



Know-how for Horticulture™

**More economically
and environmentally
responsible use of
phosphorus fertiliser
in potato cropping on
krasnozem soils in
Australia**

P G Johnson and
L A Sparrow
Tasmanian Institute of
Agricultural Research

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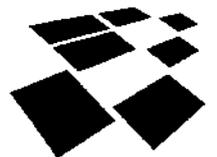
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(Project PT97003)

FINAL REPORT TO HORTICULTURE AUSTRALIA

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Tasmanian Institute of Agricultural Research

January 2002



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Summary

Phosphorus (P) is applied at high rates to vegetable crops grown on krasnozems (also known as ferrosols) in Tasmania and Victoria. Rates of 150-300 kg P/ha are not uncommon, especially for the cultivar Russet Burbank. However, crop removal is only 10-15% of this amount. This project examined the potential to reduce fertiliser P applications to potatoes on ferrosols, in order to decrease costs and also decrease phosphorus and cadmium additions to soil.

Starter phosphorus fertilisers in granular and liquid form, and as granular fertiliser in conjunction with irrigation placement were tested over three seasons. In no year was a response to starter phosphorus greater than an equivalent amount of phosphorus placed in the main band position (two bands slightly below and to the side of the seed). In the first years trial starter phosphorus was only 54% as effective as an equivalent amount of phosphorus placed in the main band during the early growth stage. There were no effects of starter P on tuber yield.

No yield responses were observed from the liquid starter treatments used in the second year's field trial. Liquid P concentrations needed to be low to avoid fertiliser injury, determined by laboratory experiments, and as a result it is likely that insufficient P was applied to produce a response. Measurements of crop senescence indicated that later senescing plots had a greater proportion of larger sized tubers. Hence factors that increase the duration of canopy cover will improve yield.

In the final year granular starter P was tested in conjunction with sprinkler irrigation and ridge applied drip irrigation. Starter treatments did not improve P uptake and there was a significant reduction in ground cover associated with the closest, spot, starter treatment. Dripper irrigation significantly improved the early uptake of main band applied P, but not starter placed P, but there was no effect on tuber yield. Drip irrigated plants tended to reach senescence earlier than sprinkler irrigated plants, which could be a consequence of increased P nutrition. However there were indications of N leaching under the drippers which may also account for their earlier senescence.

P applied as a starter band with the seed piece may be less available to the plant due to lower fine root development around the seed piece, particularly later in the season after tuber development. There may also be a less favourable soil moisture regime in the centre of the hill where the seed piece is situated. Unlike small seeded crops P deficiency is unlikely to develop in potatoes during the period between planting and the growth of roots to the main band of fertiliser, hence potatoes are less likely to respond to starter fertilisers.

Introduction

Potatoes for processing are the highest value crop in Tasmania and a major crop in Victoria. We estimate that more than 80% of Tasmanian and 50% of Victorian potatoes are grown on about 9000 ha of krasnozems (hereafter referred to as ferrosols, Isbell 1996). A further 1000 ha of potatoes are grown on ferrosols in the Atherton Tableland in Queensland, and 200 ha in the Robertson area of NSW. Ferrosols are therefore important soils for Australian potato production.

Ferrosols are soils developed on basalt which has weathered to produce finely divided iron and aluminium oxides. These minerals are responsible for the excellent structure of ferrosols, but they are also responsible for "fixing" phosphorus (Moody 1994). Ferrosols have the highest P fixing capacities of any agricultural soils in Australia. On these soils, P must be banded for good yields; without banding P fixation is accentuated. However, even with banding, rates of P needed for optimum yield and quality are often 150-250 kg P/ha (Sparrow *et al.* 1992). Low soil temperatures early in the season may also be partly responsible for the high P needs of potatoes in cooler areas like Tasmania and Victoria. The high P rates are a cost to growers which has increased recently, and also a cost to soil and potato quality because they add significantly to the soil P and cadmium (Cd) load. The consequences of continued high P rates are a greater risk of higher Cd in produce and of increased P movement to streams in eroded soil.

For potatoes on ferrosols, P is usually banded in 2 strips on either side of and about 50 mm below the seed. However, in spite of the increased P efficiency which banding affords, total crop P uptake is at most about 40 kg P/ha for a 60 t/ha crop and not all of this comes from the fertiliser. For example, Pursglove and Sanders (1981), using isotopically labelled P fertiliser, found that only 4% of the fertiliser P was recovered by the crop. Clearly there is scope to improve the efficiency with which P fertiliser is used, and closer than normal banding of P fertiliser at planting would seem a possible strategy. Despite this scope, there has been no work in Australia to look at improving P fertiliser efficiency in potatoes through close placement.

The effect of P fertiliser placement on its recovery by plants is considered to be the net effect of competing mechanisms (Holford 1989). On the one hand, concentrating the fertiliser in a smaller volume of soil decreases soil-fertiliser contact and thus minimises fixation. It also stimulates root growth in the band (Duncan and Ohlrogge 1958). On the other hand, excessive fertiliser concentration in bands can cause P to precipitate. A simulation model of P uptake constructed by Kovar and Barber (1987) showed that the optimum volume of soil to fertilise with P decreased as the P buffer power of the soil increased. Ferrosols have a high P buffer power.

There have been many studies on close placement of fertiliser, but few on potatoes have been reported. Much work has been done on P coating of pasture seeds to help establishment, most of it in glasshouse trials. This work has shown that effects of P seed coating are often most pronounced early in growth, and that the most soluble P sources, including commercial superphosphates, can actually inhibit growth because they form acidic solutions upon dissolution. The effect of acidity can be overcome by mixing such P sources with lime. Combining ammonium nitrogen with P can boost the P benefit. The ammonium is thought to stimulate P uptake (e.g. Sanchez *et al.*

1989, Rebakka *et al.* 1993) and may also decrease the amount of soil aluminium dissolved by the fertiliser because it dissolves to give a more alkaline solution (Russell 1979, Moody *et al.* 1995b). The latter could be important in ferrosols.

Tindall *et al.* (1993) report that in Idaho, USA, starter NP bands are placed above the seed in addition to conventional bands below and to the side of the seed. However, in a recent pilot pot trial, we found that a close band of triple superphosphate placed 1 cm below the seed was more effective than one placed 1 cm above. We concede that the behaviour of potato roots in pots is likely to be different from that of field potatoes. In Idaho, the close bands are applied at rates of about 20 kg/ha of both N and P. There the soils are alkaline, and mono ammonium phosphate is used to avoid generation of ammonia gas which is toxic to the germinating seed. While ferrosols are not alkaline, and diammonium phosphate could safely be used on such soils, there is a greater risk of salt induced calcium deficiency (Moody *et al.* 1995a) with diammonium than mono ammonium phosphate.

Pilot studies in Tasmania in both the field and glasshouse (Sparrow unpublished data) have suggested that seed coating is sometimes detrimental to potatoes, but that close placement within 1 cm of the seed is not. For this reason, and because of the probable difficulty of developing a practical system for coating potato seed with fertiliser, we focused our work on close placement.

The placement of some of the fertiliser with or above the potato seed piece has been shown to improve the yield of potatoes by locating the fertiliser in the region with the highest root density (Kleinschmidt, 1983). However some degree of mixing of the starter fertiliser through the surrounding soil may be desirable since the growth of young roots is limited and the roots may not encounter the fertiliser if it has been confined to a narrow band (Costigan, 1987). Alternately the P requirement of potatoes can be reduced by soaking the seed tubers in low strength P solutions (Sharma and Gerwal, 1989). The phosphorus solutions are absorbed into the interstitial spaces from where it can be absorbed into the cells. Liquids applied into the soil directly over the seed piece at planting tend to dissipate around the outside of the seed into the soil where early root growth occurs. Hence liquid starter solutions may provide a method for both placement of the starter fertiliser and allow the potential for uptake of P even before the roots develop.

Since phosphorus moves to roots primarily by diffusion, soil moisture directly affects the uptake of P from both soil P reserves and from fertiliser (Jungk and Claassen, 1997). Higher rates of irrigation can increase the recovery of both banded and broadcast P fertilisers (Baerug and Steenberg, 1971). However the effects of irrigation on starter bands has not been investigated.

The canopies of a range of crops have been shown to interact with overhead irrigation and rainfall (Xiao *et al.*, 2000, Carter *et al.*, 2000, Ellsbury *et al.*, 1996). In potatoes Saffigna *et al.* (1976) observed preferential flow of overhead irrigation water down the stems and to the outer edge of the canopy. Hence the potato canopy may redirect overhead irrigation water away from the hilled soil and into the furrows. When applying irrigation water to crops through furrow irrigation the water tends to move to the base of the hills and then upwards due to root absorption of the water in the hill (Taylor and Ashcroft, 1972). The upwards movement of water through the base of the

hill would favour P uptake from the main band position while the drier conditions in the hill would retard P uptake from the starter position.

Irrigation water can be applied directly to the hill soil through drip irrigation which may enable greater use of both starter and main band placed P and potentially increase the uptake of P retained in the soil. In addition drip irrigation increases the water use efficiency and enables better scheduling of irrigation (Shock *et al.*, 1999). Since potato yield is increased in direct proportion to reductions in average soil moisture tension (Taylor and Ashcroft, 1972), more frequent applications of water through drip irrigation can lower the average moisture tension and thereby increase yield and P uptake.

Field experiments were conducted in three consecutive growing seasons. The first experiment was designed to test the benefit of a granular starter fertiliser placed above the seed as reported by Kleinschmidt (1983). In the second year's trial the starter P was applied as a low strength liquid solution directly over the seed piece. Excavations of young plants during the first year's trial had revealed substantial root growth around and below the seed piece, but only limited growth in the soil above the seed piece. Laboratory experiments had indicated that dilute P solutions could improve the early growth of potato shoots. In the final field trial the effects of dripper and sprinkler irrigation on granular starter band treatments were compared. While the liquid treatments of the second trial had had no effect, there were indications that potato growth was strongly affected by variations in irrigation. We wanted to see if a more favourable moisture regime of the hill soil through drip irrigation promoted better utilisation of fertiliser and soil P reserves.

Methods

Forthside and Paloona 1998

In the 1998-1999 season two field trials were conducted in NW Tasmania, one at Forthside Vegetable Research Station (Paddock 11 unit C), the other on a farmer's property at Paloona, approximately 6 km south of Forth. A factorial design with five rates of starter and five rates of main band fertiliser was used. Starter fertiliser of monoammonium phosphate (MAP) was applied at rates of 0, 10, 20, 40, and 80 kg P ha⁻¹, and conventional band-placed P at 0, 30, 60, 120, and 240 kg P ha⁻¹. Main band fertiliser was placed in the standard banding position (Figure 1), slightly below and to the side of the seed piece in two rows, while the starter fertiliser was placed in a single row just above and to the side, but in contact with the seed piece. At Forthside the starter fertiliser was placed by hand from preweighed containers of fertiliser, while at Paloona, starter fertiliser was placed through a hand-held seed drill that had been modified to distribute the required rates. All plants received 200 kg N ha⁻¹ and 300 kg K ha⁻¹ in the main band.

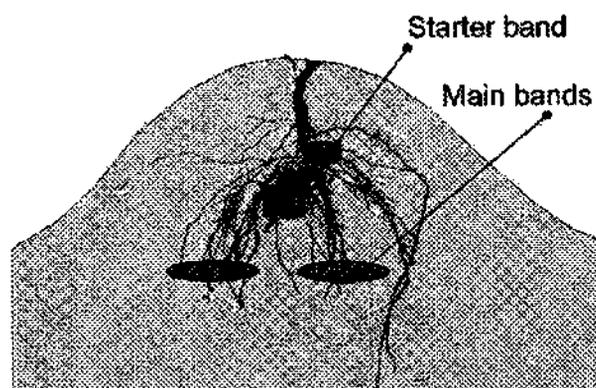


Figure 1. Location of main and starter bands used for all trial work.

At both sites the furrows were closed by hand raking after planting, and the hills were formed up three to four weeks later. Each treatment plot was four rows wide by six meters long, the outside two rows being buffers, and there was a half meter buffer at the start and finish of each plot. The previous crop was lupin followed by a regrowth lupin green manure crop. Solid set irrigation was used at Forthside and a travelling irrigator at Paloona. Crop husbandry was carried out by the farm managers at both sites. Soil samples (0-10 cm) comprising 20 subsamples, bulked for each block in each trial, were collected two to three weeks prior to planting.

Forthside 1999

Liquid starter fertilisers consisting of control (no liquid) and liquid P rates of 0, 1, 2, and 5 g P L⁻¹ were applied to plots receiving main band P of either 50 or 100 kg ha⁻¹. There were two methods of starter application either as a spot, pulsed application of 10 ml of solution directly over the seed piece, or as a band, continuous application of liquid band with 20 ml per plant. Two forms of liquid starter were used:

- i) phosphorous acid with calcium nitrate;
- ii) MAP with fine ground gypsum.

These starter fertiliser combinations were designed to supply a constant P:N:Ca ratio of 2:1:1.5 and to not adversely increase the soil pH, which may occur when diammonium phosphate is used (Moody *et al.*, 1995a).

A factorial design with incomplete randomisation in the starter treatment was used due to restrictions in changing between spot and band application methods along a planting row. Hence the spot or band treatments were alternated across 26 rows. The total P application in the liquid fertilisers was 0, 0.4, 0.8, and 2 kg P ha⁻¹.

A further series of plots received 0, 150, 200 and 300 kg P ha⁻¹ in the main band, from which a P response curve was obtained. Treatments were replicated across three blocks. The main band fertiliser also contained a uniform application of 220 kg N ha⁻¹, 300 kg K ha⁻¹ and 130 kg S ha⁻¹, and was applied through two variable rate fertiliser boxes. The trial was established at Forthside Vegetable Research Station (Paddock 3 unit J).

The liquid fertilisers were injected directly into the furrows during planting from a nozzle placed behind the planter shoe (Figure 2). Hills were formed during the planting operation. The liquid starter fertilisers were held in four litre polyethylene

containers and forced out through the nozzle by applying compressed air at 50-100 kPa to the containers.

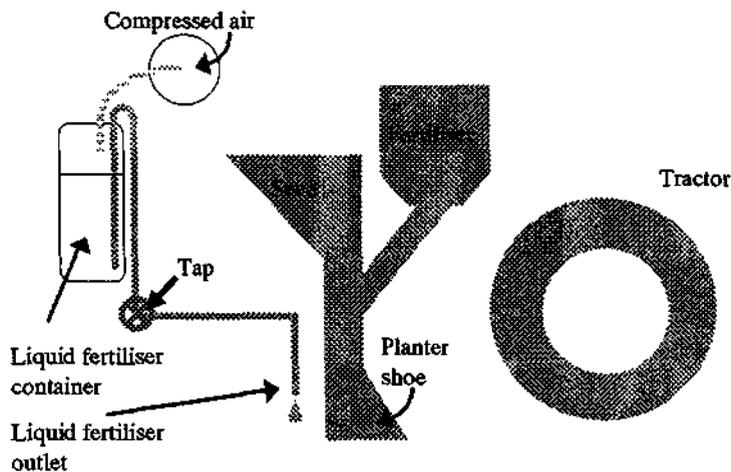


Figure 2. Diagram of equipment used to apply liquid starter treatments. Compressed air at 50-100 kPa was applied to the container of liquid fertiliser. A tap in the outlet line could be pulsed to apply the spot starter treatments or held continuously open for the band starter treatment.

The crop was sown on 4/11/99, petioles were sampled at tuber size 5-10 mm on 6/12/99, and the trial was harvested on 9/5/00. The farm manager at FVRS carried out crop husbandry. Irrigation was by travelling irrigator, with two irrigator runs in the trial. The irrigation application appeared to have a marked effect on crop senescence. Hence crop senescence was visually scored on 17/3/00 with plants being ranked from 1 for a complete green canopy to 5 for a fully senesced canopy. Soil samples were also collected from the top 5 cm of each plot during late senescence on 17/3/00. These were analysed for Colwell P and K and select samples analysed for organic carbon. The distribution of irrigation water was measured by placing catch cans across the trial prior to irrigating. Colwell P and senescence scores were compared with irrigation and tuber yield data by bulking the plot values along each of the 26 trial rows, with six plots to each row.

Forthside 2000

An experiment to evaluate the effects of irrigation, either by drippers or as overhead sprinklers, in combination with starter fertiliser as a spot or band, was established at Forthside Vegetable Research Station in paddock 2 unit J. A split plot design was used, with irrigation treatments as whole plots and the phosphorus treatments as sub plots (Figure 3). Each starter treatment was replicated four times within an irrigation plot.

The starter P treatments were placed with the seed piece either as a continuous band (B) or as discrete spots (S), with a control (C) where the equivalent amount of P was placed in the main band position and thoroughly mixed with the main band fertiliser (Figure 1). A total of 100 kg P ha⁻¹ was applied in each starter treatment (S and B), with 25 kg P ha⁻¹ as single superphosphate (SSP) in the starter position and 75 kg P

ha⁻¹ as MAP in the main band. The control (C) had 25 kg P ha⁻¹ as SSP and 75 kg P ha⁻¹ as MAP together in the main band. Nitrogen was supplied as ammonium sulphate at 133 kg N ha⁻¹ and diammonium phosphate at 67 kg N ha⁻¹. Potassium was applied as potassium sulphate at 300 kg K ha⁻¹. Additional main band rates of 0, 200, and 300 kg P ha⁻¹ were included to evaluate the P responsiveness of the site. These treatments were replicated twice within each irrigation plot. Triple super phosphate was used to supply the higher P rates. For the zero P main band treatment, the MAP was omitted and an additional 67 kg N ha⁻¹ supplied by ammonium nitrate.

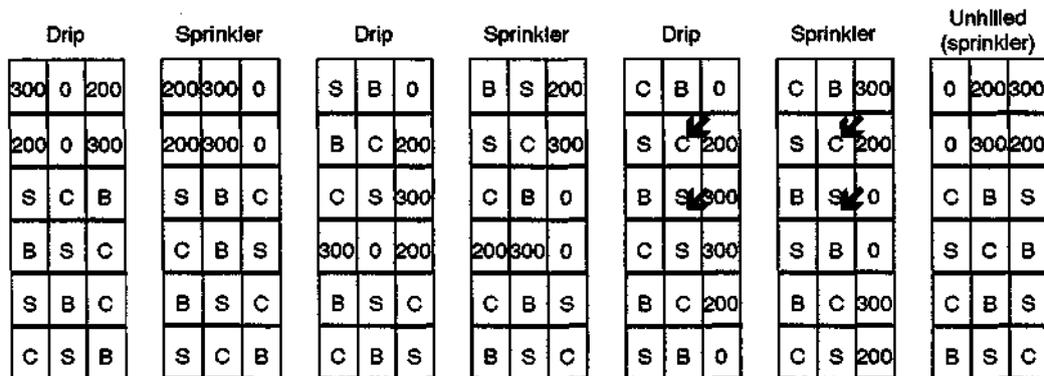


Figure 3. Experimental layout for irrigation, starter and main band rates (C control, B band, S spot). Numbers refer to P rates in kg ha⁻¹ used to establish the P response curve. The plots on the far right was left unhilled to compare root growth with and without hilling. ↙ denotes position of tensiometer arrays.

