tubers and the whole crop increased significantly ($P<0.001$) as the level of applied N increased (Figure 4c & b). As for the canopy, the highest tuber and whole crop N uptake levels were found in the 1000 kg N/ha treatment, and there were no significant differences between the 500 and 750 kg N/ha treatments. Throughout the crop growth period, differences between the 500, 750 and 1000 kg N/ha in tuber and whole plant dry matter were small or insignificant (Figures 5b & c). This suggests that plants in the 1000 kg N/ha treatment took up more N than was needed to satisfy their immediate requirements for growth. The extra N taken up in the 1000 kg N/ha treatment was initially partitioned more to the canopy than the tubers, with tuber N uptake being significantly ($P<0.05$) higher in this treatment only towards the end of the crop growth period.

Following the start of rapid tuber growth (32 DAE), N uptake by tubers paralleled that of the whole crop. When considered together with the fact that canopy N uptake did not decline markedly after the start of tuber growth, this result suggests that tuber N requirements were met largely by continued N uptake, and that there was only limited redistribution of N from the canopy to the tubers. This result is similar to that of Huett and Dettmann (1992) who also studied winter planted potatoes and found that there was no significant remobilization of N from potato tops to tubers at any growth stage. Where remobilization of N from potato tops to tubers has been reported (Kleinkopf *et al.* 1981; Millard *et al.* 1989), it has been in spring or summer planted crops and has occurred at the end of the rapid tuber growth period when solar radiation levels and possibly temperatures were declining. In our winter planted experiment, these levels increased over the growth period and would have contributed to at least maintaining growth rates and N uptake by the crop.

Daily applications of N in each treatment continued until 105 DAE. In all treatments, whole crop and tuber growth reached a maximum before this time. Nitrogen applications after the time at which maximum tuber growth was reached did not contribute to further crop growth and hence were unnecessary. For example, in the 500 and 750 kg N/ha treatments, maximum tuber growth was reached by 84 DAE (12 weeks after emergence). At 84 DAE, a total of 405 and 607 kg N/ha had been applied, respectively, in each of these treatments. If the additional N applied after 84 DAE was unnecessary, then the treatment total N levels are clearly an over-estimation of the actual N levels required to achieve the respective total tuber yields in each treatment. In fact, it is possible that the same tuber yields could have been achieved with still lower levels of applied N than that applied up to 84 DAE, because it is unlikely that continued applications of N were required right up until the time of maximum whole crop and tuber growth. These results suggest that the above-mentioned levels of total applied N required for maximum tuber yield in winter planted potatoes on Spearwood sands could be reduced by at least 95 kg/ha without impacting on yield (ie. N required for 95% of maximum yield could be reduced from 556 to 461 kg/ha).

