New Zealand Institute for Crop & Food Research Limited
A Crown Research Institute

CROP & FOOD RESEARCH
Mana Kai Rangahau

Crop & Food Research Confidential Report No. 319

Improving fertiliser use efficiency of potatoes

R J Martin[1], M D Craighead[2], S M Sinton[1], P D Jamieson[1], A M Howie[2] & T Armour[1]

November 2000

A report prepared for
The Potato Industry Research & Development Grant Committee and
Ravensdown Fertiliser Co-operative Limited

Copy 1 of 18

[1] *New Zealand Institute for Crop & Food Research Limited*
Private Bag 4704, Christchurch, New Zealand
[2] *Ravensdown Fertiliser Co-operative Limited*
Box 1049, Christchurch

Contents

1 Executive summary

The objective of this research was to investigate the possibility of reducing the financial and environmental costs of fertiliser application to potatoes

1. by more closely matching supply of fertiliser nitrogen (N) with crop demand for N using:
   a) foliar applications of a liquid fertiliser to ensure rapid uptake of N by the crop, and
   b) conventional fertiliser coated with a release inhibitor to make the fertiliser N more slowly available to the crop;
2. by estimating crop N requirement by measuring:
   a) petiole nitrate; and
   b) total plant N content.

Current recommendations for split and foliar applications should be altered so that all the fertiliser is added before the tops start to senesce and while the tubers are bulking in order to maximise tuber yield while minimising the risk of increased N leaching.

An experiment at Lincoln in the 1999-2000 season examined the effect of rate, timing and form of N fertiliser on the growth, yield and N balance of a Russet Burbank potato crop.

The experiment consisted of four replicates of nine treatments. The treatments consisted of two rates of fertiliser (150 and 300 kg/ha) in three forms (urea, Nimin coated urea and SupaN32 foliar fertiliser) applied either entirely at planting or in a variety of splits. A control treatment had no added N. Otherwise the crops were well fertilised, irrigated, and disease control measures taken to ensure that N supply was the only management limitation to growth. The crop was planted on 21 October and moulded on 1 December. Soil samples were taken to a depth of 30 cm from the whole site before planting, and then from each plot at six occasions during the season. These were used for nitrate and ammonium determinations.

Measurements of biomass production, leaf area and tuber sizes and numbers were taken at approximately four-week intervals through the season. In a selection of treatments N content of tissue was also measured. Petiole samples were taken at weekly intervals from 22 December until the tops started to die down in March.

The main results were:

- high early N applications prolonged green leaf area. Late N applications did not delay leaf senescence,
- increasing N significantly ($P<0.001$) increased tuber yield, from 59 t/ha with no N to 73 t/ha with 150 kg N/ha and 79 t/ha with 300 kg N/ha,

- urea applied early had significantly higher yields (79 t/ha) than split N applications (74 t/ha), with slow release fertiliser being intermediate (77 t/ha),
- yields increased up to February, with no further increase in yield through to April,
- specific gravities were high overall in this trial (over 1.086, or 21.5% dry matter). There was no sign of uneven growth, hollow heart or incipient hollow heart,
- early applied N increased soil N more during the main growth of the crop than split applications, but there was no difference between forms of fertiliser. However, soil N at the end of the trial was similar in all treatments,
- two-thirds of the fertiliser N applied was taken up by the plant in treatments 2 (150 kg/ha N applied early) and 3 (300 kg early N/ha), whereas only half of that applied to treatment 5 was taken up (275 kg split applications of N/ha),
- 48 kg N was unaccounted for by soil and plant N in treatment 2, 100 kg N/ha in Treatment 3, and 81 kg N/ha in treatment 5,
- the maximum amount of N taken up by the crop, for each tonne of tuber yield, increased from 2.5 kg N/ha/tonne for treatment 1 to 3.9 kg N/ha/tonne for treatment 3. So the N use efficiency declined with the addition of fertiliser N by up to 60%,
- plant N uptake was closely related to final yield. However, all the N had effectively been taken up by February, and coincided with the end of tuber bulking,
- petiole nitrate analysis indicated that, except when 300 kg N/ha was applied early, the crop was deficient in N,
- there were close linear relationships between N content of the whole plant and plant fresh weight, but the relationships depended on the rate and timing of fertiliser application,
- there was a linear relationship between leaf area and plant N uptake, and maximum leaf area index was also closely related to final yield.

The main conclusions and recommendations are that:

- the slow release fertiliser (Nimin coated urea) was no different to conventional urea in its effect on soil N, leaf area development, or tuber growth and yield,
- splitting the urea fertiliser application increased soil N status, but reduced yields compared to applying all the N early,
- the foliar fertiliser (SupaN32) had no advantage over conventional split urea applications on soil N, leaf area development, or tuber growth and yield,
- potatoes need N early to set up a large leaf area and hence high tuber yields. Therefore, split and foliar N applications should all be applied before the tops start to senesce and while the tubers are bulking,

- the petiole test and the total plant N uptake test were difficult to translate into the amount of N required by the crop or to predict final yield. Leaf area index could be a potential alternative method of predicting plant N requirements and final yield.

2 Introduction

Current fertiliser recommendations for potatoes are for very high applications of N, on the basis that any deficiency reduces yield. Applications are often split on the assumption that late N applications can maintain the crop canopy by delaying senescence. However, research both in New Zealand (e.g. Martin 1995a) and overseas (Rourke 1985) indicates that much of this fertiliser is not taken up by the crop and could well be leached to the groundwater, either during the growth of the crop or after the crop is harvested. Overseas research has shown that leachable fertiliser levels are higher under potatoes than many other crops (Sylvester-Bradley & Chambers 1992). Regional councils are becoming increasingly concerned about groundwater quality and may place restrictions on what they consider to be excessive fertiliser use. Research and farmer trials overseas indicate that applying foliar fertilisers and coating conventional fertilisers with release inhibitors have increased yields and tuber size by up to 25% compared to current practice (e.g. Arable Farming, 20 January 1998). This indicates that there may be opportunities for New Zealand potato growers to use slow release or foliar fertilisers to both increase yields while the risk of groundwater pollution.

The objective of this research was to investigate the possibility of reducing the financial and environmental costs of fertiliser application to potatoes by more closely matching supply of fertiliser N with crop demand for N. Two approaches were examined:

1. foliar applications of a liquid fertiliser to ensure rapid uptake of N by the crop,
2. applying conventional fertiliser coated with a release inhibitor to make the fertiliser N more slowly available to the crop.

Two trials have been undertaken to compare these approaches with either early or split applications of urea, and to examine fertiliser application and uptake by two potato crops. The first was a summer crop in Canterbury, planted in October 1999, the second a winter potato crop at Pukekohe, planted in May 2000.

This report is on the Canterbury trial, in which two methods of estimating crop N requirement were also examined. The petiole nitrate test (Gardner & Jones 1975; Kleinkopf et al. 1984) has been used extensively overseas to estimate crop N requirement. More recently in Britain a method has been developed using crop total N content to estimate crop N requirement, which is claimed to be superior to the petiole test (Mackerron et al. 1994).

3 Methods

The trial was carried out at Simpsons Block, on Shands Road, between Hornby and Springston, 20 km south of Christchurch. This block is owned by AgResearch. A paddock was leased by Crop & Food Research in 1999 for potato trials. The soil is a Templeton silt loam, and the crop followed barley after three years in pasture. The paddock was ploughed in the winter. Eradicane (6 ℓ/ha) was applied in September, and the site was then power harrowed to work in the chemical.

Site soil test results (0-30 cm) taken in July were, in AgResearch soil fertility quick test units, Ca 6, K 17, Olsen P 28, Mg 16, Na 11, and S 13. The pH was 5.5, and total N 0.18. A basal fertiliser mix was made up of:

- 1700 kg/ha superphosphate (@ 9% P = 150 kg P/ha,12% S = 200 kg S/ha),
- 250 kg/ha potassium chloride (@ 50% K = 125 kg K/ha)
- 300 kg/ha potassium sulphate (@ 42% K = 125 kg K/ha, 18% S = 54 kg S/ha)
- 60 kg/ha calcined magnesite (@ 55% Mg = 33 kg Mg/ha)

This was mixed by hand and then machine broadcast over the plots on 19 October. The area was then maxitilled and the urea-at-planting treatments (see below) applied by hand on the same day.

Russet Burbank potato seed tubers were ordered from Alex McDonalds Merchants Limited. The tubers were cut by hand to an estimated 50 g, then dressed with Gaucho (insecticide) and Monceren (fungicide), and dusted with fir bark dust to keep the cut surface dry. The trial area was planted with a 2 row planter on 21 October 1999.