The irrigation plots were 12 rows (9.6 m) wide by 36 m long, comprising three by six sub plots (Figure 3). Sprinkler irrigation was applied through two lines of fixed head, gear driven sprinklers placed in the outside buffer rows, i.e. 9.6 m apart. There were four sprinklers in each line and their throw was 10-11 m at 200 kPa. The precipitation rate under the sprinklers was measured to be 35 mm/hr. Sprinklers were run for between 1-1½ hours at each application. In the dripper treatment, Nelson[®] drip tape was laid at one line per row over the top of hills shortly after emergence. The drip line had an emitter spacing of 300 mm and a flow rate of 2.5 L/hr, therefore the equivalent precipitation rate at 800 mm row spacing was 10.4 mm/hr. The drippers were usually run for one hour, though on occasion they were run for up to two hours.

Soil moisture was monitored by an array of tensiometers placed at 250, 375, and 500 mm below the top of the hill and also at 250 and 375mm below the surface of the furrows. The tensiometer arrays were installed in duplicate in one dripper plot and one sprinkler plot (Figure 3). Tensiometers were constructed from a porous ceramic Soilspec[®] tensiometer tip, an appropriate length of 25 mm diameter electrical conduit, and a 100 mm long by 15 mm diameter clear acrylic tube top plugged with Soilspec[®] tensiometer tube stoppers. The tensiometers were read every 2-5 days using a vacuum gauge fitted with a hypodermic needle. The vacuum gauge was calibrated against a mercury manometer. Dripper flow rate was monitored by collecting the water from an emitter in the dripper plot and sprinkler irrigation monitored by catch cans placed across the sprinkler plot prior to irrigation. The crops were irrigated when the average soil water tension at 375 mm below the top of the hill was -40 kPa.

Both starter and main band fertiliser were applied at planting using a modified Faun[®] planter. Starter treatments were applied through a separate fertiliser box with a flexible tube that allowed fertiliser placement with the seed or with the main band fertiliser. A manually operated hinged bucket was used to store and then drop the spot treatment directly over the seed piece during planting. Each plot was four rows wide by five meters long with a one meter buffer between plots. The paddock was prepared prior to planting by mouldboard ploughing followed by rotary cultivation. The previous crop was carrots.

The crop was planted on 9/11/00 with approximately 50% emergence on 29/11/00. Full canopy closure commenced around 2/1/01 and senescence began between 27/2 and 5/3/01. The crop was harvested during 11-12/4/01. Digital images of crop ground cover were taken at regular intervals during crop growth. Differences in the ground cover were used to measure the effects of fertiliser and irrigation treatments. Soil samples were collected several weeks prior to planting on a sampling grid 4.5 m by 3.6 m over a unit of 36 m by 80 m. Soil samples were analysed for Colwell P and K and a subsample analysed for organic carbon. An unreplicated subplot comprising potatoes planted at a depth of 200 mm without hilling was included, primarily to investigate root development in the absence of hills.

Petiole sampling

Petioles were sampled twice at both Forthside and Paloona in 1998, but only once at the other trials (Table 1). Twenty petioles were taken from the 4th–5th leaves of each plot from the buffer rows. The stripped petioles were then, dried, ground and digested in nitric acid prior to analysis by ICPES. Prior to grinding the dry weight of petioles was recorded as an index of plant biomass.

Table 1. Sowing, petiole sampling and harvest dates at the trial sites.
Numbers in brackets are days after planting.

Crop stage	Forthside 1998	Paloona 1998	Forthside 1999	Forthside 2000
Sowing	16-Oct	22-Oct	4-Nov	9-Nov
0-5 mm tubers	26-Nov (41)	27-Nov (36)	6-Dec (32)	-
10-20 mm tubers	30-Nov (45)	04-Dec (43)	-	21-Dec (42)

Tuber grading and analysis

The tubers were dug by either single (1998-1999) or twin row (2000) harvester. Once harvested, the tubers from each plot were hand packed to one or two sacks and stored for up to six weeks prior to grading. In 1998 the tubers were graded into five weight categories: 0-75 g, 75-250 g, 250-450 g, 450-850 g, and larger than 850 g. In 1999 and 2000 the 75-250 g weight category was split into two categories of 75-150 g and 150-250 g. Additional categories for tubers with secondary growth, and for dumbbell shaped, cracked and rotten tubers were included, however in the results presented these categories are grouped together as reject tubers. A subsample of six to eight tubers was collected from each plot to be used for specific gravity and tissue analysis. These samples were stored at 4°C until processed. Specific gravity was measured by the weight-in-air weight-in-water method. To measure tuber nutrient content, a longitudinal slice, approximately 5 mm thick, was cut from each tuber. The skin was removed and the remainder diced and rinsed in distilled water. A 100 g subsample of diced tuber pieces was taken for oven drying at 60-70°C. The oven dry sample was

ground and 0.5 g digested in nitric acid for ICPEs analysis. Tuber nutrients were analysed from the Forthside 1998 and 2000 trials only. Tuber Cd was measured by AAS at Forthside 1998 only.

Soil analysis

Available P and K were measured by 0.5M NaHCO₃ extractable P and K Colwell (16 hour shake) and analysed by the automated colour method (Rayment and Higginson, 1992). Soil organic matter was measured by Walkley & Black wet oxidation with potassium dichromate (Rayment and Higginson, 1992). Phosphorus sorption curves were determined by the manual colour method of (Rayment and Higginson, 1992) Equilibrium phosphorus concentration (EPC) is an estimate of the soil P concentration when no P has been added and is obtained by extrapolating the phosphorus sorption curve to zero. Phosphate buffering capacity (PBC) is the slope of P sorbed (mg/kg)/log(equilibrium concentration (ug L⁻¹)) (Rayment and Higginson, 1992). PBC O&S is the slope of the phosphate buffer curve (PBC) between P equilibrium concentrations of 0.25 and 0.35mg P L⁻¹ (Ozanne and Shaw, 1968). Phosphorus sorption index (PSI 150) is the quantity of P sorbed at a given EPC, in this case 150ug P L⁻¹ (Rayment and Higginson, 1992).

Results and discussion

Forthside and Palooona 1998

Petiole nutrient analysis revealed that the main band P had a greater effect on nutrient levels than the starter band P, reflecting in part the higher rates of P applied in the main band (Table 2). In general, petiole concentrations of Al, Fe Mg and Zn were reduced by higher rates of main band P, while petiole S, K and P were increased. Petiole weight was significantly increased by higher rates of main band P. Amongst the starter treatments only petiole weight and P, Mg and Mn concentrations were affected (Table 2). Petiole Mg concentration decreased with higher rates of starter P while Mn concentrations increased. The MAP used for the starter band creates acidic conditions in the soil surrounding the fertiliser (Moody *et al.*, 1995a), which may have dissolved soil Mn. Since Mn is more mobile than Al or Fe in the soil (Moody *et al.*, 1995a), and since Mn is also more mobile in plants (White *et al.*, 1970), it tends to concentrate in leaf tissue whereas Al and Fe remain in or at the root. Chapman *et al.* (1992) also observed increased petiole Mn and decreased petiole Mg, in response to K application.

Table 2. Petiole nutrient analysis (combined Forthside and Palooona 1998 data).

	Main					FProb	Starter					FProb	I.s.d.
	0	30	60	120	240		0	10	20	40	80		
weight mg/petiole	85	105	113	120	123	<.001	102	111	110	111	113	0.002	4.04
P %	0.24	0.31	0.32	0.35	0.42	<.001	0.32	0.32	0.32	0.33	0.34	0.019	0.016
S %	0.25	0.26	0.26	0.26	0.26	0.005	0.26	0.26	0.25	0.26	0.26	0.851	0.009
Ca %	0.82	0.77	0.79	0.79	0.81	0.253	0.80	0.81	0.79	0.79	0.78	0.519	
K %	10.5	10.9	11.0	11.1	11.0	<.001	10.9	11.0	10.8	10.8	10.8	0.246	0.18
Mg %	0.45	0.42	0.42	0.40	0.42	<.001	0.44	0.42	0.42	0.41	0.40	0.003	0.021
Fe mg/kg	433	386	334	326	323	<.001	367	371	342	371	352	0.765	53.5
Mn mg/kg	271	274	267	255	262	0.063	257	265	260	279	270	0.023	14.34
Zn mg/kg	65	69	64	61	60	<.001	64	65	61	64	65	0.432	4.318

There were no significant Starter x Main Band interactions. I.s.d. applies to both main and starter means.

Tuber grading revealed that higher rates of main band P increased small tuber yields (<75 g and 75-250 g), with no changes in mid-size tubers (250-450 g and 450-850 g), and a small decrease in the yield of larger tubers (Table 3). The majority of the yield increase came in the 75-250 g size range, equivalent to a 42% yield increase from 120 kg P ha⁻¹ or more. The increase in 75-250 g tubers equated to an increase of 16% in total yield and 18% in ware yield at the highest rate of 240 kg P ha⁻¹.

Table 3. Tuber yields (t/ha) (combined Forthside and Palooa 1998 data).

	Main					FProb	Starter					FProb	i.s.d.
	0	30	60	120	240		0	10	20	40	80		
<75g	0.79	1.09	1.21	1.35	1.34	<.001	1.03	1.17	1.24	1.17	1.17	NS ^A	0.23
75-250g	18.9	23.7	25.1	28.3	26.9	<.001	23.4	25.3	26.1	24.4	23.6	NS	2.5
250-450g	20.7	21.2	22.0	22.6	22.9	NS	22.9	19.7	22.2	22.2	22.4	0.056	2.3
450-850g	8.31	6.00	6.14	6.85	7.55	NS	7.21	6.79	6.35	7.10	7.40	NS	1.95
>850g	1.38	1.48	1.05	0.44	0.77	0.032	1.44	0.41	1.46	1.00	0.81	0.025	0.72
Reject	6.48	6.26	6.75	5.71	6.16	NS	4.98	7.90	5.89	6.51	6.10	0.011	1.62
Ware	49.3	52.3	54.2	58.2	58.1	<.001	54.9	52.2	56.1	54.7	54.2	NS	3.8
Total	56.6	59.6	62.1	65.2	65.7	<.001	60.9	61.3	63.2	62.4	61.5	NS	4.0

^ANot significant (Fprob>0.05). There were no significant Starter x Main Band interactions. I.s.d. applies to both main and starter means.

Starter treatments affected the >850 g and reject tubers. However, since the number of tubers in both of these categories was low and larger tubers tended to contain more defects, there is greater potential for classing error to affect these results. When the reject and over size tuber categories were combined, (neither of these categories are accepted in the ware yield), there was no affect of either starter or main band P.

Tuber nutrition was much less affected than petioles were by fertiliser treatments (Table 4). There was a marginal increase in tuber Cd, on a fresh weight basis, due to the highest rate of main band P. However this was still well below the maximum permitted concentration (0.1 mg Cd kg⁻¹ fresh weight) by the Australia New Zealand Food Authority. Tuber P was significantly increased by higher rates of main band P, with a corresponding lower, but significant, increase attributed to starter band P.

Table 4. Forthside tuber nutrient analysis

	Main					FProb	Starter					FProb	I.s.d.
	0	30	60	120	240		0	10	20	40	80		
Tuber P %	0.16	0.15	0.15	0.17	0.20	<.001	0.16	0.17	0.16	0.17	0.17	0.022	0.010
Tuber Cd mgkg ⁻¹ fw	0.018	0.018	0.015	0.018	0.024	0.039	0.019	0.021	0.016	0.016	0.020	0.34	0.006
Specific gravity	1.088	1.091	1.093	1.091	1.091	0.014	1.090	1.090	1.091	1.090	1.092	0.661	0.0025

Starter P appears to have given a comparable response to main band P during early growth. However, linear regressions of the response of petiole P uptake to both main rate and starter rate (Table 5) revealed that the ratio of starter slope: main band slope was 0.54, indicating that the uptake efficiency of P applied to the starter band was only 54% that of an equivalent amount of P applied in the main band position. When the regression was restricted to main band rates of 0-120 kg P ha⁻¹ and compared with starter rates of 0-80 kg P ha⁻¹, the correlation was still good ($r^2 = 0.64$) and the corresponding slope ratio was 0.44. Hence the outcome was not biased by the highest rate of main band P.

Table 5. Linear regressions of petiole P uptake and ware tuber yields against both main and starter rates of P.

Slope = Δ Petiole P / Δ P rate.

	Band position	P rates	Slope	FProb	r ²
Petiole P uptake	Main	0-240	0.000719	<.001	0.72
	Starter	0-80	0.000386	<.001	
Petiole P uptake	Main	0-120	0.00106	<.001	0.64
	Starter	0-80	0.000444	<.001	
Ware tuber yield	Main	0-240	0.02885	<.001	0.14
	Starter	0-80	0.0162	0.321	

Linear regressions of main and starter rate of phosphorus on ware tuber yield produced a poor correlation, $r^2 = 0.14$. There was a significant positive effect of the main rate but no effect of starter rate (Table 5).

Forthside 1999

There were no effects of the spot or band starter P treatments, so these data were pooled. This simplified the analysis by removing the incompletely randomised treatment and allowed analysis by completely randomised ANOVA. There were no significant effects of the liquid starter fertiliser treatments on petiole nutrition, petiole weight, tuber yield or tuber size grade (Table 6). The likely cause was that while the strength of the starter P solutions was within the range that should not cause damage to emerging roots (30-150 mmol P), there was insufficient total P applied to gain a response. The highest P rate applied was equivalent to 2 kg P ha⁻¹. Only 10-20 ml of liquid fertiliser could be applied per plant since larger amounts would have necessitated excessive quantities of liquid being carried on a tractor: 10 ml per plant requires 400 L ha⁻¹. The trial was planted in moist conditions which would favour diffusion of P from soil reserves and hence could also have contributed to a lower response of the starter liquids.

Table 6. Effect of starter liquid rates on petiole weight and petiole nutrition.

	Starter Band g P/L				FProb
	0	1	2	5	
Petiole weight mg	201	206	197	196	0.707
P %	0.27	0.26	0.27	0.27	0.823
S %	0.40	0.40	0.41	0.40	0.737
Ca %	1.14	1.14	1.16	1.19	0.595
Mg %	0.39	0.39	0.40	0.40	0.636
K %	6.8	6.5	6.42	6.3	0.122

There were few effects of main band P rate on petiole nutrition (Table 7), however there was a strong response of petiole P to higher rates of main band P. The petioles were picked by two people, and there were apparent differences in the size of leaves selected, which probably introduced some additional variation in the petiole nutrition data that did not occur in the other trials. The petiole K levels were below the optimum range of 11-12% reported by Chapman *et al.* (1992) hence K deficiency may have limited responses to P despite the application of 300 kg K ha⁻¹ as fertiliser.

Table 7. Effect of main band rates of phosphorus on petiole weight and petiole nutrition.

Rate (kg P/ha)	0	50	100	150	200	300	FProb	I.s.d.
Petiole weight mg	195	196	206	188	230	191	0.153	
P %	0.26	0.28	0.27	0.30	0.35	0.35	<.001	0.035
S %	0.40	0.40	0.41	0.41	0.41	0.43	0.17	
Ca %	1.27	1.11	1.17	1.09	1.04	1.16	0.056	0.132
Mg %	0.45	0.38	0.40	0.38	0.37	0.39	0.078	0.048
K %	6.1	6.9	6.7	7.1	6.9	7.2	0.33	
Fe mg/kg	831	635	701	720	656	668	0.59	
Mn mg/kg	99	104	114	111	107	119	0.131	
Zn mg.kg	21	20	21	20	22	22	0.722	

Main band P rates of 50 kg P ha⁻¹ or more significantly increased both total and ware tuber yields (Table 8). The majority of this increase was accounted for in the 250-450 g size range. However there was also a trend for the yield of 150-250 g tubers to increase with higher P rates. Reject and under sized categories were not affected by the main band P rate.

Table 8. Tuber grading results for Forthside 1999.
Weights are in tonnes tuber ha⁻¹.

Main band P kg/ha	0	50	100	150	200	300	FProb	I.s.d.
<75g	1.1	0.94	1.09	1.44	1.1	0.96	0.160	
75-150g	8.6	6.5	7.0	7.5	5.4	6.9	0.197	
150-250g	17.8	18.5	20.1	19.5	23.3	17.4	0.062	4.39
250-450g	15.5	21.6	22.9	20.3	24.0	28.0	<.001	4.95
450g	3.0	5.6	3.9	3.8	2.7	5.8	0.342	
Reject	0.5	0.6	0.5	0.7	0.0	0.1	0.406	
Total	46.5	53.8	55.0	54.1	56.4	59.1	<.001	2.25
ware	44.9	52.2	53.9	51.2	55.3	58.0	<.001	5.86

The lack of measurable responses to the liquid starter treatments is most likely due to the low absolute rates of P used in the starter solutions, the highest rate being equivalent to 2 kg P ha⁻¹. There are difficulties in handling larger volumes of starter solutions, and risks of fertiliser injury if higher rates of P are used. With soybeans (Moody *et al.*, 1995a) found root growth was inhibited, due to salt induced calcium deficiency, when soil solution P intensities rose above 1.0-10 mmol. In hydroponically grown tomatoes, symptoms of P toxicity began to occur at a solution strength of 5 mmol P (Penalosa *et al.*, 1989). The concentrations used for the liquid starter treatments ranged from 32-160 mmol P and hence were substantially higher than P rates that are capable of causing injury to seedlings. Given the lack of response and difficulties in applying liquid starter solutions this procedure does not appear to offer much potential to improve P efficiency.

The irrigation regime used for the trial proved lacking in two regards: firstly the irrigation began too early, secondly there was uneven distribution of irrigation water across the trial unit. Irrigation of the trial began at about the time of crop emergence. This is earlier than would normally be required, especially since the crop was planted in wet conditions. However the trial was established in a paddock containing potatoes that had been planted three to four weeks earlier that required irrigation and so our

trial was also watered at this time. Normally irrigation of potatoes is avoided until after emergence so as to avoid seed piece decay (Anon, 1969) and to reduce the number of tubers set (Struik and Van Voorst, 1986, Shock *et al.*, 1992). The application of irrigation shortly after planting is likely to reduce or remove altogether any response to liquid starter fertilisers (Reiners *et al.*, 2001). Hence under more normal, drier conditions there may have been a response to the starter liquids.