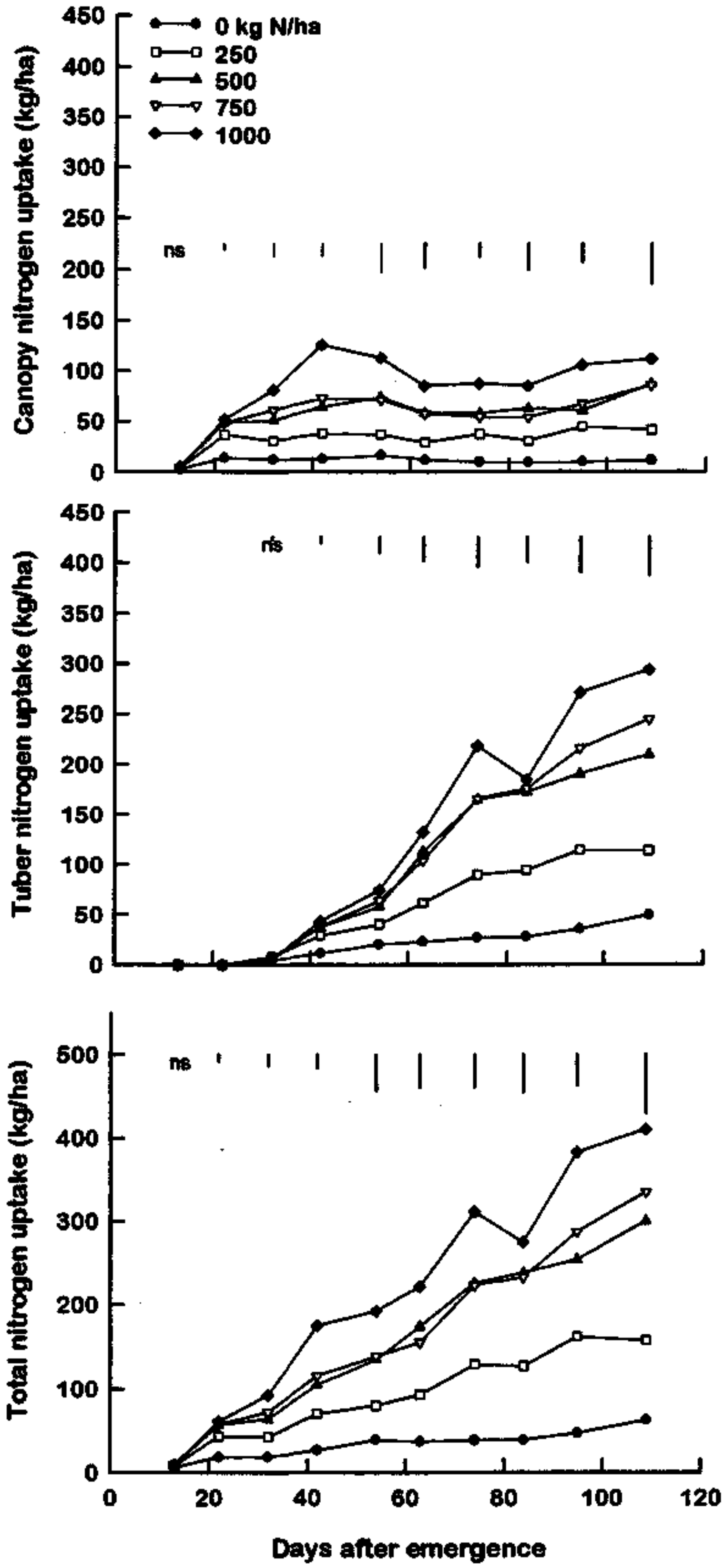

Figure 4. Effect of nitrogen application level and date of harvest on crop nitrogen (N) uptake in winter planted potatoes: (A) canopy, (B) tuber, and (C) total crop N uptake. Values are means of four replicates. Vertical bars represent LSDs ($P<0.05$).