There were four replicates in a randomised complete block trial. Plots were 9 or 10 rows wide by 10 m long. Row spacing was 77 cm and the tuber spacing within the row was 33 cm, giving a planned population of 39 350 tubers/ha.

The planned N fertiliser treatments are shown in Table 1.

Table 1: Nitrogen fertiliser treatments applied to the Lincoln potato trial.

Tmt	Total N appl	At plant (19/10)	At mould (1/12)	13/12	10/1	17/1	24/1	31/1	7/2	14/2	21/2	28/2	6/3	1/3	20/3	27/3
1	0															
2	150	150N urea														
3	300	150N urea	150N urea													
4	150	100N urea	25N urea								12.5N urea	12.5N urea				
5	300	100N urea	25N urea	25N urea	12.5N urea	12.5N urea	12.5N urea	12.5N urea	12.5N urea	12.5N urea	12.5N urea	12.5N urea	12.5N urea	12.5N urea	12.5N urea*	12.5N urea*
6	150	150N Nimin														
7	300	150N Nimin	150N Nimin													
8	150	100N urea	25N urea								12.5N F (foliar)	12.5N F				
9	300	100N urea	25N urea	25N urea	12.5N F (foliar)	12.5N F	12.5N F	12.5N F	12.5N F	12.5N	12.5N urea	12.5N F	12.5N F	12.5N F	12.5N F*	12.5N F*

* not applied

The slow release fertiliser applied was Nimin coated urea. Nimin is a mixture of oils extracted from the Neem tree of India. The waxy material was added to (coated onto) urea at a rate of 1.05%. The trade name of the product used is Godrej Nimin, which is imported by Envirocorp NZ Ltd, Christchurch.

The foliar fertiliser used was SupaN32. This contains 32% N as a 50/50 mixture of urea and ammonium nitrate, consisting of 16% urea N, 8% ammonium N and 8% nitrate N. It was applied by hand using a wand or a boom at a rate of 343 ml/plot made up to 4 ℓ/plot with water, with a wetter to assist penetration. The wetter was Contact Low Foam (Crop Care Holdings Ltd) added at 0.025%. SupaN32 is made Agrichem Manufacturing Industries Pty Ltd, Queensland and is sold by Ravensdown.

The crop was grubbed on 15 and 24 November to control weeds, and was moulded on 1 December. The N-at-moulding treatments were applied by hand immediately prior to moulding.

Subsequent urea N applications were broadcast over the crop by hand.

The crop was sprayed frequently to control diseases and aphids:

- 17 December: Bravo (1.6 ℓ/ha) and Pirimor (500 g/ha)
- 26 December: copper oxychloride (4 kg/ha)
- 6 January: Ridomil (2.5 kg/ha) and Pirimor (500 g/ha).
- 17 January: Acrobat (2.5 kg/ha)
- 28 January: Bravo (1.6 ℓ/ha) and Pirimor (500 g/ha)
- 4 February: copper oxychloride (2 kg/ha) and Pirimor (250 g/ha)
- 15 February: Acrobat 2.5 kg/ha and Pirimor (500 g/ha)
- 25 February: Bravo (1.6 ℓ/ha) and Pirimor (500 g/ha)
- 3 March: Acrobat (2.5 kg/ha), Mancozeb (600 g/ha) and Pirimor (250 g/ha)
- 17 March: copper oxychloride (4 kg/ha)

A side roll irrigation system, designed to apply approximately 12 mm water/hr, was used to irrigate across the plots. Four shifts were required to completely cover the trial. The trial was irrigated on 9 and 10 December (50 to 60 mm), 23 December (25 mm), 30 and 31 December (25 mm), 20 and 21 January (38 mm), 10 and 11 February (50 mm), 16 February (25 mm), 1 and 2 March (38 mm).

On 19 October, before any fertiliser was applied, soil samples were taken from each replicate to a depth of 0-15 and 15-30 cm for soil N analysis. On 30 November, 20 December, 10 January, 8 February, 6 March and 3 April, ten 0-30 cm samples were taken per plot. These samples were taken in the row, mid-way between plants. The samples were dried, extracted with 2M KCl, and the resulting solution analysed on a RFA-300 Continuous Flow Analyser, with one line measuring nitrate N, and another ammonium N.

Plant samples were taken from all treatments on 15 December, 11 January, 7 February, 6 March and 3 April. In addition, treatments 1, 2, 3, and 5 were sampled on 28 December, 24 January, 21 February and 20 March.

At each sampling, four plants in each of two adjacent rows were dug and separated into tubers and tops. The roots were discarded. All tubers were brought back to the laboratory. The tops were weighed in the field and a subsample of a main stem from each of three plants brought back to the laboratory and washed, if necessary, to remove any soil.

In the laboratory the tops subsample was divided into main stems and laterals. The laterals were weighed and discarded. The sixth branchlet from the top on the main stem was removed and divided into lamina and petiole. Leaf area of the lamina was determined on a Delta-T Image Analysis System. The sixth branchlet lamina was then dried at 60°C, weighed and retained for N analysis. The sixth branchlet petiole was dried at 80°C, weighed and discarded. The remainder of the main stem was divided into stem, live branchlets and dead branchlets. The live and dead branchlets were dried separately at 80°C, weighed and discarded. The main stems were dried at 60°C, weighed and retained for N analysis. At later harvests, when the tops had died down, all the top material was dried together at 80°C, the dry weight recorded and the material discarded.

The tubers were washed and allowed to dry. Then all tubers were divided into one of six length classes (0-1.5 cm,1.5-3.5 cm, 3.5-7 cm, 7-15 cm, 15-20 cm, and over 20 cm). The number and fresh weight of all tubers in each size class was recorded, and then either all the tubers (under 3.5 cm diameter) or a 3-5 tuber subsample (over 3.5 cm diameter) were sliced and dried at 60°C. After the dry weight was recorded, the two largest size classes (by fresh weight) were combined for N analysis.

The top and tuber samples for N analysis were ground and analysed on a LECO CNS-2000 machine for C and N. For the March and April harvests, a further subsample of fresh tubers was taken for specific gravity determinations from their weight in water and in air. Conversion from specific gravity to % dry matter was made using a table provided by the potato breeders at Crop & Food Research.

Petiole samples were taken on 22 December then at weekly intervals from 13 January until the tops had died, which varied from 1 to 15 March, according to treatment. A petiole sample was taken from the first fully expanded leaf on 10-12 plants/plot, dried at 80°C and stored before all samples were forwarded to ARL Laboratories at Napier.

The results were analysed separately for each harvest date by analysis of variance using the Genstat statistical package.

4 Results and discussion

4.1 Weather

The season was cooler and wetter than usual (Table 2). After emergence, mean temperature in all months was below the long-term average. From mid-November to mid-February less than 30% of days had maximum temperatures higher than 20°C. However, solar radiation was close to or above average. Rainfall over the life of the crop was close to average, but was below average in December and February, and above average in January. Significant rainfall events included 28 mm on 13 December, 49 mm over 2-4 January and 40 mm over 12-13 March.

Table 2: 1999-2000 and long term mean air temperature, solar radiation and total rainfall at Lincoln during the growth of the potato trial.

	Mean air temperature (°C)		Mean daily solar radiation (MJ/m^2)		Total rainfall (mm)	
Month	1999/2000	Long term	1999/2000	Long term	1999/2000	Long term
October	12.2	11.3	16.8	16.4	50.9	54.9
November	12.9	13.1	20.1	20.1	60.5	55.7
December	13.5	15.7	24.6	21.7	39.1	61.3
January	14.8	17	21.3	21.6	85	50.3
February	15.9	16.3	19.1	18.4	19.9	51.3
March	14	15	16.7	13.6	51.8	58.9

4.2 Irrigation

Approximately 280 mm was applied to the crop, 130 mm in December, 38 mm in January, 75 mm in February and 38 mm in March. At no stage did the crop experience drought conditions. Perversely, 38 to 50 mm irrigations were often followed within 24 hours by significant rainfall events. On two occasions during December and early January this resulted in the crop receiving 75-100 mm of water in less than a week.

4.3 Fertiliser applications

Most treatments received the planned fertiliser applications. The exceptions were treatments 5 (250 kg instead of 300 kg N/ha split as urea) and 9 (250 kg instead of 300 kg N/ha split as urea), where the final two applications of N were not made because the tops had died down by the date the applications were to have been made. In addition, urea replaced a foliar application to treatment 9 on 14 February because of continual rain. This rain also caused the split applications in treatments 4 and 8 to be delayed by one week from 14 and 21 February to 21 and 28 February.