The irrigation coverage in the region of overlap between the irrigator runs was quite uniform, 30-35 mm per run, however the first ten to twelve crop rows either side of the irrigator runs received up to 50% more water. The uneven distribution of water appears to be strongly associated with some soil properties (Figure 5). Colwell P was measured from each plot and followed a similar trend to the irrigation distribution with a greater proportion of moderate to high levels of, Colwell P > 80 mg P/kg, occurring in the rows adjacent to the irrigator runs, while there were more lower levels, <80 mg P/kg, occurring in the overlap region between irrigator runs. The proportion of tubers larger than 450 g was moderately correlated with the senescence score (Figure 4). Hence it appeared that plants that senesced early had a lower proportion of tubers greater than 450 g.

The increase in Colwell P associated with higher rates of irrigation may be due to increases in organic matter and/or soil biological activity. However since the same irrigator runs have been used over many seasons it is not possible to distinguish if the variation in Colwell P stems from long term irrigation patterns or is a consequence of the present season's irrigation only. While there was a good correlation between Colwell P and soil organic carbon ($r^2=0.92$) across all trial sites, for the Forthside 1999 data only the correlation was poor ($r^2=0.06$), suggesting that the influence of organic carbon on available P has more relevance at the scale of whole paddocks or larger areas than to variation within paddocks. While the relationships between irrigation rate and Colwell P and between senescence and the proportion of tubers > 450g were moderate, with r^2 of 0.68 and 0.69 respectively, the correlation between irrigation and senescence was poor, $r^2=0.31$. However, the lowest senescence scores occurred in the rows with the lowest irrigation rates, hence there may have been a weak effect of irrigation and soil P on the persistence and tuber size of the crop

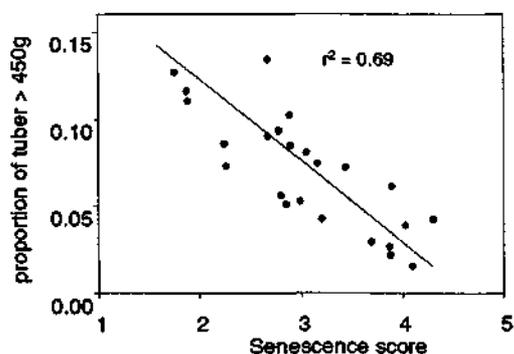


Figure 4. Correlation of the proportion of tubers > 450 g and senescence score, $r^2=0.69$ $n=26$. The greatest variation was between rows hence both tubers > 450 g and senescence score are presented as averages for the six plots within a row.

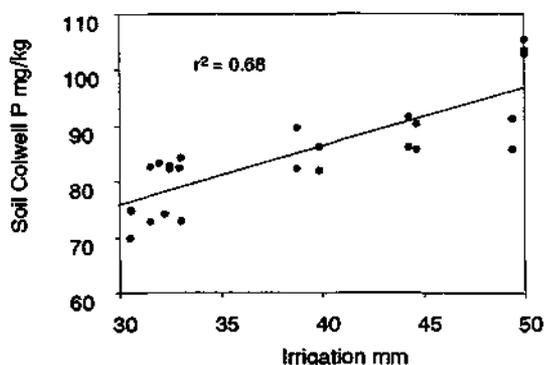


Figure 5. Correlation of soil Colwell P and irrigation rate, $r^2=0.68$ $n=26$. Since the irrigation varies only between rows, soil Colwell P was averaged for the six plots within a row. The trial was six plots to the row and 26 rows wide.

Plants that senesced late had a higher proportion of large tubers (Figure 4). Evidently the longer growing season resulted in the continued growth of existing tubers. Jenkins and Ali (1999) found that in late maturing potato cultivars, such as Russet Burbank, senescence may be delayed by low soil P levels, with the result that yield differences between low and high applied P treatments are lessened or negligible. As a further explanation the variation in senescence may arise from nitrate leaching due to higher rates of irrigation. The variation in Colwell P is most likely coincidental however higher P levels do tend to induce earlier senescence. Available phosphorus is linked to microbial pools, therefore a moister environment should increase microbial activity and hence increase the pool of available P (Sparling, 1985).

Forthside 2000

There were no effects of the starter treatments on petiole nutrition other than a small increase in nitrogen in the banded starter treatment (Table 9). Since there was no N in the starter band this effect is difficult to explain but it may be a concentration effect because the canopy cover was significantly larger in the control treatment than the spot treatment during the establishment phase (Table 9). However during the senescence phase there was a tendency for the spot treatment to have a larger canopy ground cover. A similar trend of smaller ground cover during establishment, but larger cover at senescence, was also observed with the nil P treatment (Table 10). Phosphorus deficiency tends to reduce early vigour and delay senescence (McCullum, 1978; Jenkins and Ali, 1999). This is an indication that the spot treatment may have been slightly P deficient. However there was no difference in the petiole P concentrations between starter treatments. Tuber P% was also not affected by the starter treatments.

Table 9. Effect of starter phosphorus treatments on petiole and tuber nutrients and canopy ground cover during establishment (31-52 DAP) and senescence (115 DAP).

Treatment	Petiole						Canopy cover		Tuber	
	P%	N%	Ca%	K%	Mg%	weight mg	Establishment	Senescence	P%	
MAIN EFFECTS										
Dripper	0.29	3.2	0.96	12.4	0.38	134	0.62	0.46	0.15	
Sprinkler	0.25	3.4	0.97	12.3	0.39	132	0.62	0.59	0.16	
FProb	NS	NS	NS	NS	NS	NS	NS	0.021	NS	
l.s.d.								0.082		
Band	0.27	3.4	0.98	12.3	0.39	133	0.62	0.51	0.16	
Spot	0.27	3.2	0.95	12.4	0.39	130	0.61	0.56	0.15	
Control	0.27	3.3	0.96	12.3	0.39	136	0.63	0.51	0.16	
FProb	NS	0.013	NS	NS	NS	NS	0.029	0.081	NS	
l.s.d.		0.14					0.016			
IRRIGATION X STARTER P INTERACTION										
Dripper	Band	0.28	3.3	0.96	12.3	0.38	137	0.62	0.44	0.15
	Spot	0.30	3.0	0.94	12.5	0.39	131	0.61	0.50	0.15
	Control	0.29	3.1	0.98	12.5	0.38	135	0.63	0.49	0.16
Sprinkler	Band	0.25	3.5	1.00	12.3	0.40	130	0.62	0.59	0.16
	Spot	0.25	3.3	0.96	12.3	0.39	128	0.61	0.62	0.16
	Control	0.26	3.4	0.94	12.2	0.40	137	0.64	0.58	0.16
FProb	NS	NS	NS	NS	NS	NS	NS	NS	NS	

The main band rates of P had a large influence on nutrition. There were increases in petiole P, K and weight and in tuber P% with higher rates of main band P (Table 10). There were also differences in canopy ground cover development with a lower ground cover at establishment but a higher ground cover at senescence in the zero P treatment compared to the higher rates of P. The effects of irrigation method were also more evident in the main band rate comparison than with the starter treatments alone. In the starter treatments only ground cover at senescence was significantly affected, with a lower ground cover of the drip irrigated crop. However with the main band P rates there was an increase in both petiole P and petiole weight and an increase in the establishment phase ground cover from drip irrigation (Table 10). There was also a similar decrease in ground cover due to drip irrigation in the main band comparison.

Table 10. Effect of main band phosphorus rates on petiole and tuber nutrients and canopy ground cover during establishment (31-52 DAP) and senescence (115 DAP).

Treatment	Petiole						Canopy cover		Tuber	
	P%	N%	Ca%	K%	Mg%	weight mg	Establishment	Senescence	P%	
MAIN EFFECTS										
Dripper	0.29	0.33	0.97	12.3	0.38	135	0.59	0.48	0.16	
Sprinkler	0.24	0.33	1.00	11.8	0.39	123	0.57	0.64	0.16	
FProb	0.054	NS	NS	NS	NS	0.049	0.029	0.042	NS	
I.s.d.	0.053					11.4	0.016	0.143		
P 0	0.17	0.35	0.91	10.8	0.43	64	0.35	0.78	0.15	
P 100	0.27	0.33	0.96	12.3	0.39	136	0.63	0.51	0.16	
P 200	0.29	0.33	0.99	12.2	0.35	149	0.64	0.45	0.16	
P 300	0.32	0.32	1.08	12.5	0.31	160	0.66	0.54	0.18	
FProb	<.001	NS	NS	<.001	0.002	<.001	<.001	<.001	0.005	
I.s.d.	0.012			0.218	0.025	16.0	0.027	0.117	0.014	
IRRIGATION X STARTER P INTERACTION										
Dripper	P 0	0.17	0.38	0.89	11.4	0.42	74	0.40	0.66	0.15
	P 100	0.29	0.31	0.98	12.5	0.38	135	0.63	0.45	0.15
	P 200	0.31	0.35	0.97	12.3	0.34	157	0.65	0.41	0.16
	P 300	0.39	0.31	1.03	12.7	0.36	173	0.66	0.44	0.18
Sprinkler	P 0	0.17	0.33	0.93	10.3	0.44	55	0.31	0.90	0.15
	P 100	0.26	0.34	0.94	12.2	0.40	137	0.64	0.58	0.16
	P 200	0.26	0.32	1.01	12.0	0.35	142	0.63	0.49	0.17
	P 300	0.25	0.33	1.13	12.3	0.34	147	0.65	0.65	0.18
	FProb	<.001	0.087	NS	0.017	NS	NS	NS	NS	NS
	I.s.d.	0.018			0.56					
	I.s.d.*	0.017			0.31					

* I.s.d. value is for comparison of treatments with the same level of irrigation.

There was a strong interaction of main band rate P and irrigation method on the petiole P concentration. Hence in both the dripper and sprinkler irrigated crop there was a significant increase in the P concentration between 0 kg P ha⁻¹ and 100 kg P ha⁻¹. There was also a continued increase in petiole P at higher rates of P under the dripper irrigation that did not occur with the sprinkler irrigation (Table 10). Hence dripper irrigation improved the availability of the main band P rather than the starter P. Since petioles were collected at the 10-20 mm tuber stage only, it is not possible to know if the higher P nutrition occurring under drip irrigation continued throughout the life of the crop. However, tuber P% responded to the main band P rate regardless of irrigation, which suggests the effect may not have persisted.

There were again few effects of starter P on tuber yield and size grades. The dripper control treatment yielded significantly more tubers in the 150-250 g size range, however there was no effect of starter P on total or ware tuber yields (Table 11). There were no main band P rate by irrigation interactions on tuber yield or size grades (Table 12). The largest effect of P rate occurred between the 0 kg P ha⁻¹ and higher P rates, though the total and ware yield were significantly higher in the 300 kg P ha⁻¹ treatment than both the 100 and 200 kg P ha⁻¹ treatments. Most of the yield increase

attributed to higher rates of P came in the 75-150 g and 150-250 g tuber size grades. However there was a trend for more 250-450 g tubers at the highest P rate of 300 kg ha⁻¹. Tuber specific gravity was high and unaffected by starter treatments, main band phosphorus rates or irrigation.

Table 11. Effect of starter phosphorus treatments on tuber size grades, total and ware yields and specific gravity. All weights are tonnes ha⁻¹.

Treatment	<75g	75-150g	150-250g	250-450g	>450g	Reject tubers	Total yield	Ware yield	Specific gravity	
MAIN EFFECTS										
Dripper	1.40	7.53	22.9	22.2	2.29	1.84	58.0	54.8	1.088	
Sprinkler	1.57	8.03	22.5	23.1	2.88	3.30	61.4	56.5	1.089	
FProb	NS	NS	NS	NS	NS	NS	0.07	NS	NS	
l.s.d.							4.13			
Band	1.53	7.46	22.4	22.7	2.26	2.80	59.1	54.8	1.088	
Spot	1.50	7.96	21.8	23.5	2.75	2.33	59.7	55.9	1.088	
Control	1.42	7.9	24.0	21.8	2.73	2.60	60.3	56.3	1.089	
FProb	NS	NS	0.02	NS	NS	NS	NS	NS	NS	
l.s.d.							1.36			
IRRIGATION X STARTER P INTERACTION										
Dripper	Band	1.46	7.43	23.6	21.3	1.43	2.08	57.3	53.8	1.089
	Spot	1.34	7.60	20.8	23.2	3.06	1.74	57.6	54.5	1.088
	Control	1.39	7.54	24.3	22.0	2.38	1.71	59.3	56.2	1.089
Sprinkler	Band	1.60	7.50	21.2	24.0	3.10	3.54	61.0	55.8	1.088
	Spot	1.66	8.31	22.7	23.8	2.43	2.91	61.9	57.3	1.089
	Control	1.45	8.26	23.6	21.6	3.09	3.48	61.4	56.5	1.089
FProb		NS	NS	0.02	NS	NS	NS	NS	NS	NS
l.s.d.					7.61					
l.s.d.*					1.93					

* L.s.d. value is for comparison of treatments with the same level of irrigation.

Irrigation had no effect on total or ware yields, though there was a significant (P=0.052) effect of irrigation source on the quantity of reject tubers, with a 38% reduction in reject tubers in the drip irrigated crop. Since the occurrence of secondary growth is increased by intermittent periods of water deficit (Moorby *et al.*, 1975), the more frequent water applications through the dripper irrigation system may have contributed to the reduced incidence of secondary growth.

Table 12. Effect of main band phosphorus rates on tuber size grades, total and ware yields and specific gravity. All weights are tonnes ha⁻¹.

Treatment	<75g	75-150g	150-250g	250-450g	>450g	Reject tubers	Total yield	Ware yield	Specific gravity	
MAIN EFFECTS										
Dripper	1.42	7.69	23.9	22.3	2.55	1.91	59.8	56.4	1.088	
Sprinkler	1.46	7.94	22.7	21.9	3.59	3.06	60.2	55.6	1.089	
Fprob	NS	NS	NS	NS	NS	0.052	NS	NS	NS	
l.s.d.						1.174				
P 0	1.27	5.74	17.8	20.1	4.34	3.25	52.5	48.0	1.088	
P 100	1.42	7.90	24.0	21.8	2.73	2.59	60.3	56.3	1.089	
P 200	1.63	8.73	24.4	21.2	2.96	2.03	61.0	57.3	1.089	
P 300	1.47	8.79	25.3	25.5	2.60	1.99	65.6	62.2	1.089	
Fprob	NS	0.054	0.006	0.081	NS	NS	0.002	<.001	NS	
l.s.d.		2.068	3.50	3.67			4.71	4.05		
IRRIGATION X STARTER P INTERACTION										
Dripper	P 0	1.15	5.59	17.8	20.3	3.63	2.66	51.1	47.3	1.088
	P 100	1.39	7.54	24.3	22.0	2.38	1.71	59.3	56.2	1.089
	P 200	1.58	9.09	26.6	21.0	2.29	1.50	62.1	59.0	1.089
	P 300	1.58	8.69	26.5	26.2	2.09	1.96	67.0	63.5	1.089
Sprinkler	P 0	1.40	5.90	17.9	20.0	5.04	3.84	54.0	48.8	1.088
	P 100	1.45	8.26	23.6	21.6	3.09	3.46	61.4	56.5	1.089
	P 200	1.67	8.38	22.3	21.4	3.63	2.54	59.9	55.7	1.089
	P 300	1.35	8.90	24.1	24.8	3.10	2.03	64.2	60.8	1.09
	FProb	NS	NS	NS	NS	NS	NS	NS	NS	NS

While there were no effects of starter P on nutrition or yield the proportion of ground cover during the establishment phase was affected by starter treatments, with a reduction in average ground cover of the spot starter treatment. The yields of both petioles and tuber weights were reduced by the starter treatments, though not significantly. Hence starter placed P appears to be no more effective, and possibly less effective than main band placed P. There was an initial response to the drip irrigation through an increase in petiole P uptake from high main band P rates, however this did not translate into a tuber yield increase. These results indicate that close placement of starter P does not affect the early or subsequent growth of potatoes on ferrosols. Even where an initial increase in petiole phosphorus content was obtained, through the drip irrigated crop, there was no evidence of beneficial effects in the final yield.

Overall the yield was not affected by irrigation method. This is not unexpected since the same soil moisture tensions were maintained in both treatments, and potato yields increase linearly between matric potentials of -200 kPa up to -10 kPa (Taylor and Ashcroft, 1972, Martin *et al.*, 1992). However the quantity of reject tubers was reduced by the drip irrigation. While this could be from the more frequent scheduling of the irrigation, a less even distribution of the water from the sprinkler system could also have produced the same effect. On suitable land, both the scheduling and uniformity of irrigation can be addressed with modern sprinkler irrigators, i.e. centre pivot and lateral shift, hence the remaining benefit of dripper irrigation is the lower quantity of water applied.

Although no attempt has been made to cost the two irrigation systems used in this study, where costs have been calculated they often favour less efficient but lower capital cost irrigation methods. Hence the gross margin for drip irrigation was lower than furrow irrigation in sugar beet (Sharmasarkar *et al.*, 2001) and similarly in onions the gross margin from drip irrigation was lower than that from sprinkler irrigation (Al-Jamal *et al.*, 2001). Drip irrigation has a higher capital and installation cost than sprinkler systems, and the savings in water use are not likely to offset these costs at current water prices. However with increasing prices and reduced access to irrigation water, drip systems will become more profitable.

A total of 310 mm of water was applied by the drippers and 580 mm by the sprinklers for an equivalent yield. Similar efficiencies have been found in comparisons of drip to sprinkler irrigation for potatoes elsewhere (Martin *et al.*, 1992, Waddell *et al.*, 1999) and for other crops (Moynihan and Haman., 1992). However the sprinkler irrigation rate applied in the trial was 30% higher than that used in adjacent potato crops. The average total application was 450 mm for the other potato crops in adjoining units and paddocks at Forthside during the 2000-2001 season. It was also likely that too much water was applied through the drippers since there was evidence of nitrate leaching under the drippers where virtually all the nitrate has been removed from the rooting depth (aprox 500 mm) and deposited at 600 mm and deeper (Figure 6). Hence some fertiliser N may have become unavailable to the drip irrigated plants.