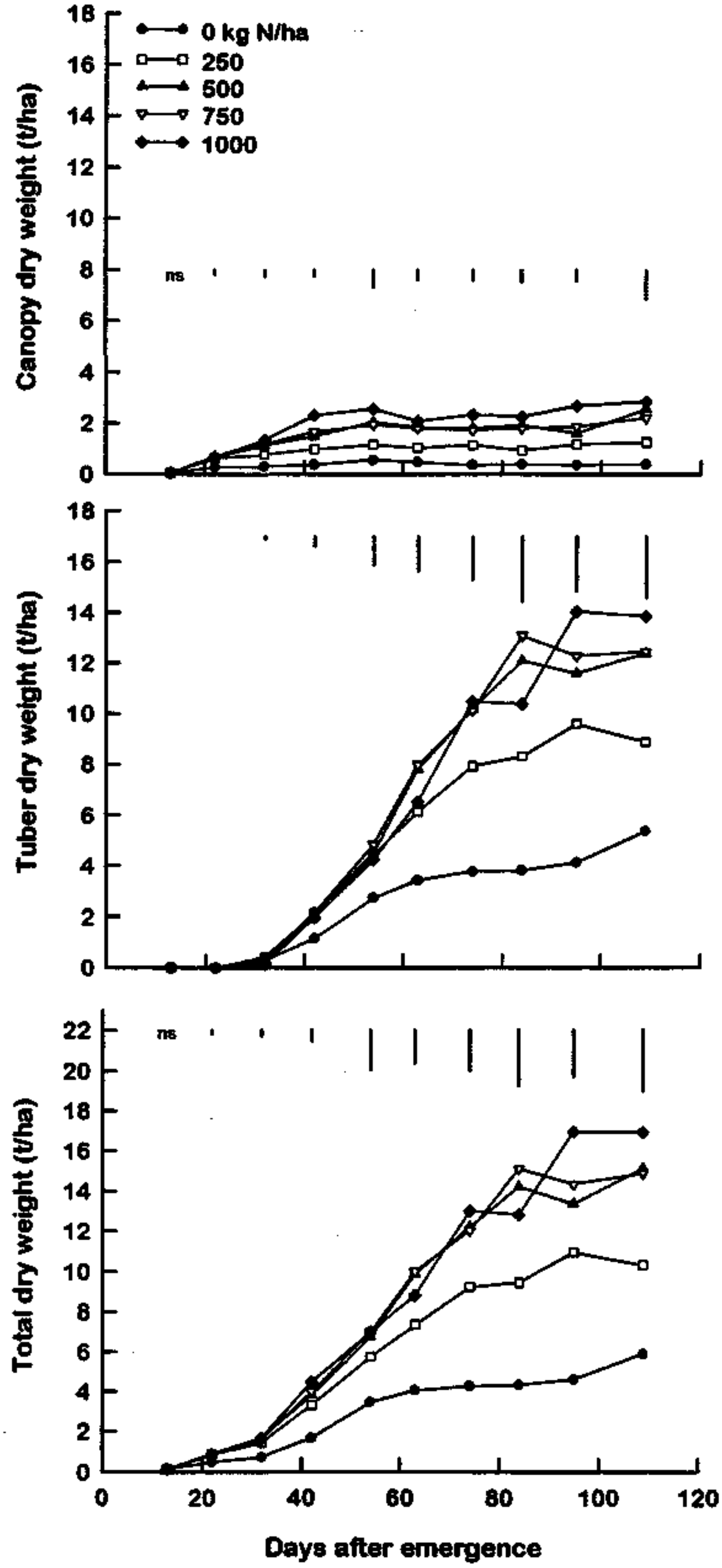

Figure 5. Effect of nitrogen application level and date of harvest on crop dry matter production in winter planted potatoes: (A) canopy, (B) tuber, and (C) total crop dry matter. Values are means of four replicates. Vertical bars represent LSDs ($P<0.05$).

Summer season
Higher canopy N uptake and dry weight levels were recorded in the summer, compared with the winter planted crop (Figure 6a). In contrast to the winter planted crop, canopy N uptake in the summer planted crop tended to decrease after reaching a maximum at between 28 and 38 DAE, particularly in the 500, 750 and 1000 kg N/ha treatments. This decrease in canopy N uptake was associated with a reduction in the rate of N uptake by the whole crop (Figure 6c) and continuing N uptake by tubers (Figure 6b), indicating that, particularly at the three highest N application levels, after maximum canopy N uptake was reached, N was remobilised from the canopy to the tubers. This same trend has been observed elsewhere for spring and summer planted potato crops (eg. Millard and Marshall 1986; Millard *et al.* 1989).

In contrast to the winter planted crop, the highest N application levels (750 and 1000 kg/ha) resulted in a significant ($P<0.05$) delay in tuber growth (Figure 7b), due to a higher proportion of total dry matter being partitioned to canopy rather than tuber growth for much of the crop growth period in these high N treatments. As a result of this delay in tuber growth, maximum tuber dry weight yields were attained much later in the 750 and 1000 kg N/ha treatments, compared with the 250 and 500 kg N/ha treatments. The final maximum tuber dry weight yields were not significantly ($P>0.05$) different for the 250, 500, 750 and 1000 kg N/ha treatments. However, maximum tuber dry weights were attained by 70 and 80 DAE in the 250 and 500 kg N/ha treatments, respectively, compared with 112 DAE in the 750 kg N/ha treatment and 122 DAE in the 1000 kg N/ha treatment.