4.4 Crop

First emergence was noted on 8 November. Up to 5% of the tubers either failed to produce shoots or the shoots were severely stunted, due to the seed crop being damaged by Roundup spray drift. Sampling of plots was adjusted to account for these gaps or stunted plants.

Odd plants in the trial also showed symptoms of various virus infections. The grubbing on 15 and 24 November controlled seedling weeds well, and, apart from some Californian thistles, weeds were not a problem in this crop.

The first flower buds were noticed on 13 December. Some of the more vigorous plots were near canopy closure by 20 December. At this time, tops in the no N plots (treatment 1) were a paler green than other plots. By 3 February, foliage in the no N plots was very pale green, low N plots light green, and high N plots dark green. The foliar application of fertiliser (treatment 9) had scorched some leaf margins, burnt holes in some leaves and killed others.

On 6 February there were very strong north-west winds all day, resulting in plants being blown over and a lot of leaf and leaf tip death.

The crop was scored for greenness of the leaves on 8 February. No N fertiliser (treatment 1) had the yellowest leaves, and 300 kg N/ha (treatments 3, 5, 7 and 9) the greenest leaves, with early applications (treatments 2, 3, 6 and 7) being greener than split applications (treatments 4, 5, 8 and 9) (Table 3).

Table 3: Colour scores on 8 February (1= yellowest, 5 = greenest), and % leaves still green on 6 March (mean of two scores from two people).

Treatment	N rate (kg/ha)	N timing	Colour score (8 February)	% leaves still green (6 March)
1	0	-	1.8	4
2	150	Early	3.3	36
3	300	Early	4.8	79
4	150	Split	2.5	22
5	300	Split	4.4	49
6	150	Early (slow release)	3	20
7	300	Early (slow release)	4.9	75
8	150	Split (foliar)	2.6	18
9	300	Split (foliar)	4.1	19

From 13 to 19 February there was a week of wet, dull weather, which prevented spraying. On 28 February some late blight infection was noted on the southern two replicates, particularly in the nil and low N plots. By this stage, the no N plots were dying back with main stems still upright.

All plots were scored for leaf colour by two people independently on 6 March. Applying 300 kg N/ha early (treatments 3 and 7) produced the highest scores (more green leaves), while applying no N fertiliser (treatment 1) produced very little green leaf (4%) (Table 3). In this trial, therefore, late N applications did not delay canopy senescence.

Leaf area index (LAI) is the area of green leaf per unit area of ground, and is a measure of the light interception capability of the crop. For potatoes, complete light interception occurs at around an LAI of 3. All treatments had reached an LAI of 3 to 4 by 15 December (Figure 1). The LAI of treatment 1 (nil N) stayed around 3.2 until 24 January and then declined until 6 March when all the tops had died. The LAI of the other treatments were significantly ($P<0.05$) higher over summer, increasing to between 4 and 6 in January and then declining steadily to zero. By 6 March only treatment 3 had a significant amount of green leaf, but by 20 March, all the tops had died. Top weights showed a similar pattern of increase and decline to leaf area index.

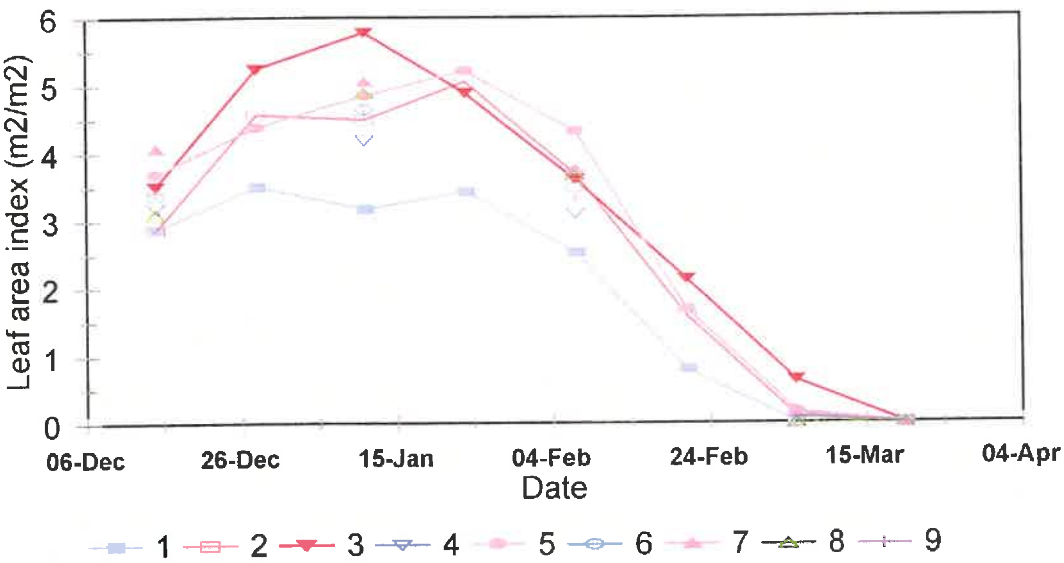

Figure 1: Leaf area index (m^2/m^2) for all treatments at each plant sampling date. Treatments 1 (no N fertiliser), 2 (150 kg N as urea applied early), 3 (300 kg N as urea applied early, 4 (150 kg N as split urea applications), 5 (300 kg N as split urea applications), 6 (150 kg N as slow release fertiliser applied early), 7 (300 kg N as slow release fertiliser applied early), 8 (150 kg N as urea plus foliar applications), 9 (300 kg N as urea plus foliar).

4.5 *Yields*

Tuber yields increased at a constant rate in all treatments up to 11 January, and in all treatments except treatment 1 up to 7 February (Figure 2). This increase continued in treatment 3 up to 21 February. The rate of this increase was 1.18 t/ha/day, a faster rate than the 0.88 recorded in a previous trial (Martin 1995), and the 0.95 t/ha/day reported by Kleinkopf et al. (1981). From 11 January treatment 1 had a lower rate of tuber growth up to 7 February, after which no further increase in yield occurred. Between 7 and 21 February the yield increase in the other treatments also ceased.

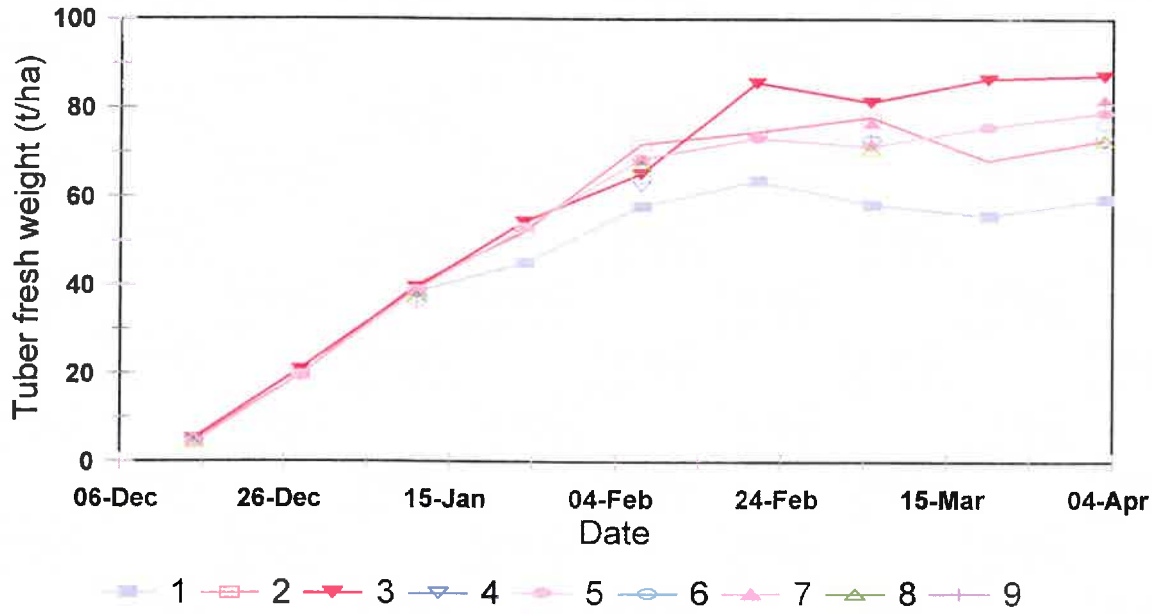

Figure 2: Tuber yield (t/ha) for all treatments at each plant sampling date. Treatments 1 (no N fertiliser), 2 (150 kg N as urea applied early), 3 (300 kg N as urea applied early, 4 (150 kg N as split urea applications), 5 (300 kg N as split urea applications), 6 (150 kg N as slow release fertiliser applied early), 7 (300 kg N as slow release fertiliser applied early), 8 (150 kg N as urea plus foliar applications), 9 (300 kg N as urea plus foliar).