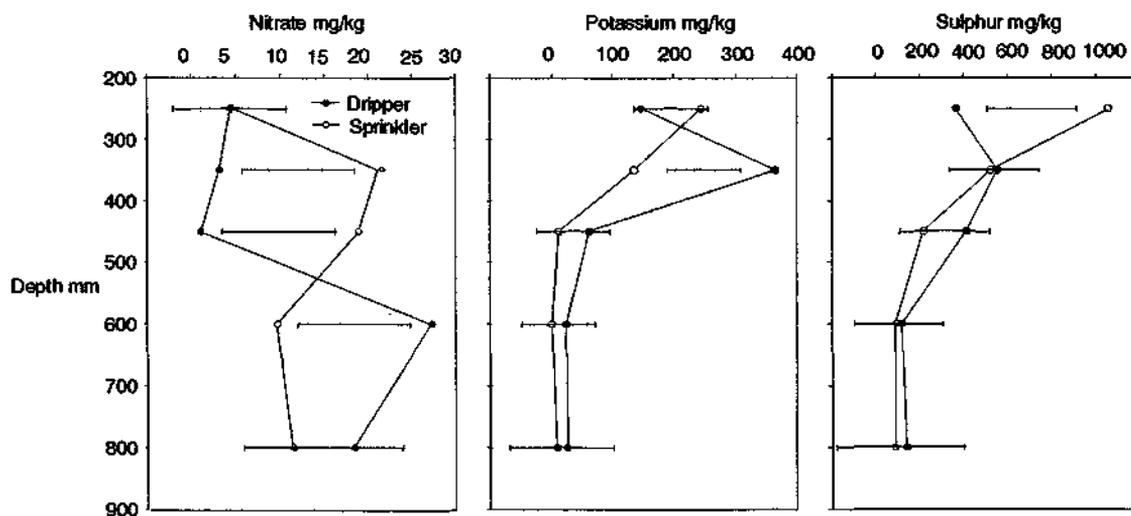


Figure 6. 1:5 water extractable ions in soil sampled after the crop had senesced. Left nitrate, center potassium, right sulphur.

The differential movement of nitrate confounds the interpretation of the earlier senescence of the drip irrigated crop compared to the sprinkler irrigated crop since early senescence may be caused by higher availability of P (Jenkins and Ali, 1999), by a reduced availability of N (Marschner, 1986) or an earlier onset of irrigation (Cappaert *et al.*, 1994). Smaller and more frequent irrigation through the drippers, and supplying part of the N through fertigation could reduce the risk of N leaching from drip irrigated crops.

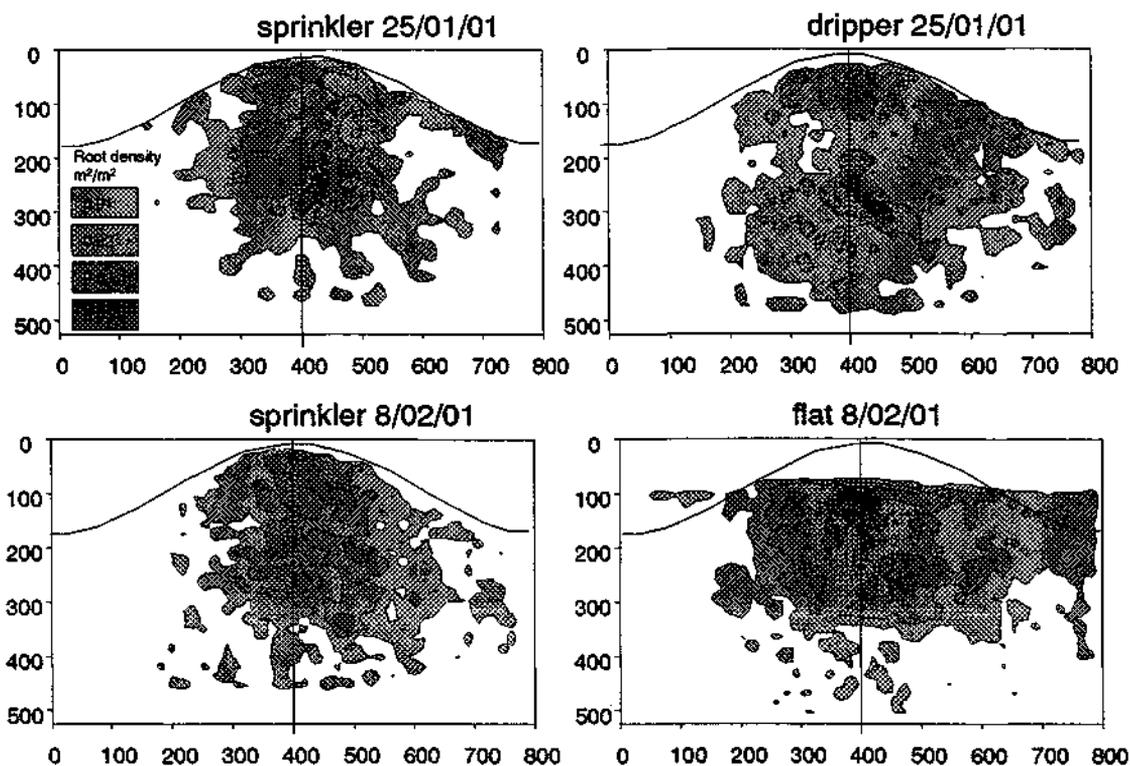


Figure 7. Root length densities under different irrigation and cultivation regimes.

There were no noticeable differences in the root distribution between dripper and sprinkler irrigated plants (Figure 7). However there was a distinct reduction in root growth under the trafficked furrow compared to the untrafficked furrow. This difference was most pronounced in the unhilled treatment where there was root growth throughout the untrafficked furrows.

Potato root development in wheeled furrows may either increase or decrease depending on the soil. Root density increased with compaction on coarse sandy loams, while on fine sandy loams it decreased (De Roo and Waggoner, 1961). In general, greater root density in compacted soil is rare and by far the most common outcome is a reduced root exploration of the compacted soil (Tardieu, 1988). Since sprinkler water is applied uniformly to the whole surface of the soil but the roots tend to be concentrated in the hills, there is a greater risk of deep percolation of the irrigation water through the furrows. This is particularly so in the trafficked furrows where there is virtually no root growth.

The root distributions closely follow the soil strength properties (Figure 8) where most root growth occurs in soil of less than 1 MPa (purple region in Figure 8). Soil strengths in the trafficked furrows increase to 2-3 MPa (green bars in middle image) after a short period of drying. Since roots are unable to grow into soil of 2-3 MPa resistance (Bishop and Grimes, 1978) the region below the plough layer (yellow-green band in Figure 8) and the compacted furrows would be inaccessible to root growth. A chisel plough was used shortly after emergence to break up the compacted traffic rows, however this was not effective since only a narrow trench along the centre of the furrow was loosened.

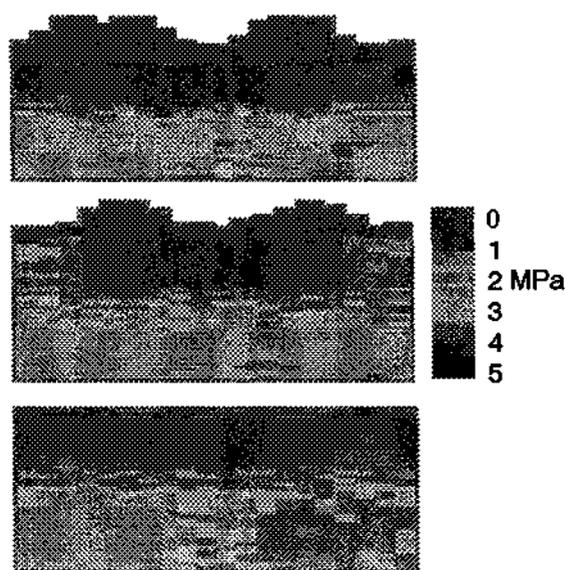


Figure 8. Soil penetration resistance under two hilled beds with trafficked furrows on the outside edge. (Top normal moisture, middle same hills but drier, bottom unhilled treatment).

While soil matric tension and volumetric water content were measured, the data did not provide sufficient spatial or temporal resolution to detect the flow patterns of water in the soil. However some assumptions can be made about the likely movement of water. The initial flow of water into uniformly dry soil is essentially independent of gravity due to the high sorptive properties of dry soil (Taylor and Ashcroft, 1972). However if the wetting front contacts soil of higher moisture content, water can drain more rapidly through the moist soil. Hence an underlying moist soil can siphon off water that would otherwise have redistributed through the drier upper horizons (Taylor and Ashcroft, 1972). The furrows of the sprinkler irrigated crop maintained a water tension close to field capacity (-10kPa), hence it is probable that deep drainage was occurring through the furrows of the sprinkler irrigated potatoes, though there is no direct evidence.

Although the furrows were chisel ploughed with no effect, a shallow winged ripper may be more effective at loosening the soil. An alternative is to grow the potatoes in a wide bed and thereby improve the efficiency of overhead irrigation by reducing the number of furrows by half. There may also be benefits by reducing runoff. On soils with low infiltration rates wide beds allow the water to lie on a flat surface and hence improve infiltration (Robinson, 1999). However, the higher moisture content in wide beds slows their warming and may contribute to delayed emergence (Mundy *et al.*, 1999), although other authors have attributed the improved emergence to higher moisture levels on flat topped beds (Prestit and Carr, 1984). Wide beds also require more energy to harvest since a larger volume of soil must be moved in the harvest operation (Thompson *et al.* 1974).

Analysis of P responses on all trial sites

Colwell P values were low for all sites except Forthside 1999, in which they were moderate (Table 13). However it was the Forthside 1999 site that had the highest response to phosphorus rate (Table 14). Phosphate sorption properties were measured only at the first year's trial sites. The Paloona site has a substantially lower PBC than

the Forthside soil though this is still within the range of values for ferrosols given by Freeman *et al.* (1998). Phosphorus sorption was not measured on soil from the other Forthside sites, however it should be similar to the site at Forthside in 1998. Potassium levels were low in all years other than Forthside 2000. The petiole K levels were sufficient at all sites other than Forthside 1999 when they were low to deficient (Chapman *et al.*, 1992).

Table 13. Soil (0-10 cm) chemical properties for the four trial sites.

Site/year	Colwell P	Colwell K	pH water	Salinity mS/cm	Organic carbon %	PBC O&S	PBC	PSI 150	EPC ug P l ⁻¹
Palooa 1998	15.8	67.5	5.4	45.2	1.87	55.08	272	67.7	43
Forthside 1998	33.0	44.2	5.9	80.5	2.48	93.81	465	72.9	50
Forthside 1999	84.7	65.9	6.5	73.0	3.69				
Forthside 2000	43.4	344	-	-	3.33				

Refer to page 11 for soil test methods: PBC Phosphate Buffer Capacity, PSI Phosphate Sorption Index, EPC, Equilibrium Phosphorus Concentration.

Our estimates of critical petiole P concentrations of 0.3-0.35% P (Table 14) are lower than those suggested elsewhere for Russet Burbank grown on ferrosols. Sparrow *et al.* (1992) recommended a range of 0.35-0.4% P while Freeman *et al.* (1998) suggests a range of 0.45-0.57% P. The predicted P rates for 90 and 95% maximum yield are likewise comparable with Sparrow *et al.* (1992) but lower than Freeman *et al.* (1998). This difference may largely be a result of the lower maximum P rates used in both the present study and that of Sparrow *et al.* (1992) (240-300 kg P ha⁻¹), whereas Freeman *et al.* (1998) used P rates up to 400 kg P ha⁻¹.

Table 14. Yield increase attributed to P and estimated petiole P concentrations and fertiliser P rates for 90% and 95% maximum yield with a maximum P rate of 300 kg P ha⁻¹ for all four trial sites.

Site/year	P0/Pmax	Critical petiole P %		P fertiliser rate kg/ha		Equation	Adj r ²
		90%	95%	90%	95%		
Palooa 1998	0.86	0.31	0.35	27	118	Y = 48.1 + 1.03 * P ^ 0.388	0.66
Forthside 1998	0.85	0.28	0.34	50	147	Y = 65.7 + 0.98 * P ^ 0.468	0.76
Forthside 1999	0.79	0.27	0.30	36	125	Y = 46.6 + 1.78 * P ^ 0.329	0.92
Forthside 2000	0.80	0.25	0.27	47	147	Y = 57.1 + 0.614 * P ^ 0.508	0.85

Equation used to fit regressions was $Y = A + B * P^C$

All sites were responsive to main band applied phosphorus with yield increases ranging from 15-20% (Table 15, Figure 9). At all sites there was an increase in tuber number but these increases were in the marketable size categories 75-450 g range. Hence main band phosphorus additions increased both the total yield and the proportion of marketable yield.

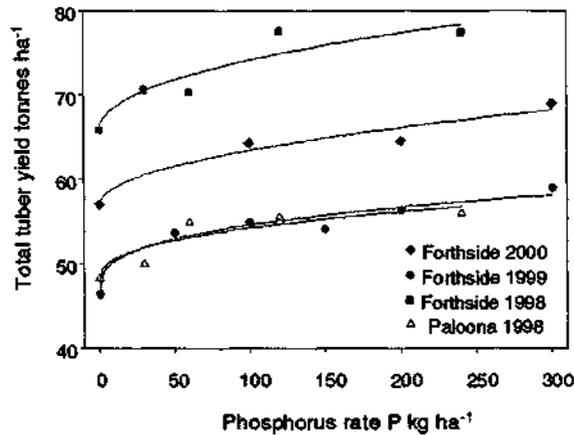


Figure 9. Yield responses of the four sites to main band phosphorus.

There was a linear relationship of petiole P to relative tuber yield calculated for all sites. However the petiole P concentrations were lower than those predicted by (Freeman *et al.* 1998) suggesting that further yield increases may be achieved by higher petiole P concentrations. Freeman *et al.* (1998) used an average upper P rate of 420 kg P ha⁻¹ compared to 270 kg P ha⁻¹ in the present study, hence higher P rates may be required to verify if yield increases can be obtained from higher petiole P concentrations.

Conclusions

There is no conclusive evidence that starter P bands improve the utilisation of fertiliser P. Granular starter P applied at Forthside and Paloona 1998 had an effect on petiole nutrition, though this response was only half that which could be attributed to an equivalent amount of main band placed P. There was no effect of starter placed P on the final yield. The liquid starter P from the second year's trial had no effect at all, though perhaps by using higher concentrations of P a response may have been obtained. However it seems unlikely that this would have been better than the previous year's response to granular P and given the rapid reaction of soluble P in P fixing soil there may well be a lower response.

In the Forthside 2000 trial, when confining irrigation to the hill soil through dripper irrigation, no responses to starter P placement were found. However, drip irrigation increased petiole P concentrations of higher main band P rate treatments. Further petiole sampling would have confirmed if the response was due only to initial differences in water infiltration into the hill, or a prolonged effect of drippers improving the availability of main band placed P. However there were no associated effects of drip irrigation on crop ground cover or tuber yield or size.

Field data and a computer model have shown that up to 25% of the water falling onto the canopies of potato crops can be shed into the furrows. The resulting lower water infiltration into the hill soil was initially proposed as a mechanism for the reduced availability of starter placed fertilisers. It is evident from the drip irrigation results, where irrigation was confined to the hill soil, that factors other than a lower absolute supply of moisture in the hills may be affecting the uptake of starter band fertilisers. Although the soil in the hill has the highest root density, which is an advantage for

phosphorus uptake (Barber, 1982), the rapid drying of soil associated with such high root density may not be favourable to P diffusion and uptake.

Measurements of soil volumetric water content and matric potential in both the sprinkler and drip irrigated treatments showed greater fluctuations of moisture in the hill soil (0-500 mm), than in the soil layers below or in the furrows, with generally moister conditions below the hilled soil. This is likely a direct consequence of the higher root density in the hill soil. Hence a reservoir of moisture maintained below the main band, through a low root density in that region (Figure 9), could facilitate P uptake (Baerug and Steenberg, 1971; Holliday and Draycott, 1968). Deeper placement of P, to take advantage of moisture at greater depth, has proved beneficial (Holliday and Draycott, 1968), but introduces the additional risks of initial P deficiency due to the increased time between emergence and interception of the fertiliser (Costigan, 1987), and unfavourable soil conditions such as higher bulk densities and low oxygen contents which can reduce root growth.

Root to soil contact can be reduced in soils of low bulk density (Pietola and Smucker, 1998). Hence roots growing in the hilled soil may easily penetrate the soil but may experience difficulties in contacting the soil and extracting nutrients. The development of tubers in and around the starter band may further disrupt root activity in the starter band region. Hence utilisation of P from the starter band may decrease after roots are damaged or dislodged from the soil by compression and soil movement associated with tuber growth. While there was no direct evidence of tuber growth affecting root activity there was ample evidence of root proliferation in the main band position (Figure 10) but no observations of such proliferation in the starter position.

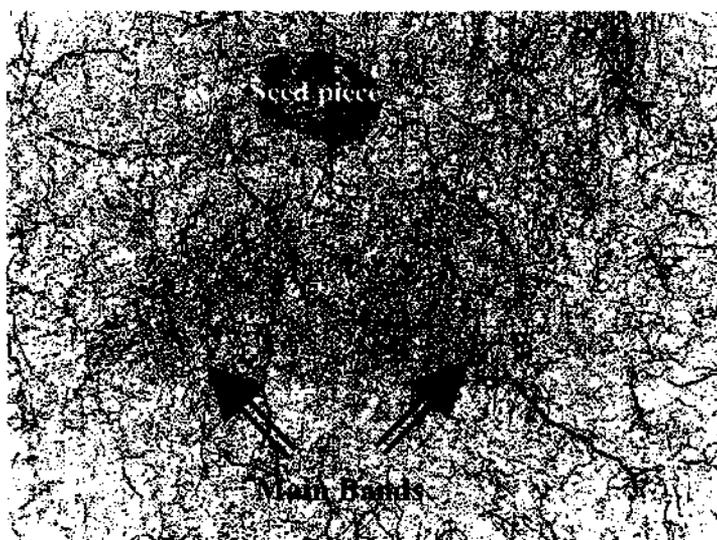


Figure 10. Formation of highly branched roots in the main band fertiliser position: seed piece is center top of picture, main band fertiliser is placed below and to the side of the seed, center of image.

In comparison to other crops, the seed piece of potatoes contains much larger reserves of both nutrients and water. Hence potatoes can establish quite substantial root and stem growth in dry and nutrient poor conditions. Adequate moisture and nutrition may accelerate the development, but is not essential for emergence (Moorby, 1968). However, small seeded crops may fail to establish if a ready source of nutrition and moisture is not at hand (Costigan, 1984). The main band fertiliser applied to potatoes

is usually placed a sufficient distance away to reduce the risk of fertiliser injury, however it appears also to be close enough to enable potato roots to contact the fertiliser before the seed borne nutrient reserves are exhausted. Hence a starter type response may be less likely to occur on potatoes.

Total tuber P uptake increased by about 2-3 kg of P for each 100kg of applied P whereas around 60-70 kg of K was removed for each 100 kg of applied K (Chapman *et al.*, 1992) (Figure 11). Hence approximately 2-3% of the applied P was removed as additional uptake by the crop. However nearly 20 kg of P ha⁻¹ was removed in the zero P plots at Forthside 1998 and Forthside 2000, hence there was a substantial contribution to the total P uptake that can be attributed to previous applications of P. Soil testing is therefore advisable to determine the quantity of residual P and whether reductions can be made in the rate of fertiliser P applied.