In the summer planted crop, daily application of N in each treatment continued until 101 DAE. In the 250, 500 and 750 kg N/ha treatments, no further N uptake by the whole crop occurred after 70 DAE, hence N applied after this time was unnecessary. At 70 DAE, 176, 352 and 529 kg N/ha had been applied in the 250, 500 and 750 kg N/ha treatments, respectively. On this basis, as in the winter planted crop, the final total N application levels were an over-estimation of the actual quantities of N required to achieve the maximum yield in each treatment. Using the treatment total N application levels, it was shown above that 498 kg N/ha was sufficient for maximum yield of potatoes planted in summer on a Spearwood sand. However, the N uptake data shown here, indicate that N applications could have stopped at 350 kg N/ha without affecting final yield. This N application level is lower than that previously found necessary for 95% of maximum yield of summer planted potatoes on a Spearwood sand (417 kg/ha, Hegney and McPharlin, unpublished). In this previous study, N was applied in 10 equal applications at weekly intervals beginning at emergence. The data presented here show that, for a summer planted potato crop on Spearwoods sands, applications of N later than 10 weeks (70 days) after emergence do not contribute to further yield increases. Also, the apparent lower level of N required for maximum yield in the present study may be an indication that, in summer planted crops, greater N use efficiencies can be achieved by applying N on a daily rather than weekly basis.