Significant differences in mean yields from 21 February to 3 April were obtained with rate and method of application. Urea applied early (treatments 2 and 3) produced significantly higher (P<0.01) yields (79 t/ha) than split N applications (74 t/ha), either when applied as urea (treatments 4 and 5) or foliar fertiliser (treatments 8 and 9). Slow release fertiliser (treatments 6 and 7) was intermediate (77 t/ha).

Table 4: Mean tuber yields (t/ha) from 24 February onwards.

Rate	Yield (t/ha)	Form	Yield (t/ha)
No N	59.4	No N	59.4
150	73.0	Urea early	79.3
300	79.3	Slow release	77.1
		Urea split	73.4
		Foliar split	74.5
LSD (5%) v. No N	4.2		4.6
LSD (5%) other	2.7		3.8

The levelling off of yield in February (Figure 2) indicated that applications of N in the split application treatments after the beginning of February may not have had any effect on yield, and that all the N should have been applied in December and January when the tubers were still bulking.

There was no significant difference in overall tuber numbers between treatments, but the proportion of large tubers (over 7 cm diameter) was significantly less for treatment 1 (82%) then for the other treatments (92%) (Table 5). Very few tubers reached a diameter of over 15 cm.

Table 5: Percentage of tubers over 7 cm in diameter.

Treatment		11 Jan	7 Feb	6 Mar	3 Apr
1	No N	61.9	87	82.1	80.9
2 to 7	+ N	58.9	87.7	91.9	91.1
LSD (5%)		11.67	4.88	3.63	3.31

Tuber numbers stayed very consistent over harvests (Figure 3). The increase in tuber numbers over 7 cm in diameter was mirrored by the decline in smaller tuber numbers, indicating that there was no tuber initiation after 28 December. The decline in total tuber numbers after February was due to the number of empty, small (0-1.5 cm) tubers at these harvests, which were lost during harvesting and washing.

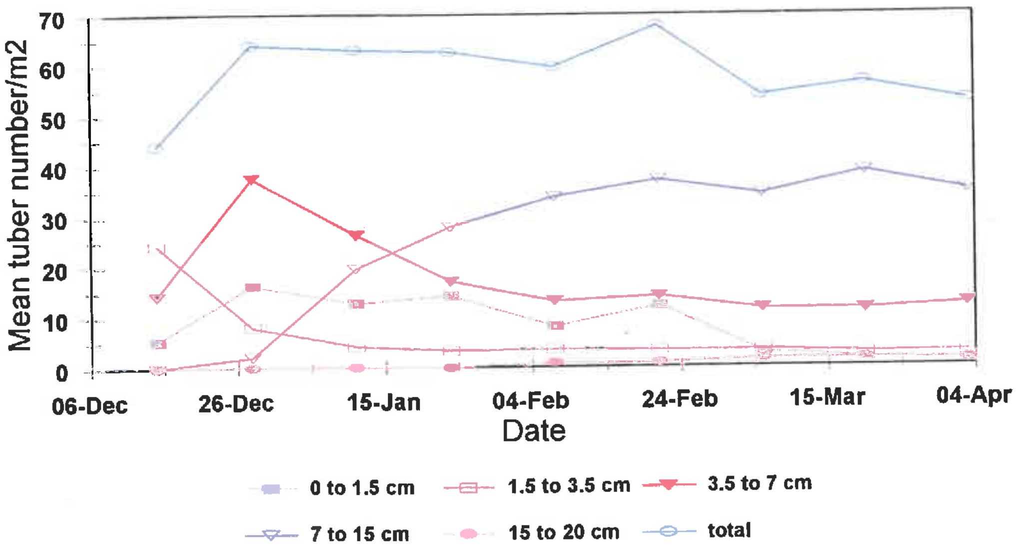

Figure 3: Tuber number/m² in each length grade and total number of tubers at each plant sampling date averaged across all treatments.

Specific gravities were high overall in this trial, averaging over 1.088 (22% dry matter). At the 6 March harvest, there were significant decreases in specific gravity with increasing rate of N fertiliser, from 1.098 (24% dry matter) for no N fertiliser to 1.086 (21.5% dry matter) for 300 kg N/ha (Table 6). At the 3 April harvest, there was a similar result, but the decrease in specific gravity with increasing N was less. Specific gravities were not as high as those found by Martin (1995b), but this crop was not left to mature in the field. They were still, however, considerably higher than the 20% assumed in potato models (Mackerron & Waister 1985).

Table 6: Specific gravities at the 6 March and 3 April harvests (with % dry matter in brackets).

Rate of N	6 March	3 April
0	1.098 (24.1)	1.099 (24.2)
150	1.091 (22.4)	1.088 (22.0)
300	1.086 (21.5)	1.086 (21.5)
LSD (0 v others)	0.0025	0.0038
(100 v 300)	0.0016	0.0024

The potatoes were of a high quality, with no sign of uneven growth and no sign of hollow heart or incipient hollow heart during the growth of the crop.

4.6 *Petiole nitrates*

The changes in petiole nitrate are shown in Figure 4. The background levels separated by the dotted lines are those recommended for potatoes in Idaho (Kleinkopf et al. 1984).

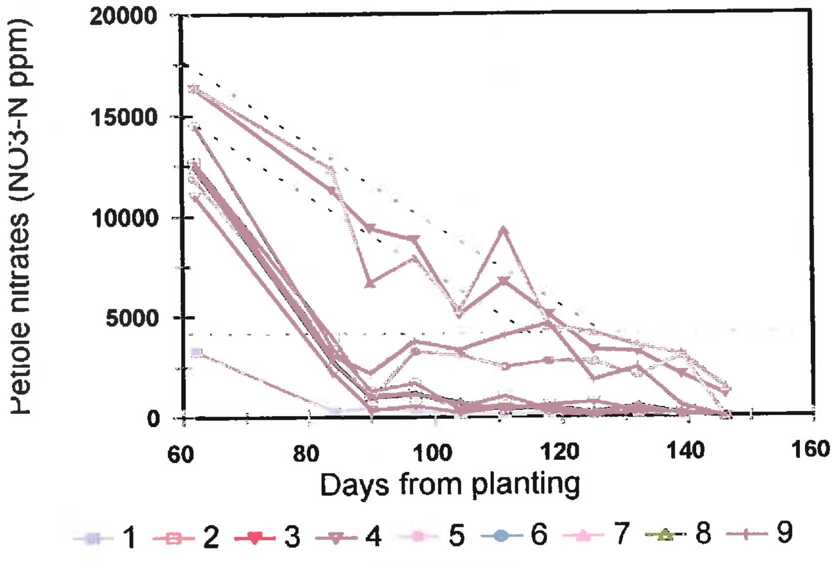

Figure 4: Petiole nitrate concentration (ppm) for all treatments at each petiole sampling time. The background levels separated by the dotted lines are those recommended for potatoes in Idaho (Kleinkopf et al. 1984): N levels are excessive above the upper dotted line, adequate between the two sloping lines, inadequate between the lower sloping line and the horizontal line, and deficient below the bottom horizontal line. Treatments 1 (no N fertiliser), 2 (150 kg N as urea applied early), 3 (300 kg N as urea applied early, 4 (150 kg N as split urea applications), 5 (300 kg N as split urea applications), 6 (150 kg N as slow release fertiliser applied early), 7 (300 kg N as slow release fertiliser applied early), 8 (150 kg N as urea plus foliar applications), 9 (300 kg N as urea plus foliar).

The level of petiole N in the no N treatment would, according to the Idaho recommendations, have been deficient during the trial. There was no difference in petiole N between the slow release fertiliser and the conventional urea fertiliser at either the 150 or 300 kg/ha rate at any sampling. If 300 kgN/ha was applied early adequate petiole N levels (according to Idaho guidelines) were produced, but the 150 kg N/ha application was well into the inadequate range at the start of sampling, and in the deficient range thereafter.