Recommendations

Starter P bands of the type used in the study have not proven beneficial in reducing the quantity of P required by potatoes. It is likely that the moisture and soil properties in the starter band position are less conducive to P uptake than conventional deeper banding positions. In addition potatoes have a large reserve of nutrients that enable substantial growth before supplemental nutrition is required. Hence starter bands cannot be recommended as a practice to reduce P inputs on potatoes.

Potential areas of further research arising from this project include;

- Deep banding the P fertiliser to make use of moister soil at lower depths.
- Wide beds to improve water use, through more effective infiltration and larger root systems.

In view of the limitations of starter P, continued efforts must be made to ensure efficient P use and to limit P loss to the environment through:

- Use of soil and tissue testing
- Use of erosion control measures to restrict soil loss from the sloping land where ferrosols are typically located

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Appendix 1

Publications and Presentations

Johnson, P., Sparrow, L. A., and Doyle, R. (1999) More efficient use of phosphorus fertilisers on ferrosols. *Potatoes Australia* 10 41-42

Johnson, P., Sparrow, L. A., and Doyle, R. (2000) Improving phosphorus efficiency on red soils. Forthside Vegetable Research Farm Field Day 2000

Johnson, P., Sparrow, L. A., and Doyle, R. (2000). Improving phosphorus efficiency on red soils. *In* "Potatoes 2000: Linking research to practice", pp. 121-124, Adelaide.

Johnson, P., Sparrow, L. A., and Doyle, R. (2000) A method for obtaining three dimensional root densities. Poster Paper NZSSS/ASSSI Soil 2000 Conference Lincoln University 3-8 December 2000.

Johnson, P., Sparrow, L. A., and Doyle, R. (2001) Responsible uses of phosphorus fertiliser for potatoes on red soils, Potato and Vegetable Agricultural Research and Advisory Committees, Devonport 15 August 2001.

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Introduction

Significantly more P is applied in fertilisers than is removed in the harvested component of potato crops grown on ferrosols. The nutrient budget, quantity of nutrient removed in crop:quantity of applied nutrient, in a 50-60 tonne potato crop range from 60-100% for N and K while P does not exceed 20%. Within the budget the actual contribution of fertiliser P is between 10-20% of the P recovered in the crop (Pursglove and Sanders, 1981), the remaining 80-90% comes from soil P reserves. Hence an equivalent quantity of more than 80% of the applied P remains in the soil after the crop has been removed. While there is an economic inefficiency in P use, there are potentially serious concerns with associated health and environmental risks from such high surplus additions of P.

The heavy metal cadmium is an impurity in all phosphate fertilisers. Potatoes accumulate Cd in the tubers, and since potatoes are consumed in higher quantities than other vegetables, potatoes are the primary source of dietary Cd intake. While this issue has been addressed through the combined reduction in fertiliser Cd concentrations and an upward revision of the allowable limit of Cd, phosphatic fertilisers are still the primary source of new Cd additions to soils.

The loss of P offsite in ground water and erosion run off can contribute to eutrophication of water ways. Tasmanian ferrosols are at risk to soil erosion due to the high cropping intensity and the steep slopes of cropped soils. Hence the accumulation of large P reserves in the top soil poses an increased hazard of off site P removal.

The primary cause of the low efficiency of P fertilisers is the strong reaction of P with soil minerals. Soils are dynamic media with which can react in a number of ways to applied nutrients. Some reactions between fertilisers and soils involve simple exchange mechanisms where a large proportion of applied nutrients, e.g. NH_4^+ and K^+ , is adsorbed to soil particles and released as these nutrients are subsequently removed from the soil solution. Other reactions lock up or retain nutrients more strongly, thereby reducing their availability to crops. Such retention reactions are common with phosphatic fertilisers and usually involve precipitation of the phosphate anion with polyvalent cations of metals like Al, Fe, Ca, Mg or its adsorption to hydroxy groups on the surface of iron and aluminium oxides. Krasnozem soils (Ferrosols) are formed from basalt deposits and are particularly rich in Fe and Al (Isbell, 1994) and, and as a result, have amongst the highest phosphorus retention capacities of soils (Moody, 1994).

Fertiliser efficiency is also dependent on the interaction between plant roots and the form and distribution of nutrients in the soil. Additions of fertilisers affect a suite of other soil attributes. While most changes are benign, some can impair a root's ability to grow or acquire nutrients, even if only in localised regions around the fertiliser. Root growth in the immediate vicinity of fertilisers may be restricted by toxicities, most commonly aluminium (Bruce *et al.*, 1988), ammonium (Bennett and Adams, 1970; Moody *et al.*, 1995a) and manganese (White *et al.*, 1970), and deficiencies of calcium (Bennett and Adams, 1970; Moody *et al.*, 1995b). To maximise fertiliser efficiency, phosphorus must be in a position and chemical environment where it is at its highest availability to the root system. It is important to understand the

development and physiological responses of roots growing into fertilised soil in order to optimise the utilisation of applied fertilisers.

Phosphorus uptake is broadly related to root surface area, hence young seedlings with small root surface areas rely heavily on seed reserves of P and on soil and fertiliser P close to the emerging roots. The current industry practice is to band fertilisers in two rows 50mm beside and up to 50mm below is the with potatoes (Anon, 1969; Hocking and Ireland, 1984; Regel, 1988). Since there is a moderate time delay between planting and root interception of fertiliser some minor phosphorus deficiency may occur during this time. Starter fertiliser bands are separate bands placed close to the seed where full bands would cause seed burn (Costigan, 1984). Phosphorus in starter fertiliser bands is intercepted earlier, when plant phosphorus demand is higher, and potentially before much phosphorus has been retained by the soil. The additional phosphorus supply of the starter fertiliser may promote more vigorous early growth and improve the overall phosphorus efficiency of the crop.

Potato plant

Growth and development

The planting season for potatoes in cool climates is limited by low initial soil temperatures and the risk of late frosts at the start of the season. At the end of the growing season the crop can be restricted by either high transpiration rates in dry climates, late blight (*Phytophthora infestans*) infections, or early frosts or cold periods (Moorby and Milthorpe, 1975). Hence in most regions there are well defined windows during which potatoes may safely be grown.

Potato sprouts usually emerge within two weeks of planting (Figure 1). However sprout growth may have initiated prior to planting and such sprouts are more likely to develop into shoots, since they are able to suppress the development of still dormant sprouts. The rate of sprout development depends mostly on the soil temperature, although additional moisture, and nutrition (Moorby, 1978). The optimum temperature for sprout growth is 20-25°C (Baerug and Steenberg, 1971).

Initially there is a net efflux of carbohydrates and nutrients from the seed piece until the plant develops sufficient leaf area, about 200-300cm² (Moorby and Milthorpe, 1975) to supply its own carbohydrates (Harris, 1978a; Rowe, 1993). Carbohydrates produced before tuber bulking are used to increase the size of the plant (Beukma and VanDerZaag, 1990) with additional root growth supplying a greater proportion of the plants nutritional needs. Tuber initiation coincides with the emergence of inflorescences, and is induced by short day length and low soil temperature (Okazawa 1967 cited in (Sattelmacher and Marschner, 1978)).

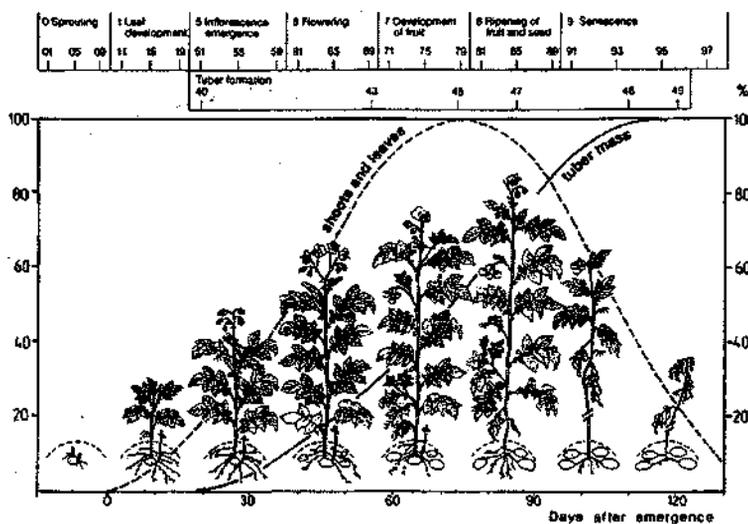


Figure 1 Development of the potato plant (after Hack et al. 1993 C in [Klobe, 1997(a)])

High nitrogen levels also retard tuber initiation by promoting vegetative growth (Harris, 1978a) thereby delaying tuberisation and potentially reducing yields. Temporary N withdrawal induced by low soil temperatures or nitrate leaching may initiate early tuberisation (Sattelmacher and Marschner, 1978). Tubers become the dominant sink for carbohydrates and nutrients from about two weeks after tuber initiation (Harris, 1978a)

The onset of senescence may also be influenced by N nutrition, where high N rates delay senescence (Marschner, 1986). Inadequate phosphorus nutrition also delays maturity (Ozanne, 1980) while high P promotes tuber initiation and earlier senescence. (McCollum, 1978).

The potato plant can be distinguished into three parts (Baerug and Steenberg, 1971):

1. The haulm, consisting of the leaves, stem and flowers, is the ariel part of the plant except for the small underground part of the halum reaching to the seed tuber.
2. Roots, which in the case of plants grown from seed tubers, develop from the nodes of the stem and stolons. Seedlings develop a tap root which later becomes fibrous.
3. Tubers, includes the tubers and the stolons which emerge from leaf axils on the underground region of the halum. Each tuber is formed from an enlarged section of stolon.

Since the roots are the primary organ through which nutrients are intercepted and acquired their development and physiology shall be discussed in more detail.

Root development

Root growth begins immediately after planting from tubers with active sprouts (Beukma and VanDerZaag, 1990). Roots growing from seed tubers form an adventitious root system directly off nodes on the main shoot (Cutter, 1978) while those developing from seed form a tap root system (Marschner, 1986) which later becomes fibrous (Moorby, 1978). In cv. Russet Burbank, adventitious roots emerge first from the lowest node of the stem, and then continue to develop sequentially up the stem (Gracie, 1995). Roots do not develop from dormant eyes on the tuber once the main shoots are growing unless these shoots break dormancy and develop into shoots (Moorby, 1978). (Robins *et al.*, 1967) describes potato root systems as developing from one to two dominant roots from each bud and that roots emerging from buried nodes are rare. There is considerable variation in the pattern of root development particularly between early and late maturity types, with later maturing cultivars developing larger root systems (Iwama, 1998). There tends to be an inverse effect of the number of sprouts on root weight. Hence competition occurs between shoots and roots for limited seed resources which are most likely to be carbohydrates since increasing the mineral nutrition around seed tubers does not alleviate competition (Morris, 1967).

Potato roots do not readily grow below temperatures of 10°C (Epstien, 1966) and (Sattelmacher and Marschner, 1978) (Figure 2). Maximum root development occurs at 20-25°C (Beukma and VanDerZaag, 1990) and (Sattelmacher and Marschner, 1978), but highest tuber yield is obtained at slightly lower temperatures due to a reduction in respiration rate and an earlier onset of tuber initiation (Beukma and VanDerZaag, 1990).

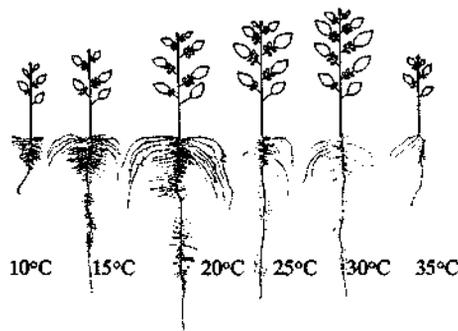


Figure 2. Effects of temperature on root and shoot growth of potato seedlings from B. Sattelmacher in Marschner 1990.

The distribution of roots is also affected by soil temperature, hence in heated soil potato roots were found to grow deeper than in unheated soil (DeRuijter *et al.*, 1996). Similarly corn plants have been shown to grow roots at a steeper angle in warmer soils (Mosher and Miller, 1972). The growth patterns observed by (Kleinschmidt, 1983; Weaver *et al.*, 1922) where roots were observed growing horizontally close to the soil surface, may have been caused by cooler temperatures in the lower soil layers (Mosher and Miller, 1972; Rab and Willatt, 1987). Hence fertiliser positioning may need to account for differences in soil temperature.

Approximately 90% of potato roots from mature plants occur within 200mm of either side of the seed piece (Rab and Willatt, 1987). Maximum root length occurs at relatively shallow depth, 100-150mm (Lesczynski and Tanner, 1976); (Rab and Willatt, 1987) with more than 90% of roots in the 0-300mm depth range (Rab and Willatt, 1987) and (Myers, 1984). Rooting depth can be restricted by sub soil compaction (McDole, 1975) and (Sojka *et al.*, 1993), lateral (DeRoo and Waggoner, 1961), and waterlogging (Myers, 1984). Although deeper rooting can occur in well structured soils, down to 1 m (Kutschera, 1960), the root density is low and nutrient and water uptake from such deep roots is not likely to contribute much to the overall requirements of the plant. Maximum roots density is reached after about 50 days from planting (Pursglove and Sanders, 1981; Rab and Willatt, 1987).

Root distribution and phosphorus uptake are also affected by soil texture. Hence phosphorus was found to be removed in equal amounts from within, from below and to the side of hills in sandy soils but proportionally more phosphorus was removed from within the hill by plants in clay soil (McCorquodale and Moorby 1968) and (Newboulder *et al.* 1968 cit in (Harris, 1978a) p164). This probably reflects the greater capacity of the clay soil to supply both phosphorus and moisture and the lower resistance of sandy soils to root growth. Texture also affects the pattern of root growth in compacted soils. Hence root growth may increase in compacted sandy soils (DeRuijter *et al.*, 1996) but decrease in heavier texture soils (Iwama, 1998; Vos and Groenwold, 1986).

Potato roots first emerge from above the seed tuber, directly off the shoot. The best location for early interception of starter fertilisers would be just beside and above the seed tuber. Although the most likely sprout to develop on a seed piece is from the upper most eye (Beukma and VanDerZaag, 1990), sprouts from the sides of seed

pieces may also develop. However the range of positions from which sprouts may emerge makes precise location of a starter band difficult and may result in some variation in growth rates. Such problems are not encountered with smaller seed crops where there is less variation in the position of root emergence. Because potatoes are shallow rooted they require nutrients and water to be concentrated in the topsoil (Harris, 1978a).

Phosphorus nutrition

The phosphorus content of seed tubers changes little during the period from planting to emergence. Changes that do occur are mostly due to nutrient leaching and respiratory loss of carbohydrates (Pursglove and Sanders, 1981). After emergence the concentration of phosphorus in both the tuber and developing shoots decreases by dilution in the rapidly expanding tissue. The decrease in shoot P in potato tissue follows a sigmoidal pattern, from about 0.6% at emergence to 0.2 % at maturity, (Klobe and Stephan-Beckmann, 1997b) and (Harris, 1978a) with the greatest decrease occurring in the first six weeks after emergence. Similar decreases in phosphorus concentration were observed by (Menary and Hughes, 1967) with tomatoes.

Phosphorus concentration at maturity is lowest in the stem, about 0.2%, while the tubers and leaves contain about 0.3% phosphorus (Klobe and Stephan-Beckmann, 1997a; Klobe and Stephan-Beckmann, 1997b). The very high phosphorus requirement of potato at 30-45 days after emergence (Figure 3) coincides with both the maximum shoot demand and the beginning of tuber bulking. After tuber initiation there is a net export of phosphorus from the shoot to the developing daughter tubers (Klobe and Stephan-Beckmann, 1997a; Klobe and Stephan-Beckmann, 1997b).

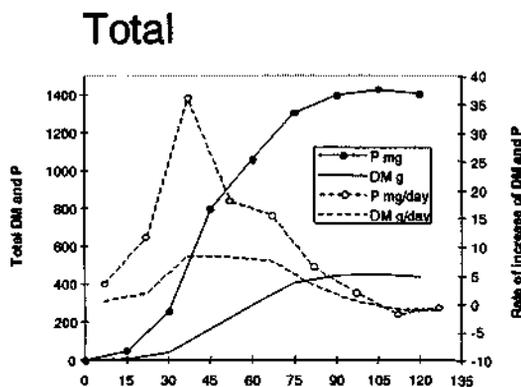


Figure 3. Total phosphorus uptake and dry matter accumulation for potato crops from (Klobe and Stephan-Beckmann, 1997a; Klobe and Stephan-Beckmann, 1997b).

Early root growth on potatoes is restricted to zones close to the seed tuber. Since phosphorus uptake is predominantly by diffusion (Jungk and Claassen, 1997) the acquisition of phosphorus is proportional to the root surface area. When the root system increases in size the surface area in contact with the soil increases and more phosphorus is obtained from the bulk soil. Fertiliser phosphorus placed at sowing is in contact with the soil for at least 30-40 days during which time only small quantities of phosphorus are taken up by the plant (Lorenz and Vittum, 1980). However due to the small size of the early root system the plant relies on high the concentrations of

fertiliser phosphorus during early growth stages. After emergence there is a rapid decrease in the partitioning of fertiliser phosphorus to non fertiliser soil phosphorus due to the increasing size of the root system (Pursglove and Sanders, 1981). Phosphorus nutrition is therefore most important during the early growth stage, when the smaller root system places a greater dependence on fertiliser phosphorus than soil phosphorus (Pursglove and Sanders, 1981).

Most of the phosphorus absorbed through the roots moves into the shoot through the transpiration stream before transferring to the phloem and returning to the stolons and roots. Xylem connections between roots and stolons have been shown to transfer water and nutrients direct to the tubers (Kratzke and Palta, 1985). Such transfer would account for only small amounts of phosphorus acquisition but may be important for the acquisition of Ca by tubers (Moorby, 1978). Phosphorus and other nutrients can be retranslocated from shoots to roots during periods of restricted water availability (Harris, 1978a) indicating tubers are a more competitive sink for nutrients than shoots. Hence when there are severe moisture fluctuations the critical level of phosphorus needs to be higher to allow for some retranslocation of phosphorus to roots during dry periods (Marschner, 1986).

Higher moisture contents improve phosphorus fertiliser efficiency (Baerug and Steenberg, 1971) possibly from an increase in the proliferation of roots (Rab and Willatt, 1987) but also by improving P diffusion (Jungk and Claassen, 1997). Higher soil moisture allows more prolific early root growth due to reduced soil strength (Klepper *et al.*, 1983) and improved nutrient diffusion (Jungk and Claassen, 1997). Phosphorus diffusion is also influenced by soil texture, with lower values and slower phosphorus release rates occurring in heavy textured soils (Vegh *et al.*, 1989).