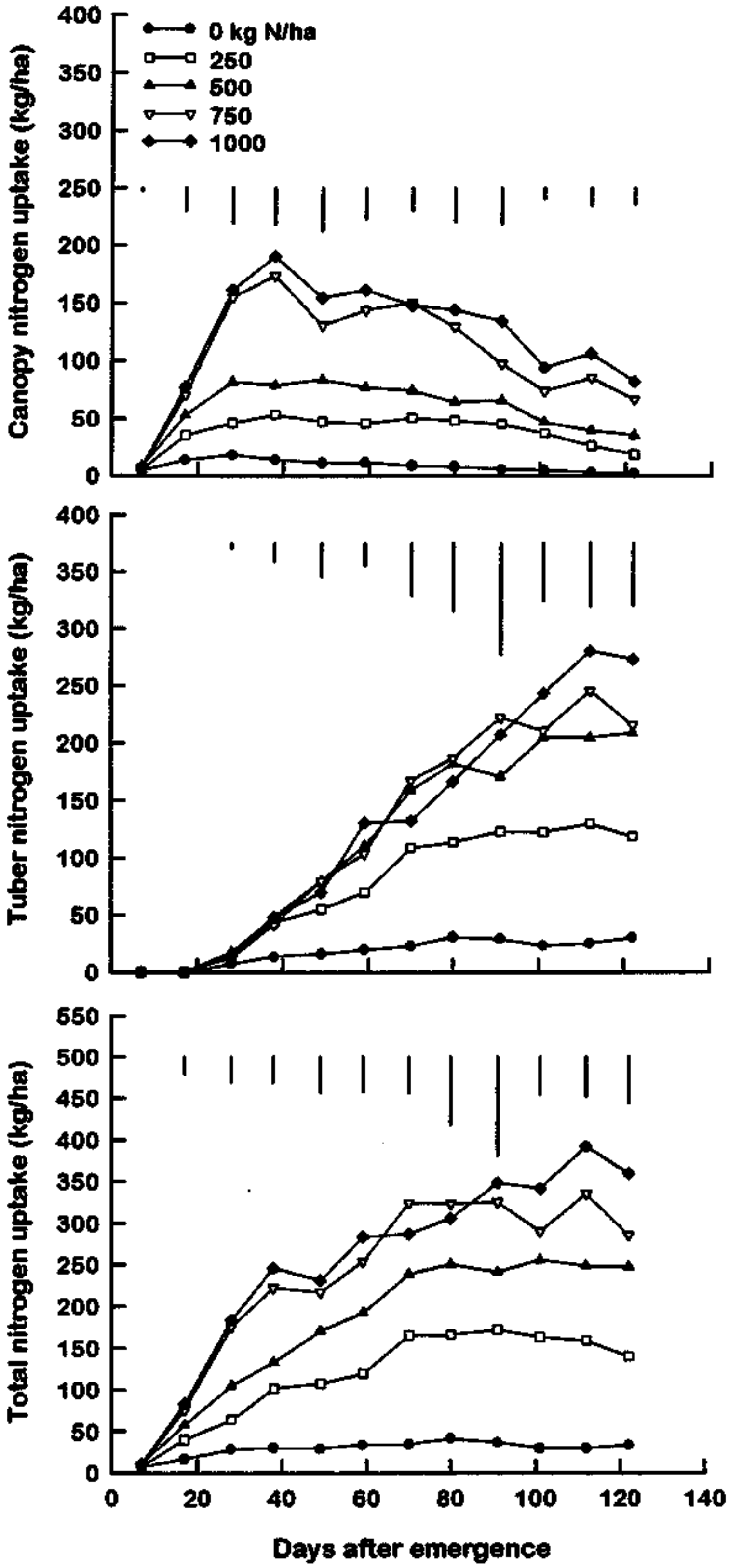

Figure 6. Effect of nitrogen application level and date of harvest on crop nitrogen (N) uptake in summer planted potatoes: (A) canopy, (B) tuber, and (C) total crop N uptake. Values are means of four replicates. Vertical bars represent LSDs ($P<0.05$).