Early and split urea or foliar applications of 150 kg N/ha produced the same petiole nitrate levels. Petiole nitrates from the 300 kg N/ha split urea or foliar applications were not significantly different to the 150 kg N/ha split application level up to the 26 January sampling, but were higher thereafter, although they were still in the deficit range of the Idaho recommendations.

So, according to the petiole nitrate N levels and the Idaho recommendations, this crop, apart from two treatments, was inadequate or deficient in N for the whole trial. Petiole N levels were around 10 000 ppm lower than for Russet

Burbank in a previous trial (Martin 1995a), but tuber yields were 8-11 t/ha higher for equivalent fertiliser levels. This indicates that petiole N levels may need calibration for New Zealand conditions or to take into account other agronomic factors to avoid recommending excess N fertiliser. Timing and method of sampling may also reduce variability between crops (Martin 1995a).

The first sampling was taken on 22 December, and the second on 13 January. If the first samples had been immediately sent away for analysis, it is unlikely, because of the Xmas-New Year close down, that the results would have been available before the second sampling, by which time the petiole nitrate levels in most of the treatments was in the deficient range. A faster means of measuring plant N status at this critical stage of potato growth is, therefore, required. One possibility is the petiole sap test, described by Martin 1995a, although this technique does require careful sampling to produce consistent results (Mackerron et al. 1995).

4.7 *Soil mineral nitrogen*

The changes in soil mineral N are shown in Figure 5. Soil N in the top 30 cm of soil in the no N treatment 1 declined throughout the trial from 96 to 16 kg/ha (based on the assumption that the initial bulk density of 1 remained constant through the course of the trial).

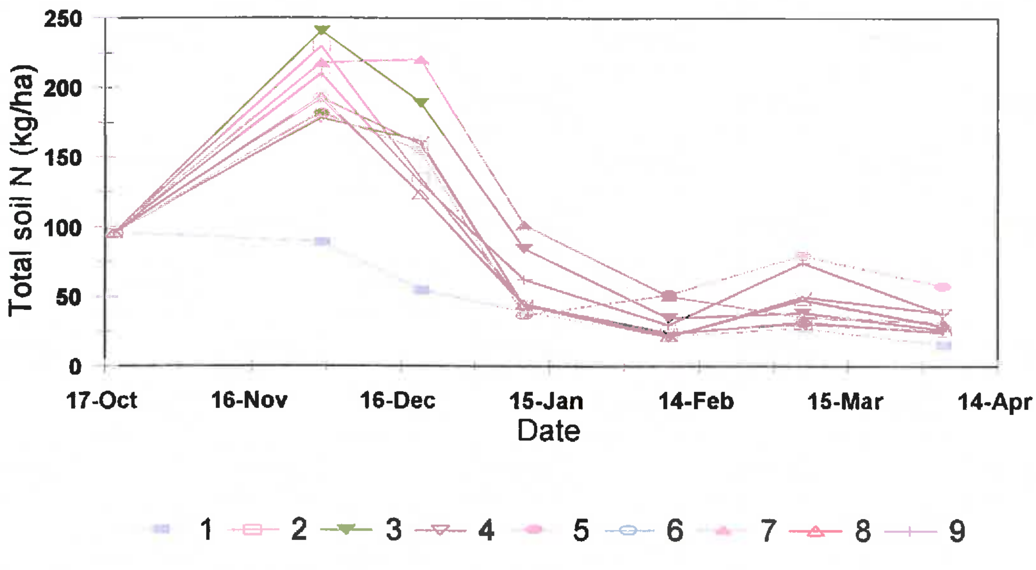

Figure 5: Total KCl extractable soil nitrogen (kg/ha) to a depth of 30 cm at each soil sampling date. Treatments 1 (no N fertiliser), 2 (150 kg N as urea applied early), 3 (300 kg N as urea applied early, 4 (150 kg N as split urea applications), 5 (300 kg N as split urea applications), 6 (150 kg N as slow release fertiliser applied early), 7 (300 kg N as slow release fertiliser applied early), 8 (150 kg N as urea plus foliar applications), 9 (300 kg N as urea plus foliar).

Applying early N fertiliser increased soil mineral N in November and December. However, from 8 February onwards, soil N under these treatments was little different to the no N treatment. The 300 kg N/ha early applications resulted in higher soil mineral N than 150 kg N/ha in November and December, but there was no difference between urea and slow release fertiliser.

At the 30 November sampling, 30% of the soil N in the N fertilised plots was in the ammonium form compared to 9% in the nil N plots. At all subsequent samplings, less than 7% of the soil mineral N was in the ammonium form and there was no consistent difference in the level of soil ammonium between treatments.

Applying urea as split applications did not increase soil mineral N as much as when all of the urea was applied early (by 30 November), but from 8 February onwards there was no difference in soil N in plots to which all urea had been applied early and those receiving split applications. At subsequent samplings plots receiving split applications of N had significantly higher soil N than early N applications.

Applying the split application of N as foliar fertiliser had the same effect on soil N as when it was applied as solid urea.

4.8 *Soil nitrogen balance*

The amount of N mineralised from the soil organic pool during the growth of the crop was calculated from the no N treatments as the maximum N taken up by the crop (148 kg N/ha) minus the change in soil extractable N (68 kg N/ha), i.e. 80 kg N/ha. This, together with any change in soil N plus any N fertiliser applications, was used to calculate the soil N balance. The cumulative change in the soil balance over the course of the trial is shown in Figure 6.

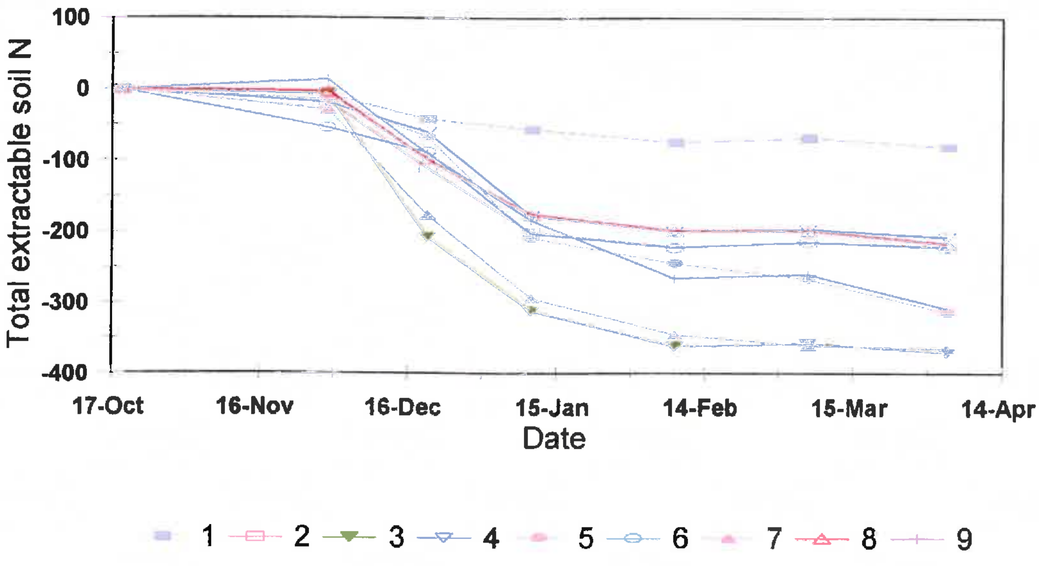

Figure 6: Cumulative change in soil nitrogen balance (kg/ha) to a depth of 30 cm at each soil sampling date. Treatments 1 (no N fertiliser), 2 (150 kg N as urea applied early), 3 (300 kg N as urea applied early, 4 (150 kg N as split urea applications), 5 (300 kg N as split urea applications), 6 (150 kg N as slow release fertiliser applied early), 7 (300 kg N as slow release fertiliser applied early), 8 (150 kg N as urea plus foliar applications), 9 (300 kg N as urea plus foliar).

The loss of N from the N fertiliser treatments will include that lost to the crop, to leaching, or retained in the soil in organic forms not extractable with KCl. There was only a very small difference (288 to 302 kg N/ha) in the overall loss of N from those treatments receiving 150 kg N/ha, irrespective of timing or rate. If 300 kg N/ha was applied early over 100 kg more N/ha was lost than following split applications from 20 December to 6 March, and 56 kg N/ha more was lost by 3 April.

There was little change in soil N up to 30 November, when the crop was moulded, but it then declined rapidly to 8 February. After this there was little further change except in treatments 5 and 9 (the 300 kg split N application), where there was a further decline from 343 kg N/ha on 6 March to 391 kg N/ha on 13 April.