Irrigation

Potatoes are highly sensitive to water stress (Beukma and VanDerZaag, 1990). A range of linear relationships have been proposed to explain tuber yields in terms of irrigation (see Table 1). In principal, transpirational loss should bear the closest relationship since this is a measure of stomatal conductance and hence the quantity of CO₂ assimilated, however transpirational loss needs to be normalised to mean vapour pressure deficit to be valid and hence is more difficult to measure.

Table 1. Relationship of tuber yield to measurements of irrigation application or irrigation use. Tuber response as tonnes per irrigation unit

Tuber response	Irrigation unit	Author
0.1-0.2t mm ⁻¹	mm of irrigation	(Harris, 1978b)
0.12 t kPa ⁻¹	kPa increase in soil water matric potential	(Taylor and Ashcroft, 1972)
0.58 t mm ⁻¹ kPa	mm transpired/(mean vapour pressure deficit)	(Rijtema and Endrodi, 1970).

Crops that produce vegetative storage organs, such as potatoes and sugar beet, tend to have high transpiration rates that continue through until the final stages of growth (Figure 4). This is in contrast to grain crops that rapidly decrease transpiration during grain filling. Hence irrigation needs to be maintained right through the growing season of potato crops.

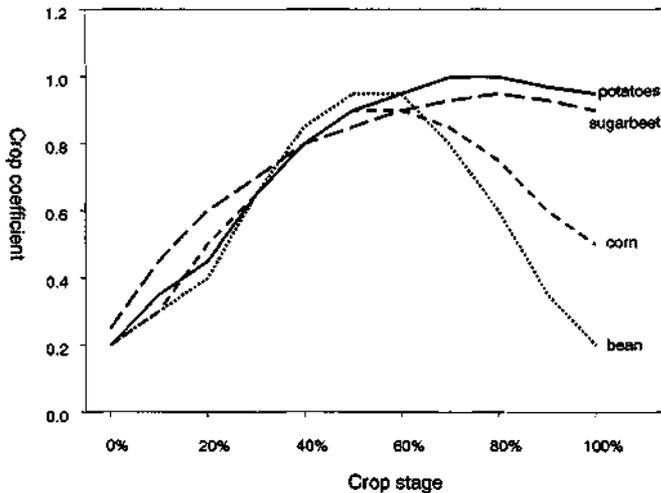


Figure 4 Crop coefficients compiled from data of (Hargraves, 1968; Jensen, 1975). Root crops like potatoes and sugarbeet both have high evaporation rates through the final third of the growing season.

Increasing the soil moisture status from low to medium improved phosphorus uptake by more than 60% (Baerug and Steenberg, 1971). Although the higher rates of irrigation increased the efficiency of broadcast fertiliser more than banded fertiliser phosphorus (Figure 5), banded phosphorus was always more efficient, regardless of the irrigation regime. This is since banded phosphorus is located deeper in the soil where it is less subject to moisture fluctuation (Stieber and Shock, 1995).

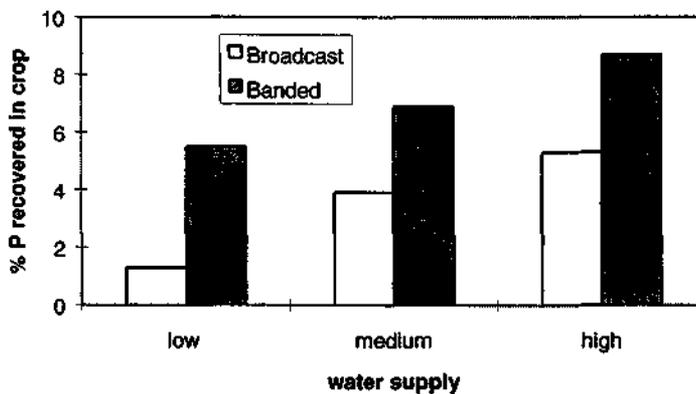


Figure 5. Effects of irrigation and phosphorus placement on %P recovered in crop (after Baerug and Steenberg 1971)

While phosphorus uptake is increased in proportion to the irrigation intensity the frequency and timing of irrigation has more effect on the crop than the quantity of water used (Cotching, 1997; Harris, 1978b) (Shock *et al.*, 1999). Both over and under watering can reduce yields (Cotching, 1997). Excessive irrigation reduces the nitrogen contents of plants by leaching of soil nitrates (Sparrow, 1994; Stark *et al.*, 1993; Stieber and Shock, 1995) and in poorly drained soils reduces the proportion of air filled pores and oxygen uptake of roots (Myers, 1984). Under-watering reduces uptake of phosphorus and other nutrients (Baerug and Steenberg, 1971; Ozanne, 1980). Hence the effects of water are to solubilise the fertiliser (Blanchar and Caldwell, 1966a), to increase diffusion of phosphorus and other nutrients in the fertiliser (Jungk and

Claassen, 1997), and improve root growth and uptake of phosphorus (Barber, 1995; Rab and Willatt, 1987).

Soil temperature is reduced by irrigation (Baerug and Steenberg, 1971) which may retard growth early in the season when soil temperatures are lower. However higher moisture levels in flat topped hills were found to increase emergence of potatoes (Prestt and Carr, 1984). Since high soil temperatures can delay tuber initiation (Bodlaender 1963 cit in (Allen and Scott, 1980)), early irrigation may be beneficial during periods of high temperature early in the season.

Tuber quality can be dramatically affected by moisture fluctuations (Eldredge *et al.*, 1992). Since the tubers are swollen stolons, the growth is not by three dimensional expansion, but by initial linear growth followed by secondary expansion. A retardation in the growth rate, such as that caused by drought, causes a slowing of the rate of cell expansion. Upon resumption of growth, a narrow length of tuber remains, marking the period of drought (Robins *et al.*, 1967). Such narrowings dramatically reduce the suitability of tubers for processing or fresh market use.

Soil properties and phosphorous dynamics

Ferrosols

Ferrosols are derived from basic igneous rocks such as basalt and in some cases dolerite (Isbell, 1994). They are strongly structured soils, due to the presence of large amounts of aluminium and iron oxides, with only minor changes in physical properties with increasing depth. The strong structural properties make them highly desirable for horticultural production, though there are some serious degradation problems occurring from the intensive use of these soils (Bridge and Bell, 1994).

Clay contents in ferrosols are high, 50 > 80% in the top soil, and tend to increase moderately through the sub soil (Bridge and Bell, 1994; Isbell, 1994; Moody, 1994). It is usual for ferrosols to have a high organic matter content in the surface soil that decreases rapidly with depth. The accumulation of organic mater in the surface significantly increases the cation exchange capacity hence the higher chemical fertility of the surface layer of ferrosols (Moody, 1994). Organic matter content and acidity both tend to increase with higher annual rainfall (Isbell, 1994).

A summary of chemical and physical data of ferrosols are given in Table 2. Soil phosphorus properties change strongly with depth. There is a ten-fold reduction in available phosphorus (Colwell) from 84 mg/kg in the top soil to 9 mg/kg in the subsoil, and a doubling of the phosphorus sorbtion index between the surface and sub soil. The accumulation of phosphorus in the top soil reflects both the higher organic matter content and the very slow rate of movement of surface applied phosphatic fertilisers to lower depths in ferrosols (Murdoch and Nash, 1995). Phosphorus sorbtion indices are high and the increase in sorbtion indices in the sub soil was most strongly correlated with the higher levels of citrate-dithionite extractable Al due to the lower pH (Moody, 1994) and due to sequestering of Fe and Al by organic colloids in the surface horizons (Dubus and Becquer, 2002). Soil pH buffer capacity also changes in direct proportion to the organic matter content.

Table 2. Some chemical and physical properties of eight agricultural krasnozems soils (data from (Moody, 1994))

Property	A Horizon		B Horizon	
	Range	average	range	average
Clay %	26-66	(56)	47-78	(68)
Organic C	1.0-4.5	(2.5)		
Effective CEC	3.5-12.3	(8.1)	1.5-10.6	(5.5)
pH w	5.1-6.5	(5.9)	5.1-6.5	(5.8)
PHBC	19-45	(30)	13-34	(19)
Colwell P	13-252	(84)	2-26	(9)
Phosphate sorbtion index	41-85	(64)	68-249	(130)
Citrate dithionite	Fe%	4-16	7-16	(10)
	Al%	0.2-1.8	(0.9)	0.3-1.8

Kaolin and Fe/Al oxy hydroxides are the prevalent clay compounds in Ferrosols (Isbell, 1994) (Moody, 1994). The Fe/Al oxy hydroxides are responsible for their strong structural properties (Bridge and Bell, 1994) and they also have a very high

affinity for P (Moody, 1994). This effect is demonstrated by the phosphorus fertiliser requirements of ferrosols compared to other soils, Table 3.

Phosphorus responses are still likely when soil test results show moderate or high amounts of available soil phosphorus (Pitt, 1984) (Sparrow *et al.*, 1992). Only minor reductions in the basal phosphorus application rate of 135kg P/ha occur with increases in the levels of extractable phosphorus (Pitt 1984). Sparrow (1992) found similar phosphorus rates for 95% maximum yields in soils ranging from 112-210 mg/kg phosphorus Colwell, in the higher range for soil phosphorus for Ferrosols. Even at high extractable phosphorus levels there can be yield responses to rates of phosphorus greater than 650 kg P/ha (Pitt, 1984).

Table 3. Fertiliser phosphorus requirement of potatoes grown on Ferrosols and other soils

Soil	Soil test P mg kg ⁻¹	P rate kg P ha ⁻¹	Reference
Coarse sand	Colwell ^A >7.5	None	Maier <i>et al.</i> 1989
Loam sand/clay	Colwell 30-40	None	"
Sand	Colwell 0-10	100	Hegney <i>et al.</i> 1989
Sand	Colwell >35	None	"
Sandy loam	Colwell <40	75	Sparrow <i>et al.</i> 1993
Sandy loam	Colwell >40	50	"
Low P fixing soil	Olsen ^B >15	None	Tindall <i>et al.</i> 1991
High P fixing soil	Olsen <5	230	"
High P fixing soil	Olsen >30	None	"
Ferrosol	NA	100-120	Guerra <i>et al.</i> 1990
Ferrosol	Olsen <20	90	Strange & Marshall 1990
Ferrosol	Colwell >100	>150	Sparrow <i>et al.</i> 1992
Ferrosol	Olsen <8	150	De Jong (cited in Sparrow <i>et al.</i> 1992)
Ferrosol	Colwell <10	>135	Pitt 1984
Ferrosol	Colwell >10	135	"
Ferrosol	Olsen <5	160	Freeman <i>et al.</i> 1998
Ferrosol	Olsen >40	50	"

^A Colwell extractable P

^B Olsen extractable P

Phosphorus pools

Two factors can explain the phosphorus supply from a soil. These are the soil solution phosphorus concentration, referred to as the intensity factor, and the amount of readily adsorbed P, the quantity factor (Probert and Moody, 1998). Only a very small fraction of the soil phosphorus, less than 0.1%, exists in the soil solution. The quantity factor encompasses both the mineral and organic phosphorus that is in equilibrium with the solution P (Figure 6).

When fertiliser P is added to soil it first dissolves into the soil solution. Then, depending on the cations and soil minerals present in the soil, P is precipitated or adsorbed into the labile pool. This process continues until a new equilibrium is reached. When the solution P concentration is decreased by plant uptake, phosphorus can dissolve or be desorbed from labile pools to re enter the soil solution. In this way the soil solution concentration is buffered by the quantity of phosphorus in labile forms. The ratio of intensity to quantity gives an indication of the soil's supply capacity for a given nutrient (Holford, 1997; Probert and Moody, 1998).

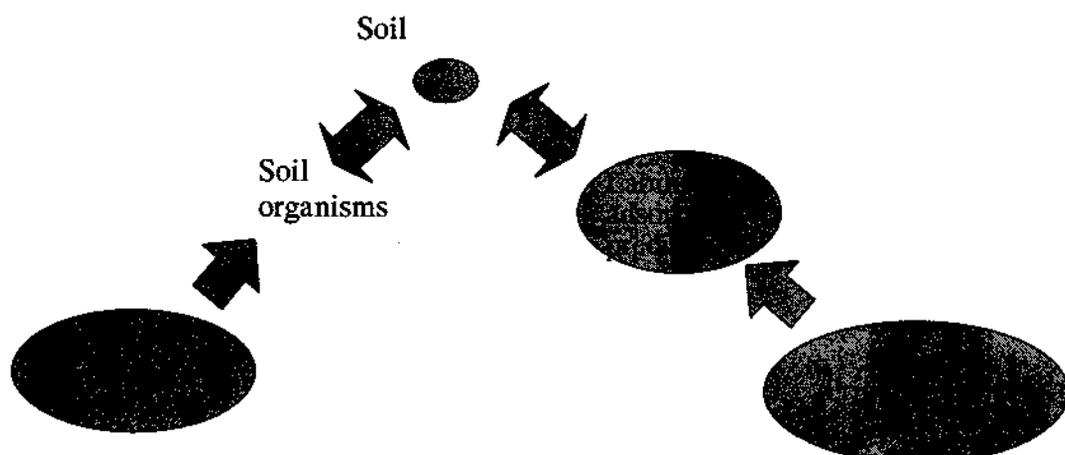


Figure 6. Soil phosphorus pools

P occurs in both mineral and organic forms in the soil. The proportion of organic to inorganic phosphorus depends greatly on the phosphorus fixing qualities of the soil: soils with a greater phosphorus fixation tend to contain a larger inorganic mineral pool of phosphorus (Jackman, 1955).

Soil phosphorus reactions

Fixation of P is a complex and variable process. There are two domains of phosphorus fixation, at low phosphorus concentration, phosphorus fixation is by adsorption to clay minerals, while at high phosphorus concentration, phosphorus is precipitated as low solubility crystalline products (Lindsay *et al.*, 1989). However there is an arbitrary separation between the two modes since adsorption continues at high phosphorus concentration but because the rate of precipitation increases greatly once solutions become saturated, precipitation is the dominant form of phosphorus fixation at higher concentration.

Sorption at low phosphorus concentration

Unlike the simple electrostatic forces involved in cation retention, anion adsorption involves more complex reactions (Bohn *et al.*, 1979). Although electrostatic interactions occur between clays and anions, the capacity of some clay minerals to adsorb anions exceeds the net positive charge of the soil. This type of sorption, known as specific anion sorption, is the process whereby most fixed phosphorus is retained on acidic soils (Bohn *et al.*, 1979). Specific adsorption involves the exchange of anions with hydroxyl ligand groups on the clay minerals. Kaolin and the Fe/Al oxyhydroxide minerals, the most prevalent minerals in ferrosols (Moody, 1994), both contain large surface areas with exposed hydroxyl groups that readily participate in ligand exchange with anions.

Phosphorus sorption is thought to occur by two processes commonly referred to as the fast and slow reactions (Bohn *et al.*, 1979). The fast reaction occurs within one to three hours in a high phosphorus fixing soil and involves a combination of non specific adsorption and specific ligand exchange.

Slow reactions are responsible for the gradual reduction in available phosphorus (Agbenin and Tiessen, 1997). Several reaction mechanisms are possible for the slow

reaction: solid state diffusion of phosphorus into the adsorbing particle (Barrow, 1987), diffusion of phosphorus through micropores, which depends on the crystallinity of the adsorbing surface (Agbenin and Tiessen, 1997), and the simultaneous dissolution and precipitation of clay minerals with PO_4^- (Bohn *et al.*, 1979). However slow diffusion has been implicated as the most likely sorption process operating in oxisols (Wan and El-Swaify, 1998).

Precipitation at high phosphorus concentration

Phosphorus readily forms precipitates with calcium (Bell and Black, 1970; Bouldin and Sample, 1959; Lehr and Brown, 1958) and numerous reaction products have been identified. $\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$ precipitates in saturated monocalcium phosphate solutions in the absence of soil (Lindsay and Stephenson, 1959a). This precipitation was found to be the major reaction governing the concentration of solution phosphorus at high phosphorus concentration from monocalcium phosphate solutions. Taranakites, precipitates of NH_4^+ and K^+ with P may also form in conjunction with other cations, such as Fe^{3+} , Al^{3+} or Ca^{2+} , when these nutrients are banded with phosphorus (Adams, 1980). The calcium phosphates and taranakites formed in alkaline conditions and are moderately soluble and these alkaline precipitates are considered as slowly labile phosphorus (Lindsay *et al.*, 1959) and are only stable at higher pH (Barber, 1995).

Variscite and strengite, $\text{Al}(\text{PO}_4)_3$ and $\text{Fe}(\text{PO}_4)_3$ respectively, may form under acidic conditions, though they have only been observed under moderate phosphorus and aluminium solution strengths when soil temperatures are greater than 90°C (Lindsay *et al.*, 1959), or at high solution strengths of aluminium and phosphorus under strongly acidic conditions (Hsu, 1982). Variscite and strengite become increasingly less soluble at high pH (Figure 7). The high phosphorus concentrations needed for variscite and strengite to occur are only likely to be found in fertiliser bands (Lindsay *et al.*, 1959) and (Hsu, 1982). At low temperature and low solution concentrations, amorphous Al-PO_4 is formed (Hsu, 1982). Hence there is the possibility that variscite and strengite formed around acidic fertiliser bands will dissolve once the pH increases.

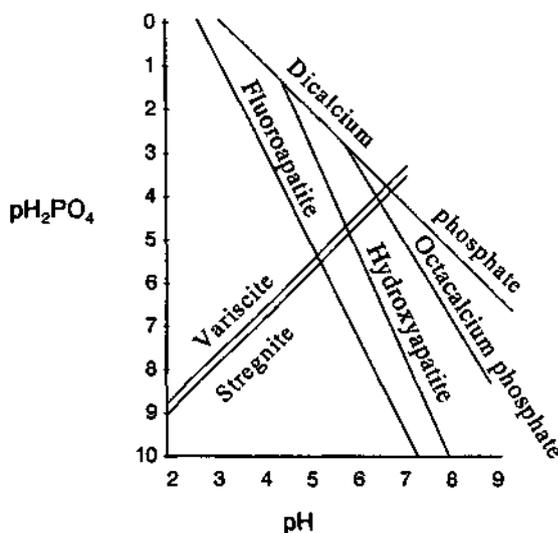


Figure 7. Solubility diagram for phosphorus compounds at 25°C , 5mmol Ca. After (Lindsay and Moreno 1960)

Organic matter

Soil organic matter is a complex material that includes a range of forms from recently applied plant debris to highly residual humic compounds (Black, 1957). Organic matter can affect soil phosphorus retention both indirectly by its effects on soil pH and directly by the competition of organic anions with phosphorus for sorption sites (Deb and Datta, 1967; Ierich and Ohno, 1997; Iyamurewye and Dick, 1996; Moshi *et al.*, 1974), and by the complexation of polyvalent cations (Conyers, 1990). Higher organic matter contents increase the negative charge of soil (Moody, 1994) and the greater negative charge repels orthophosphate from colloidal surfaces there by reducing phosphorus adsorption (Jungk and Claassen, 1997).