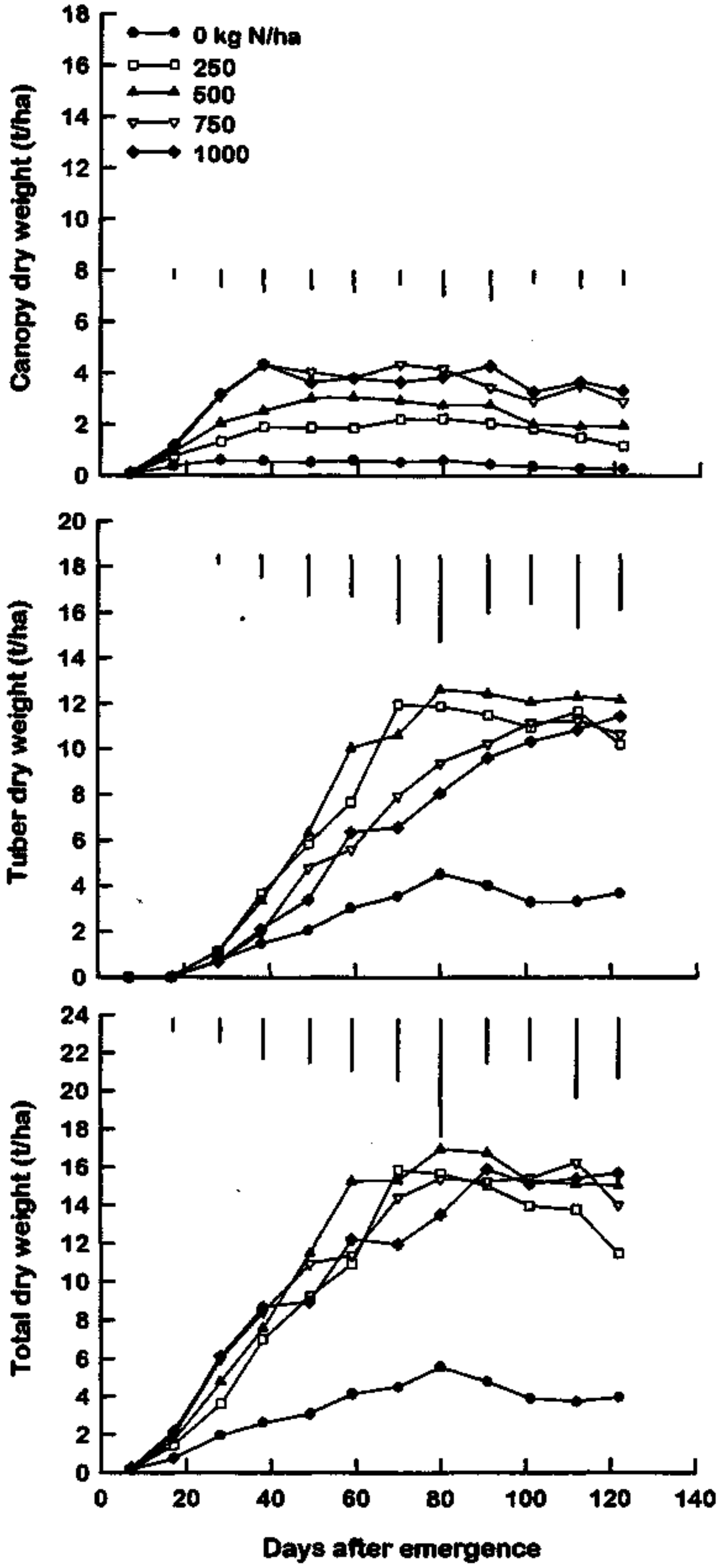

Figure 7. Effect of nitrogen application level and date of harvest on crop dry matter production in summer planted potatoes: (A) canopy, (B) tuber, and (C) total crop dry matter. Values are means of four replicates. Vertical bars represent LSDs (P<0.05).

Percent N recovery

The percent N recovered in the whole crop and in tubers decreased as N application level increased (Table 2). The N recovery percentages for each treatment were similar for the winter and summer planting times. Higher recovery percentages than those shown in Table 2 would have been recorded if N applications had ceased in each treatment when crop growth and N uptake ceased.

Table 2. Effect of N application level on percent N recovered ((kg N.ha in plant part/total kg applied N/ha)*100) in the whole crops and in tubers in winter and summer planted potato crops.

Treatment N Level (kg/ha)	Winter Planting Percent N recovered in		Summer Planting Percent N recovered in	
	Whole crop	Tubers	Whole Crop	Tubers
0	-	-	-	-
250	63	46	68	47
500	60	42	51	42
750	45	33	45	33
1000	41	29	39	27

Soil N levels

The importance of minimising the amount of N that is applied to potato crops on sandy soils in order to minimise N leaching is illustrated in Figure 8. As N application level increased, the level of N in the soil profile at the time of harvest increased. For each treatment, the soil N levels at harvest were higher in the winter than in the summer planted crop, despite higher initial soil N levels in the summer planting. In the winter planting, all treatments in which N was applied, resulted in the soil N levels below 15 cm depth being higher at the time of harvest than at planting. In the summer planting, in all treatments, soil N levels to a depth of 60 cm declined between planting and harvest, at depths below 60 cm in the 1000 kg N/ha treatment and 90 cm in the 750 kg N/ha treatment, soil N levels were higher at harvest than at planting.