In the treatments where N fertiliser was applied, between 20 and 40% of the soil N was in the ammonium form at 20 November, soon after the fertiliser was applied. However, by 20 December the amount of soil N as ammonium ions decreased to around 5% and changed little thereafter.

In this trial, soil N was measured to a depth of only 30 cm. However, Lesczynski & Tanner (1976) showed that more than 85% of potato roots were in this layer, and Tyler et al. (1983) showed that most soil N after harvest was in the top 30 cm.

4.9 *Crop-soil nitrogen balance*

Plant N status was measured on samples from treatments 1 (0N), 2 (150 kg N as urea applied early), 3 (300 kg N as urea applied early), and 5 (300 kg N planned (275 actual) as urea half applied early and half as split dressings through until March). The total N uptake by these treatments is shown in Figure 7.

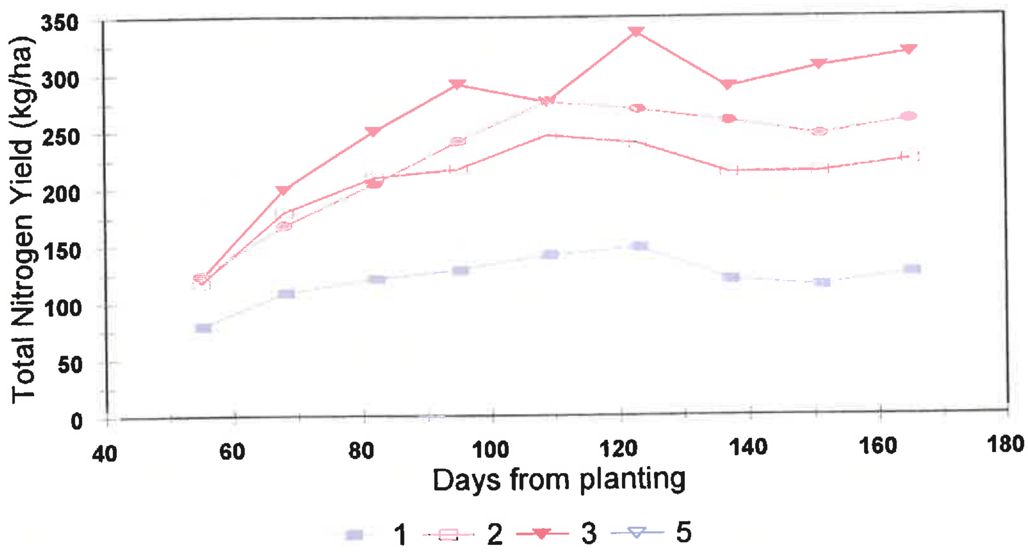

Figure 7: Crop N uptake (t/ha) for all treatments at each plant sampling date. Treatments 1 (no N fertiliser), 2 (150 kg N as urea applied early), 3 (300 kg N as urea applied early, 4 (150 kg N as split urea applications), 5 (300 kg N as split urea applications), 6 (150 kg N as slow release fertiliser applied early), 7 (300 kg N as slow release fertiliser applied early), 8 (150 kg N as urea plus foliar applications), 9 (300 kg N as urea plus foliar).

N uptake changed little in treatment 1 after early January. The rate of N uptake, up to the maximum N uptake, for treatments 3 and 5 was 2.8 kg N/ha/day. This is lower than the 3.5 kg N/ha/day reported by Martin (1995b), but still higher than the 2.4 kg/ha/day regarded as the minimum to prevent N being depleted from the tops and roots during growth (Westermann & Kleinkopf 1985), and also higher than N accumulation rates in Britain (Harris 1978).

Table 7 gives the soil-plant N balance when the N content in the plant (Figure 7) was highest. When total N in the plants that received no N fertiliser was maximal, they contained 148 kg N/ha, and the soil contained 25 kg N/ha. The initial soil N at planting was 96 kg N/ha, and the remaining 77 kg N/ha must have come from mineralisation of soil organic N. We assumed that the rate of mineralisation was consistent between treatments, irrespective of fertiliser application, and that this amount of mineralised N was available to the plants, in addition to any fertiliser added.

Table 7: Total plant N and extractable soil N levels, the recovery of applied N fertiliser (kg N/ha) and N use efficiency calculated when the N level in the plant was at a maximum (assuming N mineralisation was the same under all N treatments).

Treatment no.			1	2	3	5
Fertiliser treatment			nil	150 early	300 early	300 split
Date of maximum N in plant			21 Feb	7 Feb	21 Feb	7 Feb
Maximum N in plant	(a)		148	247	336	276
N in soil (average of 2 closest samplings)	(b)		25	28	37	66
Fertiliser N applied before max plant N	(c)		0	150	300	250
N in soil and plant	(d)	(a+b)	173	275	373	342
N supply from soil	(e)	(d)0N	173	173	173	173
N supply from fertiliser left in soil	(f)	(d)-(e)	0	102	200	169
Fertiliser N left in soil	(g)	(b)-(b)0N	0	3	12	41
Fertiliser N in plant	(h)	(f)-(g)	-	99	188	128
Fertiliser N 'lost' from system	(i)	(c)-(f)	-	48	100	81
Fertiliser N in soil as % N applied	(j)	100(g)/(c)	-	2	4	16
Fertiliser N in plant as % N applied	(k)	100(h)/(c)	-	66	63	51
Fertiliser N 'lost' from system as % N applied	(l)	100(i)/(c)	-	32	33	32
Mean final yield (t/ha)	(k)		59.2	73.4	85.2	74.9
Kg N uptake/tonne tubers	(m)	(a)/(k)	2.5	3.37	3.94	3.68

Adding 150 kg N/ha early (treatment 2) increased crop N by 99 kg/ha, 300 kg N/ha early (treatment 3) increased crop N by 188 kg/ha, and 300 kg N/ha split (treatment 5) increased crop N by 128 kg/ha, a result of both increased crop biomass and increased crop N content (data not presented). Little fertiliser N was left on the soil in treatments 2 (2%) and 3 (4%), but 16% of the fertiliser N applied to treatment 5 was left in the soil.

Two-thirds of the fertiliser N applied to treatments 2 and 3 was taken up by the plant, whereas only half of that applied to treatment 5 was taken up. Westermann et al. (1988) had fertiliser recoveries of 60-80%, but Tyler et al. (1983) reported recoveries as low as 39%. Martin (1995b) had fertiliser N recoveries of 58% for 150 kg N/ha and 74% for 300 kg N/ha.

Some 48 kg N was unaccounted for by soil and plant N in treatment 2, 100 kg N/ha in treatment 3, and 81 kg N/ha in treatment 5. These amounts are around 25% higher than for the same fertiliser application rates in the trial reported in Martin (1995b). Part of the reason for the greater N loss in this trial may have been leaching resulting from the 165 mm of water received by the crop over 3 weeks from 13 December to 4 January.

In this trial, the maximum amount of N taken up by the crop for each tonne of tubers produced increased from 2.5 kg N/ha/tonne for treatment 1 to 3.9 kg N/ha/tonne for treatment 3 (Table 6), very similar to other results with Russet Burbank (Kleinkopf et al. 1981; Martin 1995b). So the N use efficiency declined with the addition of fertiliser N by up to 60%.

All the N had effectively been taken up by the crop by February, and coincided with the end of tuber bulking. There was also no change in tuber N content after February. Using ^{15}N, Millard et al. (1989) found that all N taken up by the crop initially goes to the tops, and is then translocated to the tubers. So, to have any effect on growth and yield, any N application needs to be applied well in advance of this time. Ojala et al. (1990) recommended that N uptake should be completed two to three weeks before the start of canopy senescence, which in this trial was mid-January.

4.10 *Prediction of plant N uptake*

Mackerron et al. (1994) claim that total plant N uptake is a more reliable method of predicting plant N requirements than petiole nitrate. They used near infrared reflectometry (NIR) techniques to measure plant N, which is quick and simple, once successfully calibrated. In treatments 1, 2, 3 and 5 of this trial and equivalent treatments in Martin (1995b), plant N uptake was closely related to final yield (Figure 8).