Returning crop residues to soils may increase phosphorus availability to subsequent crops (Ierich and Ohno, 1997). Green manures are the best source of organic anions since they are readily decomposable, the microbial activity is greater and more carboxylic acids produced. Mature crop residues are only slowly decomposable and contain more lignified, inert, material (Moody, 1994) and hence have less effect on soil P.

Soil pH

Raising soil pH dramatically alters the surface charge of ferrosols, and other soils with large amount of pH-dependent charge (Moody, 1994) (Figure 8). Although net charge in the surface soil becomes negative above pH 3.5, the positive charge responsible for some phosphorus retention only approaches zero at pH > 4.5. The greater amount of negative charge in the top soil is due to a higher organic matter content, while in the sub soil with lower organic matter contents, there is still positive charge at pH > 6. These effects are mirrored in the higher sorption indices for Ferrosol subsoils (Table 1).

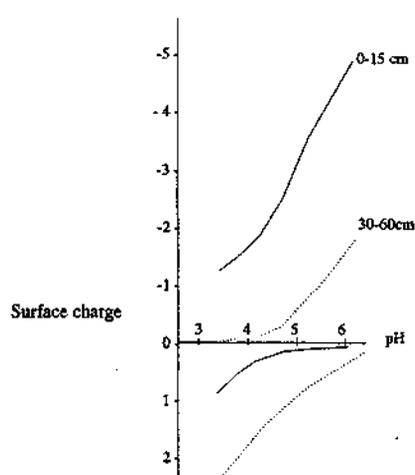


Figure 8. Surface charge changes with pH of Ferrosol from north Qld. (after Gillman, 1984 in (Moody, 1994))

(Barrow, 1987) provides some insight to the interactions of pH and phosphorus sorption. Phosphorus sorption often decreases when pH increases from acidic to slightly acidic conditions, then increases again when the pH becomes neutral and higher (Barrow, 1987; Holford, 1983). (Barrow, 1987) suggests several reasons for these observations.

1. There may be greater biological mineralisation of phosphorus at higher pH
2. Interactions with Al are affected by pH, removal of Al at higher pH may either reduce (Adams, 1980; Kamprath, 1970) or increase phosphorus adsorption (Haynes, 1982).
3. Phosphorus may be made more labile at low pH due to acidic dissolution of mineral P. Such an effect may mask additional phosphorus sorption at low pH through the release of acid labile phosphorus into solution, hence apparent sorption decreases.
4. The species and concentration of soil solution cations affect the relationship of sorption to pH. Low ionic solution strengths and monovalent cations species lower sorption at higher pH.

Some of these reactions are contradictory, however they highlight the complexity of reactions that occur in limed soils. The influence of pH on phosphorus retention or release depends on both the mineral and organic pools of P. Low carbon to P ratios favour mineralisation of organic phosphorus, while high ratios support immobilisation of P in organic forms. (Russell, 1973) p306 suggests C to P ratios, though more variable than C to N ratios, should be around 100:1-2. However the C to P ratio can be increased in soils with higher P retention properties (Jackman, 1955).

At around pH 7 and higher, dihydrogen phosphate deprotonates to monohydrogen phosphate. The resulting additional negative charge, increases the affinity of the phosphate ion to the remaining positively charged adsorption sites (Barrow, 1984). This effect moderates the expected reduction in phosphorus adsorption from the increased pH.

Phosphorus reacts strongly with calcium and increasing the Ca activity such as by lime application may induce Ca-PO_4^- precipitation (Barrow, 1984) (Bell and Black, 1970). Hence when Ca(OH)_2 was used as the liming material, sorption decreased when pH increased from 5.5-6 but increased again above pH 6 (Naidu *et al.*, 1990) (Figure 9). Whereas when KOH was used as the liming material, phosphorus sorption continued to decrease with increases in pH above pH 6, Figure 9 (Naidu *et al.*, 1990) (He *et al.*, 1997).

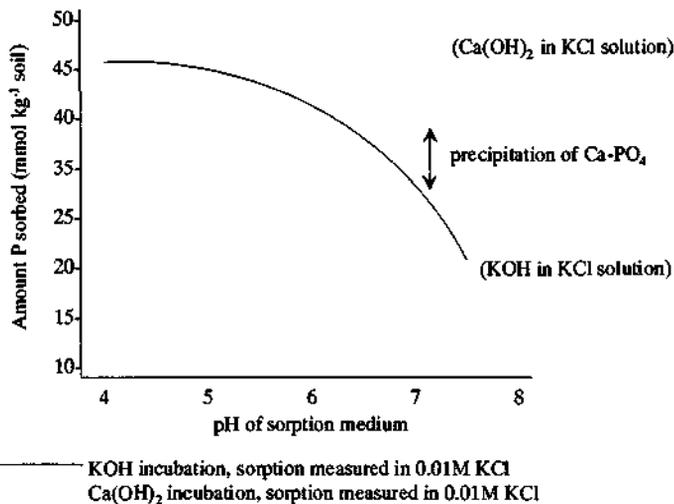


Figure 9. Effects of liming material and cation species on phosphorus sorption, from (Naidu *et al.*, 1990).

Phosphorus diffusion and plant uptake

Before phosphorus is available for plant uptake it must first be transported from within the soil or soil solution to the plant root. The acquisition of nutrients by roots occurs by two processes. Either the nutrients are intercepted by the root during growth, or they are brought to the root by transport through the soil solution. Nutrients that are intercepted either move directly into the root or may diffuse short distances from the soil (Jungk and Claassen, 1997). Nutrient transport occurs by both diffusion and mass flow. Mass flow, where the nutrients are brought to the root in convective currents of soil solution used by the plant for transpiration (Jungk and Claassen, 1997) is a significant source of uptake only when the concentration of the ion in soil solution is high in relation to the needs of the plant, e.g. Ca, Mg, and nitrate. Ca and Mg may be in such excess in the soil solution that they form precipitates on root surfaces (Barber, 1995). Ions that interact strongly with soil colloids, such as, phosphorus, ammonium, and potassium, reach the root predominantly by diffusion (Jungk and Claassen, 1997).

The rate of phosphorus diffusion in pure water is around 10^{-5} cm²/s, however within soils this rate is reduced by an order of three to six fold to around 10^{-8} - 10^{-11} cm²/s due to interactions of phosphorus with the adsorbing surfaces of soil. The actual rate of diffusion, known as the effective diffusion, D_E , depends on the properties of the soil, where ($D_E = D_{\text{aqueous}} \times (\text{volume water content}) \times (\text{tortuosity})/(\text{buffer power})$). D_E can be increased by as much as 25 times over the volumetric water contents found in soils (Jungk and Claassen, 1997). Hence soil moisture will strongly affect phosphorus diffusion and uptake as well as root growth. Soil phosphorus buffer power can vary between 100-2000 $\mu\text{m/g}$ for available phosphorus and is a major influence on the diffusion of phosphate in soil (Jungk and Claassen, 1997). The tortuosity of a soil increases in proportion to the fineness of soil texture, hence diffusion is reduced in clay soils compared to sands. The form of phosphorus also affects diffusion, where diffusion of $\text{H}_2\text{PO}_4^- > \text{HPO}_4^{2-} > \text{CaHPO}_4$ (Lewis and Quirk, 1967a). Hence increasing the pH, which changes the phosphate ion from H_2PO_4^- to HPO_4^{2-} , will decrease diffusion. Krasnozems, with their high phosphorus affinity and high clay contents, will have a relatively low D_E .

With in fertiliser bands the ionic environment can influence the diffusion of phosphorus either by co-diffusion in ion pairs, e.g. NH_4^+ and PO_4^{3-} where diffusion is increased (Peaslee and Phillips, 1970), or by precipitation of phosphorus minerals, such as $\text{Ca}_3(\text{PO}_4)_2$ thereby reducing diffusion (Bouldin and Sample, 1959). (Bell and Black, 1970) found the diffusion of phosphatic fertiliser sources to increase in the following order; DAP>MAP>MCP. The increasing diffusion follows the same order as their saturated solution pHs of 8.00, 4.00 and 1.48 respectively, indicating that acid soluble cations retard diffusion. The presence of NH_4^+ would reduce phosphorus sorbtion by ion pair formation (Barrow, 1984) However, (Aitken and Hughes, 1980) believed the greater diffusion of ammonium phosphates resulted in eventually more phosphorus being fixed from less mobile P forms since a larger volume of soil is contacted by the P solution.

There are two modes by which plants may improve nutrient uptake, either by an increase in root length (Smyth and Cevalier, 1984), or by increased nutrient uptake efficiency (Jungk and Claassen, 1997). Increases in the P uptake rate from the addition of P can be substantial but are not in direct proportion to the increase in solution P concentration (Jungk and Claassen, 1997). Some plants are adapted to low soil phosphorus diffusion rates, hence increasing solution phosphorus does not increase uptake (Barber, 1980) and in the zone near fertilisers the concentration of phosphorus may be so high that the uptake rate of many plants becomes saturated (Marschner, 1986). Where this occurs increasing the nutrient concentration above the uptake limit will not immediately benefit the plant. However the additional nutrient may be useful by extending the duration of high levels of available phosphorus near the root.

Root proliferation increases uptake of P due to the larger surface area in contact with the fertilised soil. However there is a time lag for root density to increase. When plants do not increase root area in response to applied phosphorus it is the volume of soil containing phosphorus that most strongly affects P uptake (Strong and Soper, 1973). Uptake of phosphorus can be greatly improved by the presence of root hairs, which extend from just behind the root tip to where the exodermis is formed and may be up to 0.1 mm long. Although only small in length it is the extra distance root hairs reach into the soil, not the additional surface area, that enables the increase in P uptake. Hence the benefit of root hairs depends on the relationship between D_E and the root hair length. Root hairs must be at least as long as D_E to have significant benefit (Jungk and Claassen, 1997). Since D_E is low in krasnozem soils, root hairs may be beneficial, however potato roots do not appear to form root hairs under normal growing conditions (personal observation) and their presence was not reported by Cutter (1978) or Kratzke (1985).

Phosphorus uptake occurs along a greater length of the root than most other nutrients, (Barber, 1980). Uptake rates of phosphorus may remain high after the endodermis has formed (Ozanne, 1980), hence the aging and suberisation of roots does not exclude phosphorus uptake. Higher soil temperatures may also increase uptake from the apical region by stimulating cell growth and uptake (Marschner, 1986). Uptake of monovalent H_2PO_4^- is up to ten fold greater than divalent HPO_4^{2-} , hence raising the pH may reduce plant phosphorus uptake (Barber, 1980).

Response of roots to nutrition

Root length density, a measure of the length of root per volume of soil, tends to decrease exponentially with soil depth (Greenwood *et al.*, 1982). Hence the greatest uptake efficiency of strongly buffered nutrients, such as P, is in the surface layers and in the period before the plant begins the reproductive phase, where maximum root proliferation occurs (Barber, 1995). Nutrients that are absorbed by mass flow, such as nitrate, can still be efficiently absorbed at lower depths where root length density is lower, provided there is adequate moisture (Jungk and Claassen, 1997) but this is often only a minor source for the nutrient.

Under nutrient deficient conditions, primary and secondary roots tend to proliferate while tertiary root growth decreases (Narayanan and Balakrishma Reddy, 1982). Primary and secondary roots grow longer and enable the plant to exploit new regions of soil while tertiary roots are shorter enabling the plant to feed on high nutrient zones. Hence the phosphorus concentration, along with other nutrients, particularly nitrogen, influences whether the roots seek new regions of soil or remain and proliferate in zones of high nutrient concentration.

Nitrogen has a strong influence on root proliferation. Localised placement or banding of fertiliser N and/or phosphorus stimulates nearby root growth (Drew, 1975; Miller and Ohlrogge, 1958; Robinson, 1994)]. To achieve a beneficial response to banded N and P both nitrogen and phosphorus must be intimately mixed (Blanchard and Caldwell, 1966a). Sattlemacher in (Marschner, 1986) found differences in root growth to different N sources. Nitrate increased the size of the root system while ammonia increased the incidence of root branching (Figure 10). Acidification by exchange of H^+ for NH_4^+ absorbed by the plant roots may also increase the dissolution of phosphorus (Riley and Barber, 1971). Such acidification may also increase the rate of uptake of phosphorus due to an increase in the proportion of $H_2PO_4^-$ to HPO_4^{2-} (Hagin and Tucker, 1982).

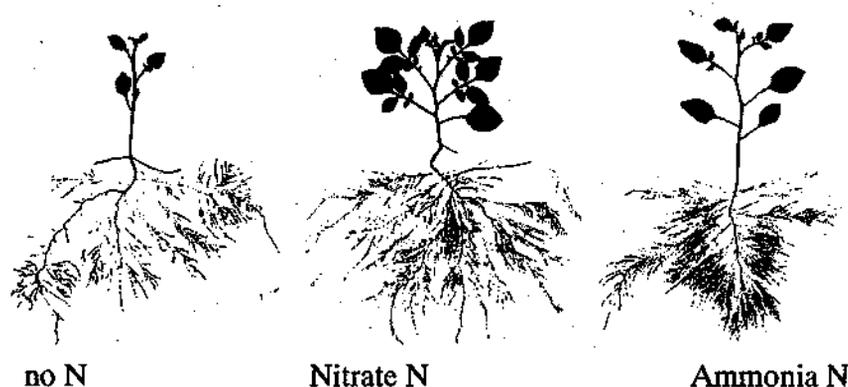


Figure 10. After Sattlemacher, B., cit in (Marschner, 1986) phosphorus 433, Potato seedling root growth in sandy soil with different nitrogen sources.

High rates of banded fertiliser and banding with the seed tubers delayed emergence of potatoes when fertiliser blends containing urea and DAP were used (Chu *et al.*, 1984). (Meisinger *et al.*, 1978) also observed yield decreases with urea and DAP based fertilisers, but they did not provide details on the soils type used.

Measurements of roots

There are two principal methods of root system measurement, destructive coring or soil profile methods and non-destructive rhizotron methods. Soil coring and profile wall methods, where the roots in a known volume of soil are measured, are useful for obtaining net root production, as root length per volume of soil, but yield no information on the rates of root growth, rates of root initiation or death (Thorupkristensen and Vandenboogaard, 1998) Total root production can only be measured by repeated measurements on the same group of roots (Majdi, 1996). Currently the best procedure for repeated measurements on roots is through rhizotron studies (Roland *et al.*, 1996).

Rhizotrons simply involve growing roots adjacent to transparent surfaces which allow the roots intercepting the surface to be observed. Minirhizotrons, round or rectangular tubes, can be inserted in the ground for *in situ* field studies. Rhizotron studies have become much less time consuming over the last decade with advances in digitising and image manipulation software (Majdi, 1996; Roland *et al.*, 1996). There are a range of methods for collecting, digitising and manipulating images ranging from quite expensive miniature video camera systems (Andren *et al.*, 1996; Goins and Russelle, 1996; Roland *et al.*, 1996; Smit and Zuin, 1996) to quite simple telescopic attachments to allow photographic cameras to be used (Poelman *et al.*, 1996). Direct digital or VCR equipment becomes more cost effective when large numbers of images are processed (Andren *et al.*, 1996).

Rhizotrons have an influence on the root systems. Roots intercepting the rhizotron wall are prevented from growing into the volume of soil occupied by the rhizotron and instead turn and grow along the soil rhizotron interface. This tends to increase the density of roots observed compared to soil coring, though not always, (see (Roland *et al.*, 1996). However correlations between coring and rhizotron studies can be quite high with sixteen out of twenty six studies having $R^2 > 0.7$.

Soil aggregation

The degree and nature of soil aggregation has implications for the chemical and hydrological properties of the bulk soil. Well aggregated soils can be considered as a collection of discrete soil aggregates surrounded by a matrix of more or less connected inter-aggregate pores (Gupta *et al.*, 1989). Inter-aggregate pores are usually in the size range of 10-0.1 μm whereas the intra-aggregate pores are 30-1000 μm (Hamblin, 1987). Hence, there is a distinct bimodal distribution of pores in an aggregated soil (Gupta *et al.*, 1989). In non-aggregated soils macropores tend to be disconnected, though long macropore chains may exist, and are surrounded by a matrix of soil (Radulovich *et al.*, 1992).

Upon wetting an aggregated soil, water is drawn into the aggregates by the matric suction of the small inter-aggregate pores. Significant water conductivity occurs only once the aggregate pores fill and a water film develops over the surface of the aggregates. When the rate of water influx is increased the thickness of the film increases, thereby increasing the hydraulic conductivity. Chemically, the most important component of an aggregated soil is the surface of the aggregates, since almost all of the water movement in aggregated soils occurs along this boundary (Wan and El-Swaify, 1998).

Ferrosols are highly aggregated soils (Isbell, 1994), hence fertiliser P diffusing into the soil solution initially reacts with clay particles at the aggregate surface only. This reactive surface layer on aggregates is in the order of 200µm thick (Linguist *et al.*, 1997). However over long periods of time, sorbed P may slowly diffuse to layers deeper in the aggregate (Linguist *et al.*, 1997; Wan and El-Swaify, 1998).

Microbial interactions

Both bacteria and fungi have been found to increase phosphorus availability to plants in soils. These organisms are able to produce phosphatase enzymes that mineralise both organic and inorganic forms of P. Some common soil fungi, *Aspergillus* and *Penicillium* species, have high phosphorus mineralising abilities (Kucey *et al.*, 1988). Mycorrhiza fungi commonly form associations with plant roots, including solanaceous plants (Mcarthur and Knowles, 1993; Wang *et al.*, 1993). While mycorrhizal fungi improve phosphorus nutrition by increasing the root's absorbing surface area in contact with soil, they are unable to dissolve phosphorus in forms not already available to plant roots (Ae *et al.*, 1990; Morel and Plenchette, 1994). (Niemira *et al.*, 1996) have shown that mycorrhizae stimulate potato tuber initiation and (Niemira *et al.*, 1995) demonstrated increased resistance to dry rot fungi (*Fusarium sambucinum*) in microtuber potatoes inoculated with mycorrhizae.