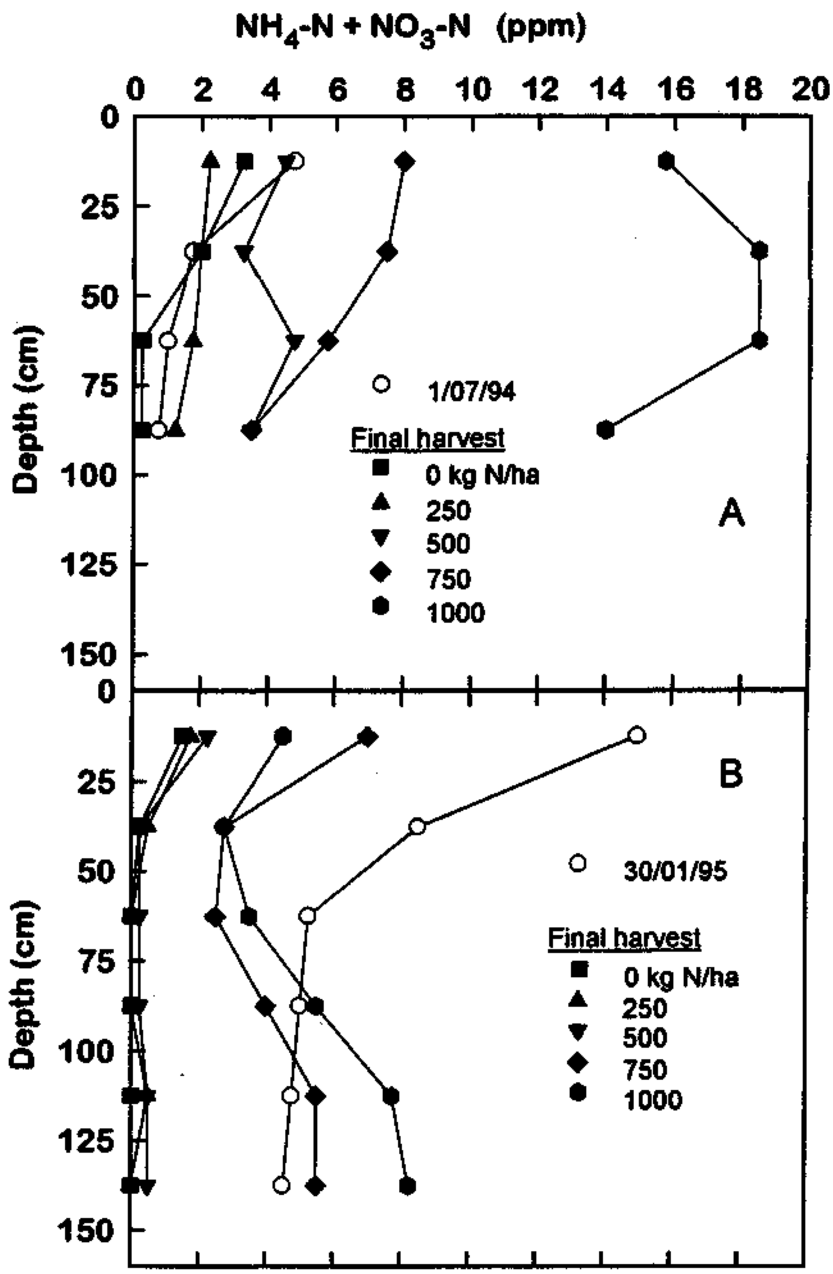

Figure 8. Nitrogen (ammonium-N + nitrate-N) levels at various soil at the time of planting and at harvest in response to levels of N applied during the growth of winter (A) and summer (B) planted potatoes. Values are means of four replications.

Conclusions

By adopting a plant growth and N uptake monitoring approach, it has been possible to determine when crop growth and N uptake reach a maximum and hence when no further N applications are necessary for both summer and winter planted potato crops. The fact that, in both seasons, crop growth and N uptake ceased before treatment N applications were complete, demonstrates that simple relationships between treatment total N application levels and final crop yield may result in over-estimations of actual crop N requirements.

The results of this study suggest that, on Spearwood sands, approximately 460 kg N/ha applied up to 12 weeks after emergence is required for maximum yield of winter planted crops, and 350 kg N/ha applied up to 10 weeks after emergence in summer planted crops. Further evaluations may show that these N levels can be reduced still further without impacting on tuber yield. Further work is also required to directly assess the relative efficiency of daily versus weekly applications of N.

The data presented in this study can form the basis of a potato crop nitrogen demand model for potatoes on the Swan coastal plain. Such a model should now be developed to enable improved prediction of crop N requirements under different climatic conditions.

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