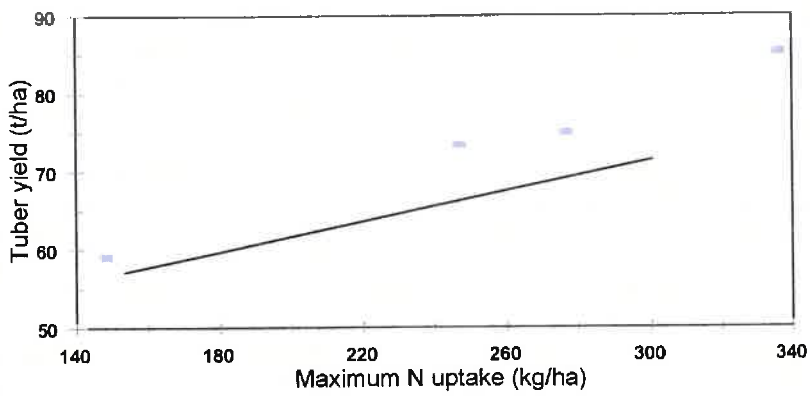

Figure 8: Mean final tuber yield (t/ha) v maximum N uptake (kg/ha) for treatments 1 (no N fertiliser), 2 (150 kg N as urea applied early), 3 (300 kg N as urea applied early, and 5 (300 kg N as split urea applications). Solid line is the regression line (R^2=99%) for previous data from Martin (1995b).

Mackerron et al. (1994) claim that, for any cultivar, there is a stable relationship between plant N uptake and the fresh weight of the whole plant, which can be shifted from one level to another by applications of N fertiliser.

When we applied this to the data for treatments 1, 2, 3 and 5 we found that there were close linear relationships between N content of the whole plant and the plant fresh weight (R^2=91%), and the slope depended on the rate and timing of the N application (Figure 9). Mackerron et al. (1994) claimed that when the slopes of the regression lines in Figure 9 are plotted against total N uptake, there is a linear relationship, which can be used to predict how much supplementary N needs to be applied to achieve a certain yield, provided the N content of the crop at harvest is known. For this trial this relationship is plotted in Figure 10.

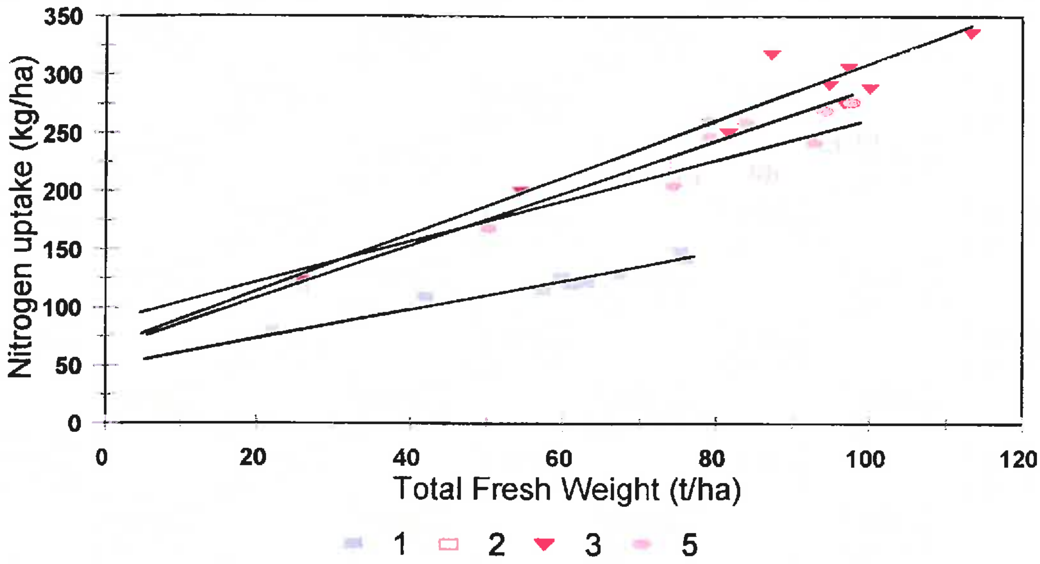

Figure 9: Crop nitrogen uptake (kg/ha) plotted against total fresh weight (including tubers) (t/ha) for treatments 1 (no N fertiliser), 2 (150 kg N as urea applied early), 3 (300 kg N as urea applied early), and 5 (300 kg N as split urea applications). Slope of the regression lines are treatment 1: 1.14, treatment 2: 1.59, treatment 3: 2.37, and treatment 5: 2.09.

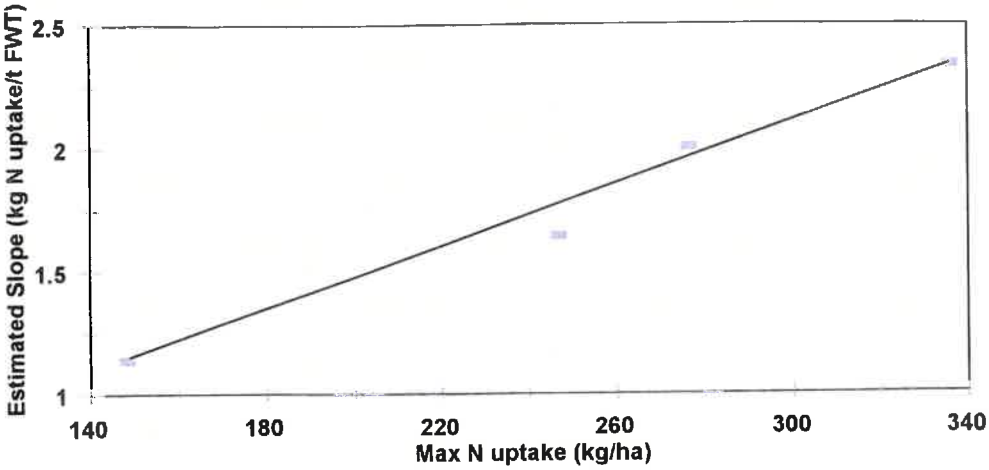

Figure 10: Mean concentration of N in the plant (the slopes from Figure 13) plotted against maximum N content in the plant for treatments 1 (no N fertiliser), 2 (150 kg N as urea applied early), 3 (300 kg N as urea applied early), and 5 (300 kg N as split urea applications). Slope of the regression line = 0.00678.

In order for these relationships to be of value, they must hold for different sites and years. The closest comparison that can be made for Russet Burbank potatoes with comparable fertiliser applications in New Zealand is with the results of Martin (1995b), who did not measure total fresh weight, but did measure total dry weight. When total N uptake is plotted against total plant dry weight for treatments receiving no N fertiliser and those receiving N fertiliser (Figure 11), the relationship between biomass and N uptake was close for the two years when no N fertiliser was applied. However, there were very different relationships for the treatments that did receive N fertiliser between the two years; this trial had a much higher N uptake at a given biomass than that of Martin (1995b).

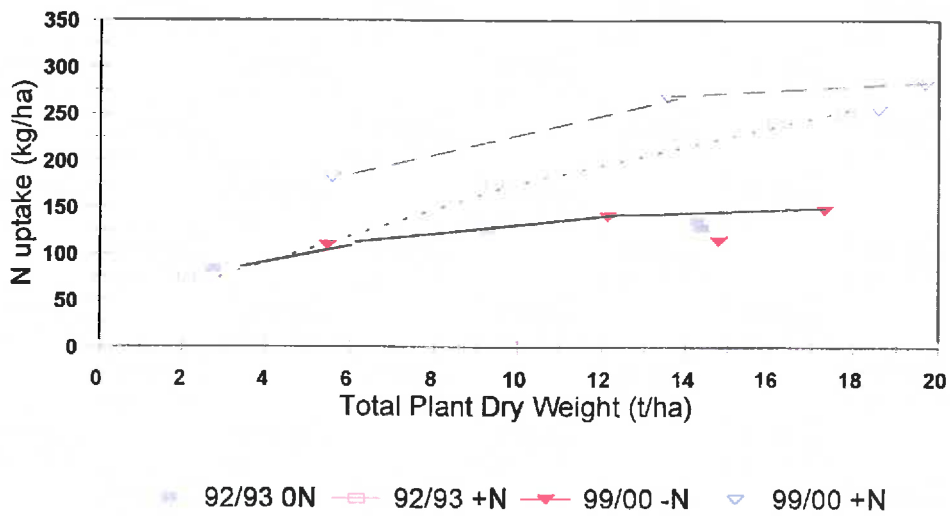

Figure 11: Crop nitrogen uptake (kg/ha) plotted against total dry weight (including tubers) (t/ha) for no N fertiliser (treatment 1) and applied N fertiliser (mean of treatments 2, 3, and 5) for this trial (1998-99), together with the equivalent fertiliser treatments from Martin (1995b) (1992-93). Solid line = 0N (both sites), dotted line = +N (1999-2000), hatched line = +N (1992-93).