Mycorrhizal symbiosis occurs at the expense of carbohydrates from the host plant. Carbohydrate supply is regulated by the host plant depending on the phosphorus status of the roots (Lu *et al.*, 1994). Modest soil phosphorus levels result in reduced production of root carbohydrate exudates further increases in soil P reduce and eventually cease the symbiotic relationship (Tinker, 1980). However the phosphorus content of individual roots, not that of the whole plant, influences VAM colonisation. Hence, roots that grow outside of localised band-applied phosphorus and into low phosphorus soil are able to form effective VAM associations (Lu *et al.*, 1994). When phosphorus is band applied, VAM associations occurring in the unfertilised bulk soil may increase phosphorus efficiency in crops capable of forming these associations.

Fertiliser placement

There are three categories of fertiliser placement: broadcast, banded and starter fertilisers. Overlap exists between each category. When fertilisers are broadcast they are mixed thoroughly with all or a significant proportion of the rooting depth soil volume. When band placed, the volume of fertilised soil is reduced by placing the fertiliser as continuous lines, or sometimes as pulses, usually slightly adjacent to the seed. Band placement is used to reduce the quantity of fertiliser lost by fixation to soil and to promote vigorous root growth in the fertilised region (Barber, 1995). Starter fertilisers are a specific variation on band placement where a small quantity of fertiliser is placed close to the seed to promote early growth (Costigan, 1984). In most circumstances the full rate of fertiliser required for the crop placed this close would cause fertiliser injury. Starter fertilisers may be used with either banded or broadcast fertilisers.

Traditionally, fertiliser placement has been by broadcasting, where fertilisers are placed directly on the soil surface before or during cultivation. This is the simplest form of fertiliser application and is still widely practised. However only 2% of the soil volume in the root layer may be supplied with phosphorus by broadcasting (Engelstad and Terman, 1980). Band placement below and to the side of the seed was seen as the most efficient method for larger applications (Brown, 1946). A summary of yield responses of banded fertiliser at 50mm beside and 50mm below the seed piece against other locations is show in (Table 4). Placing the fertiliser on the same level or slightly beside and below the seed gives the highest yields.

Table 4. Relative yield responses for different fertiliser placements, relative yield at 50mm beside and 50mm below seed set to one. Data compiled from experiments comparing two or more banding positions with on at 50mm beside and 50mm below seed piece (Brown, 1946; Campbell *et al.*, 1945; Cooke, 1948; Cumings and Houghland, 1939; Holliday and Draycott, 1968; Soltanpour, 1969; Widdowson *et al.*, 1974)

Depth mm from seed	0	25	50	75
75				0.86
50	0.95			
25	1			
0	0.93	1.03	1.1	0.98
-25	0.94		0.96	
-50	0.94		1	
-75			1	
-100				
-125				
-150			1.26	

More recent banding experiments have confirmed early conclusions that banding is more effective than broadcast fertilisers (Sparrow *et al.*, 1992). However (Yost *et al.*, 1979) when working with Oxisols found initial broadcast phosphorus applications followed by lighter band applications in following years provided the most efficient use of fertiliser. (Aitken and Hughes, 1980) found banding only significantly improved yield compared to broadcast fertilisers at low rates of phosphorus

application. This result was also found by Fox and Kang (1978) for corn. Kamprath (1967) and Holford (1989) found complete mixing to be advantageous as this distributed phosphorus throughout the soil volume and maximised the potential root interception of P. However soil properties have large influence on the likely response to banding, hence on light textured soils with low P fixing properties, favourable responses to broadcast P are often found (Hegney and McPharlin, 1999).

(Barber (1995a) found phosphorus utilisation was greatest when phosphorus was mixed with around 5-15% of the soil volume depending on the phosphorus retention properties of the soil. Soils with high phosphorus retention capacities reached their optimum fertilised ratio at lower P mixing volumes. This is the optimum condition between allowing root access to the confined phosphorus in the band and preventing loss of phosphorus to fixation when phosphorus is mixed with larger soil volumes. When the phosphorus retention capacity of the soil increases, the volume of fertilised soil should be decreased (Barber, 1995). However, even on high phosphorus retaining soils there is a limit to the soil volume which fertilisers can be restricted due to inefficiencies resulting from the reduced root contact with fertiliser.

Banded fertiliser

The general recommendations for banding fertiliser with potatoes are 5cm to the side (Hocking & Ireland 1984) or 5cm to side and 5cm below the seed piece on each side (Anon 1969, Regel 1988, Westerman 1992, Myuller 1991). Other variations include 2.5cm to the side and 2.5cm deep (Regel & Sampson 1987) which was later revised due to fertiliser injury, banding with the seed when low rates of phosphorus fertilisers were used (Prumel, 1957), and banding above the seed when initial root growth tended to be horizontal (Kleinschmidt, 1983).

Jacob et al. (1949) found total phosphorus fertiliser uptake for potatoes was lower than other crops including corn, soybean, and cotton, because the root system of potatoes was smaller. (Pursglove and Sanders, 1981) supposed the low root density of potatoes was likely to hinder further improvements in phosphorus recovery. However (Prumel, 1957) believed phosphorus banding in potatoes was less effective because roots quickly extend out beyond banded regions into the bulk soil. Substantial amounts of soil phosphorus can then be removed from the bulk soil (Prumel, 1957).

Starter fertiliser

Starter fertilisers are small bands of fertiliser that are placed closer to the seed than the main body of fertiliser, either broadcast or banded. They are intended to improve the early nutrition and hence vigour of the crop (Engelstad and Terman, 1980). Crops often require higher phosphorus concentrations during early growth (Scott, 1988) and close placement of immobile nutrients, such as P, is important, especially under cool conditions when phosphorus uptake is reduced (Klepper *et al.*, 1983). Starter fertilisers have proved advantageous where early root growth is restricted (Costigan, 1987), Al toxicity occurs (Sloan *et al.*, 1997), soil temperatures are low (Robson *et al.*, 1959), or soils have a low phosphorus status. The first three responses occur when bulk soil phosphorus levels are adequate for normal growth, hence the response is to the positioning of P.

Harmful interactions of fertilisers

Gracie (1995) found banding above tubers would reduce yield in soils with low buffering of N and P due to leaching of toxic concentrations of nitrogen and phosphorus into the root initiation zone. Soil solution of high phosphorus concentration can diffuse or be displaced to zones of active root growth where root inhibition may then occur. Under these circumstances fertiliser should either be placed further from the seed or mixed with a greater volume of soil (Barber, 1995). Ammonium ions, which are more toxic to roots than is P at high concentrations (Gerendas *et al.*, 1997) are retained less strongly than phosphate and can diffuse further from the band (Blanchar and Caldwell, 1966a). NH_4^+ toxicity is more likely to occur in soils with low CEC which are unable to buffer the increase in NH_4^+ concentration. Ferrosols with their high CEC are not likely to permit NH_4^+ concentrations to develop to toxic levels (MacLean, 1983; Moody *et al.*, 1995b)

Close placement of fertilisers may cause injury to seedlings by a range of salt and specific ion effects. Cation concentrations may be substantially increased around fertiliser bands (Lindsay and Stephenson, 1959a). MCP, Super and MAP reduce the pH in the vicinity of fertilisers. Dissolution of the soil minerals releases substantial amounts of Al, Fe, Si and Mn into solution (Lindsay and Stephenson, 1959a; Moody *et al.*, 1995b). This may cause both Al and Mn toxicities and possible H toxicity. (Lindsay and Stephenson, 1959a) found Mn, released from around MCP bands, remained in solution longer than Fe and Al and was able to diffuse further into soil than Fe or Al. This is due to greater solubility of Mn at higher pH, stable up to pH of 6 (Bohn *et al.*, 1979), and the lack of precipitation reactions between Mn and phosphorus (Lindsay and Stephenson, 1959a). Evidence indicates that Mn levels an order of magnitude lower may be capable of inducing yield reductions where roots are exposed to Mn for longer durations (Moody *et al.*, 1995b). Hence the ionic environment in the immediate vicinity of the fertiliser band can restrict or prevent root growth. Nutrients in the fertiliser band may be in a chemically "available" form, as measured by soil nutrient analysis, but biologically inaccessible to the plant (Blanchar and Caldwell, 1966b; Moody *et al.*, 1995b).

Salinity

Salinity affects plant growth at low levels by reducing the water potential and restricting the plant's ability to absorb water (Winter, 1974). At higher EC, root growth itself can be inhibited (Moody *et al.*, 1995a). (Moody *et al.*, 1995a) found a linear relationship between EC and relative root elongation of soybeans across a wide range of soils and N and K fertiliser types. An EC of 4.1 dS/m was sufficient to reduce short term root growth of soybean seedlings by 10%. However reductions in root elongation may become apparent before reductions in yield (Moody *et al.*, 1995a).

Potatoes are moderately salt sensitive (Winter, 1974) and Maas and Hoffman (1977 cited in Marschner, 1986) found an average $\text{EC} > 2 \text{ dS/m}$ as the threshold for yield decline in potatoes, with a 25% reduction in yield reduction at 4 dS/m. (Nadler and Heuer, 1995) found an EC in irrigation water of 6 dS/m was sufficient to reduce marketable yield of potatoes.

Aluminium

Aluminium affects root growth through inhibition of nutrient uptake and interference with cell division (Marschner, 1986) p486. Al may precipitate, often with P, either in the root-free space or in close association with the nucleus. The accumulation of aluminophosphates within the root-free space is caused either from precipitation of soluble aluminophosphates within the root, or by adsorption of phosphate to previously precipitated Al hydroxy polymers (Marschner, 1986). Such phosphorus is not readily available for plant uptake. The binding of Al to phosphate groups of DNA increases the stability of DNA and prevents strand separation, essential for replication. Hence Al bound to DNA inhibits cell division. Potatoes are relatively tolerant to Al toxicity (Hooker, 1981).

Manganese

Potatoes are somewhat more sensitive to Mn toxicity with growth being reduced by concentrations of 25 ppm in solution cultures (Hooker, 1981). Mn uptake is more influenced by the bulk soil pH than by the pH of fertiliser bands (White *et al.*, 1970). When fertiliser bands were very acidic, from the use of MCP and Al salts, Mn toxicity did not occur when the bulk soil around the band had been limed (White *et al.*, 1970). Cation uptake occurs through mass flow throughout the whole soil profile in contact with roots (Menary and Kruger, 1966). Hence small zones of high Mn availability are unlikely to greatly affect total Mn uptake. However very high Mn concentrations may cause root damage, (Wong and Bradshaw 1982 cited in (Horst, 1988)).

Calcium deficiency

Calcium is essential for cell growth, being used in cell wall formation and for cellular regulation. Ca has a stimulatory effect on phosphorus uptake. However this effect appears to be significant only at low solution phosphorus levels (Robson *et al.* 1970). Ca deficiency may be induced by precipitation of Ca with PO_4^{3-} (Moody 1995b). Ca promotes the induction of lateral roots, at concentrations as low as 0.1 mM. Mg functions in a similar way to Ca, i.e. it stimulates phosphorus uptake and is involved in cellular regulation, though Mg is not required for cell wall synthesis and so is not needed in as large amounts as Ca (Adams, 1980). Mg has no stimulatory effect on root growth (Poovaiah and Reddy, 1991) and cannot replace Ca.

Ca is prevented from moving across cell membranes (Marschner 1974 cited in Greenwood and Collier 1979), hence very little Ca enters the phloem from the xylem. Phloem has a high pH and a high concentration of P. Any Ca that does enter the phloem is rapidly precipitated with phosphate (Van Goor and Wiersma 1974 cited in Green and Collier 1979). Ca must be present at the growing tip since there is little redistribution of Ca (Greenwood and Collier, 1979) and the root will suffer deficiency (Hooker, 1981). Most soils supply enough Ca for adequate growth. However Ca concentrations may be reduced to deficient levels when the activity of another cation is increased, e.g. NH_4^+ (Moody 1995b), when Ca is lost by precipitation with phosphate (Naidu *et al.*, 1990), or when Ca deficiency is induced at high phosphorus concentrations due to the simultaneous uptake of Ca and phosphorus (Robson *et al.* 1970).

The response of plants to soil calcium status shows a better correlation with calcium activity ratio than the absolute Ca concentration in the soil solution (Khasawneh, 1971).

Calcium Activity Ratio $Ca_{AR} = [Ca]/\Sigma([Ca]+[Mg]+[K]+[Na]+[Al]+[NH_4^+]+[Fe])$. The typical Ca_{AR} for adequate root growth of soybeans ranges from 0.05 (Moody *et al.*, 1995a) to 0.15 (Carter 1979, Bruce *et al.* 1988). (Moody *et al.*, 1995a) suspects the higher values of Carter and Bruce are due to the omission of Na from the Ca_{AR} equation.

While Ca_{AR} may be reduced substantially by the addition of fertilisers this effect is usually offset by an increased displacement of Ca from the cation exchange complex of soils by the fertiliser cations. This buffering effect will depend on the ECEC of the soil. Soils with a high cation exchange capacity such as ferrosols are able to buffer the change in fertiliser cation addition.

Alternate methods of fertiliser placement

Seed treatment

Several authors (Carter, 1967; Hathcock *et al.*, 1984) seed coats have been widely used on pasture and crop species. (Scott, 1988) concluded that seed coatings may be over four fold as effective as banding, the response being greatest when soil phosphorus levels are low. Coating seeds also favours supply of nutrients to crop plants over weeds (Scott, 1988). Beneficial responses from seed coatings often occur at low levels of phosphorus and or N, 1-5% SSP or NPK mix, due to a range of toxicity and desiccant effects occurring at higher fertiliser coating concentrations (Scott, 1988).

Sparrow 1998 (unpublished) has tried coating potatoes but found difficulties applying the seed coat, and toxic effects from salt and acid injury. Potential benefits from seed coating may include diffusion of phosphorus and other nutrients directly into the tuber, locating phosphorus closer to sites of early roots emergence, and reducing the surface area of phosphorus in contact with soil. However there are potential difficulties, which may include fertiliser injury to both tuber and new roots/shoots, lack of uptake due to poor root development in the zone immediately beneath the tuber, and technical problems with applying the coat.

(Sharma and Gerwal, 1989) showed savings of 25-50kg P/ha could be made by soaking seed tubers in 0.4% phosphorus solutions depending on the phosphorus status of the soil. Phosphorus soaking was less effective when levels of soil available phosphorus were higher. (Barerjee *et al.*, 1990) found responses to phosphorus soaking were less than an additional 25 kg P/ha. (Pursglove and Sanders, 1981) observed no yield increases from soaking. They believed this was due to leaching of the phosphorus from tubers before emergence.

Absolute quantities of 0.5-1 kg P/ha were absorbed by the tubers from the soaking treatment (Sharma and Gerwal, 1989). The quantity of phosphorus absorbed depends on the metabolic activity of the tubers; non dormant tubers absorb more P. This would indicate storage of some phosphorus, by active process within cells. Absorbed phosphorus is transferred to mitochondria, the organelles responsible for the

metabolic and energy relations of the plant. Phosphate may then be stored with Ca as stable precipitates. Phosphorus soaking possibly elevates cellular phosphorus concentration, which improves early root growth (Sharma and Gerwal, 1989). Soaking in phosphorus solutions may be viable if combined with fungicide or hormone treatments already given to tubers. The effectiveness of tuber soaking depends on both soil phosphorus status and the physiological state of the tubers. Alternately, the phosphorus content of seed tubers could be increased by high fertiliser applications in seed crops. However increasing the N content of seed tubers by higher fertiliser rates has proved difficult (Harris, 1978a).

Irrigation

Fertigation has been used with potato crops (Papadopoulos, 1992, DeJong, 1997). Papadopoulos, (1992) found the optimum fertiliser ratio of N, P, and K was 120, 40 and 130 mg/l respectively. This approximates to a ratio of 4:1:4, which is lower in phosphorus content than most fertilisers applied to potatoes, which tend to be around 1:1:1 (Marshall, 1984). However, the annual application of phosphorus was still, over a three year period, 132 kg/ha, which is as high as required for other phosphorus fixing soils, hence fertigation had not improved fertiliser efficiency. On average 22 kg/ha of phosphorus were removed annually in the 30-50 tonne crop giving a 17% phosphorus recovery efficiency. Soil nutrient levels with trickle irrigation must exceed those for whole profile irrigation due to the reduced effective root volume from trickle irrigation (Bar-Yosef *et al.*, 1989).

Foliar sprays

Foliar applied phosphorus at up to 100 kgP/ha, in multiple sprays at tuber initiation increased yields of tubers over 60mm by 12% to 58 t/ha when compared to broadcasting (Lewis and Ketterwell, 1992). This result may not have been significant in comparison to banding since (Sparrow *et al.*, 1992) found similar increases attributed to banding fertilisers, 8-16%, compared to broadcast fertiliser on Ferrosols with high phosphorus contents. (Singh and Kamath, 1989) found foliar sprays as the least effective phosphorus application method when compared with basal and split applications on canola.

Leaf surfaces are sheathed with a hydrophobic wax layer. This surface prevents excessive water loss from the leaf, but also prevents water from entering the leaf from outside. Foliar uptake is restricted to the ectodesmata, small openings that transgress the cuticular layers (Marschner, 1986). As a guide, solutions can be up to 1% strength before leaf injury occurs, and leaves may hold up to 400 l/ha (Marschner, 1986). This would allow 4 kg of phosphorus to be applied in each spray. Thus, ten or more sprays would be required to supply all the phosphorus for an average potato crop assuming all the foliar phosphorus is utilised. Full utilisation is unlikely as canopy development is not complete until after the period of greatest phosphorus demand i.e., at emergence and shortly after. Without complete canopy closure much of the spray falls on the soil where it is of limited use to the crop (Pursglove and Sanders, 1981). Micronutrient deficiencies are more suitably treated by foliar applications. Fe, Mn at high pH and Mo in acidic soils are some examples where foliar applications have been successful (Marschner, 1986). Although significant quantities of foliar P may be absorbed within the leaf, up to 25% of applied P, only a small fraction, around 1% the total applied P

is mobilised and is able to move to other regions of the plant (Wittwer *et al.*, 1963). Hence foliar feeding P does not appear to be any more efficient than soil applied P.

Fertiliser quality

Cadmium

About 10-15% of Tasmanian Russet Burbank potatoes have a Cd content more than 0.05mg/kg fresh weight (Sparrow and Salardini unpublished data). However, in 1996 the Australian and New Zealand Food Authority increased the maximum permitted Cd concentration from 0.05 to 0.1mg/kg fresh weight. Current evidence suggests that nearly all Tasmanian growers would meet the new requirement (Sparrow and Salardini, 1997). Tuber Cd increased to a greater extent with increases in the banded P rate, compared to the broadcast P rate (Sparrow *et al.*, 1992). (McLaughlin *et al.*, 1993) evaluated the response of potatoes to four phosphorus sources: SSP, RP, DAP and MAP. However the sites were non responsive to phosphorus and no effect of yield, Cd content, or tuber quality was found. The major effect controlling Cd accumulation in South Australia was the EC of the soil solution, specifically its chloride content. Hence irrigation water quality is a major control of Cd content.

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