This suggests that using the relationship between N uptake and total biomass to predict plant N requirements has the same limitations as the petiole nitrate test in that other seasonal or agronomic factors will affect the relationship (Allison et al. 1999), and there is still the problem of translating these relationships into final yield.

11 *Other possible predictors of yield*

Another possible indicator of plant N requirement is leaf area index, which is the area of leaf per unit area of ground. Allison et al. (1999) showed that there is a linear relationship between leaf area and plant N uptake, and this is supported by our results (Figure 12). Vos & van der Putten (1998) showed that leaf size in potato is very responsive to N supply due to an effect on leaf expansion rate.

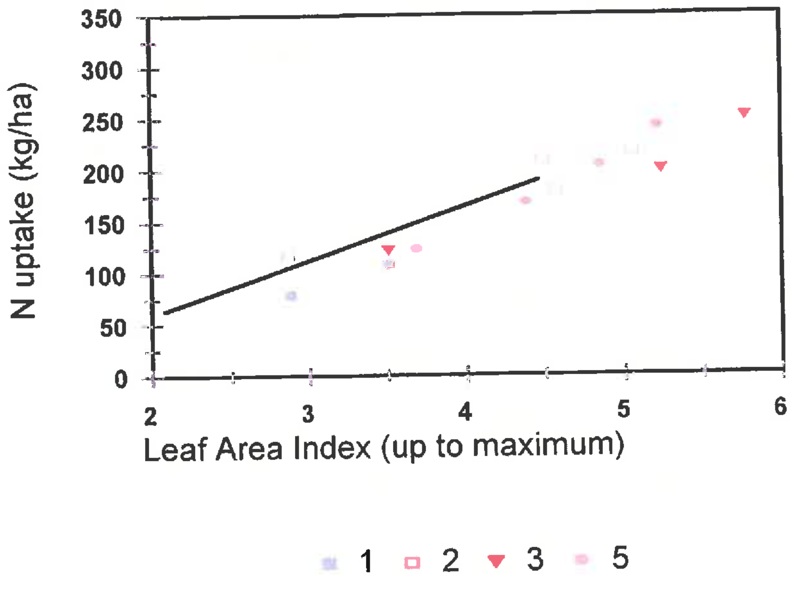

Figure 12: Leaf area index v. N uptake (kg/ha) for treatments 1 (no N fertiliser), 2 (150 kg N as urea applied early), 3 (300 kg N as urea applied early, and 5 (300 kg N as split urea applications) up to the maximum leaf area index for each treatment. Solid line is the regression line (R^2=98%) for previous data from Martin (1995b).

The relationship between leaf area index and N requirement may need to be calibrated for different cultivars, soil types and agronomic practices, and may also be affected by growing conditions, such as temperature (Allison et al. 1999). However, there was a very similar relationship between N uptake and leaf area index between this trial and a previous trial (Martin 1995b). Also, comparing both trials, maximum leaf area index was closely related to final yield (Figure 13), indicating that this approach has promise.

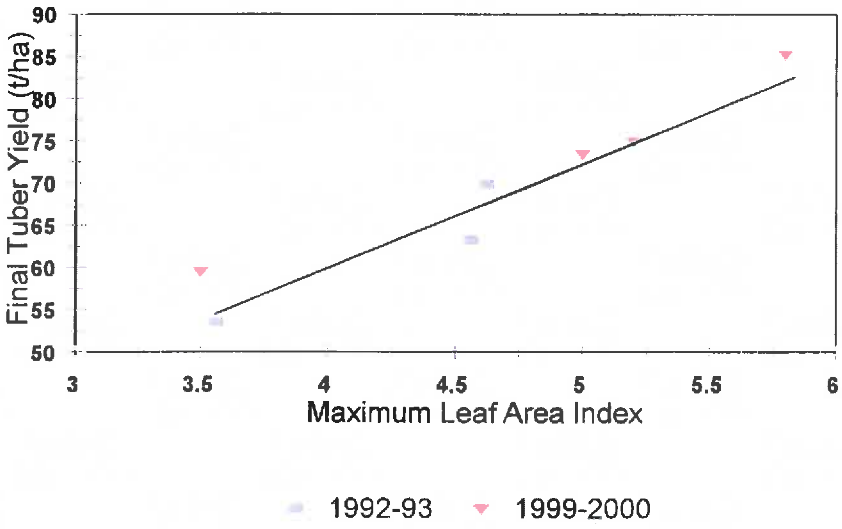

Figure 13: Final yield (t/ha) v. leaf area index for 1992-93 (data from Martin, 1995b) and this trial. Points represent different N treatments. Slope of the regression line is 12.2 (R^2=0.92).

Leaf area index can easily be measured in the field, but the equipment is expensive. However, consultants could use that equipment in the same way they schedule irrigation using the neutron probe. More easily measured possible proxies for leaf area index could include crop height, % ground cover, and date of canopy closure, and trials could indicate target times for, say, when a certain canopy height or ground cover should be achieved. Maximum leaf area indices were achieved in mid-January in all treatments in both trials, indicating that any N applications to increase and maintain leaf area index would have to be applied before then.

5 Conclusions

The slow release (Nimin coated urea) was no different to conventional urea in its effect on soil N, leaf area development, or tuber growth and yield. This product, as supplied, was therefore ineffective in supplying N more effectively to the plants. It is not known if the same result would have been obtained from a heavier coating or a different formulation of this product, or the use of another slow release coating, but ideally a slow release fertiliser would need to be able to supply N at a rate to maximise leaf area index without losses to leaching occurring.

Splitting the urea fertiliser application slowed and reduced the amount of extractable N in the soil, both during and at the end of the trial. However, yields were reduced by 5 t/ha. Although 25 kg less N/ha was applied to the split application (treatment 5) than to the early application (treatment 3), this missed application was probably too late to affect N uptake and yield. It is more likely that the loss in yield was because a number of the N applications were applied after tuber bulking had finished.

The foliar fertiliser (SupaN32) had no advantage over conventional split urea applications on soil N, leaf area development, or tuber growth and yield. Although 25 kg less N/ha was applied to the foliar application treatment 9 than to the split urea application treatment 5, this missed application was probably also too late to affect N uptake and yield.

These results suggest that current recommendations for split and foliar applications should be altered so that all the fertiliser is added before the tops start to senesce and while the tubers are bulking in order to maximise tuber yield while minimising the risk of increased N leaching. In the case of this trial, this would have been before the end of January.

Both the petiole test and the total plant N uptake test were difficult to translate into the amount of N required by the crop or to use to predict final yield. A alternative may be to use leaf area index as a method of predicting plant N requirements and final yield.

6 Acknowledgments

This work was funded by the Potato Industry Research & Development Grants Committee, Ravensdown Fertiliser Co-operative Limited, and the Public Good Science Fund.

We acknowledge the assistance of Myles Rea, Emma Griffiths, and Charles Wright in carrying out this trial.

7 References

Allison, M.F.; Allen, E.J.; Fowler, J.H. 1999: The nutrition of the potato crop. British Potato Council Research Report 807/182. 92 p. (Available at Http:/www.potato.org.uk)

Arable Farming January 20 1998. Fertiliser additive - yield and quality booster? Pp. 30-31.

Gardner, B.R.; Jones, B.R. 1975: Petiole analysis and the nitrogen fertilization of Russet Burbank potatoes. *American Potato Journal 52:* 195-200.

Harris, P.M. 1978: The potato crop: the scientific basis for improvement. London, Chapman Hall.

Kleinkopf, G.E.; Westermann, D.T.; Dwelle, R.B. 1981: Dry matter production and nitrogen utilization by six potato cultivars. *Agronomy Journal 73:* 799-802.

Kleinkopf, G.E.; Kleinschmidt, G.D.; Westermann, D.T. 1984: Tissue analysis: a guide to nitrogen fertilization for Russet Burbank potatoes. *University of Idaho College of Agriculture Current Information Series No. 743.* 3 p.

Lesczynski, D.B.; Tanner, C.B. 1976: Seasonal variation of root distribution of irrigated, field-grown Russet Burbank potato. *American Potato Journal 53:* 69-78.

Mackerron, D.K.L.; Waister. P.D. 1985: A simple model of potato growth and yield. Part I. Model development and sensitivity analysis. *Agricultural and Forest Meteorology 34:* 241-252.

Mackerron, D.K.L.; Young, M.W.; Davies, H.V. 1994: Strategies for optimising nitrogen fertilisation of potato. Http://www.sac.ac.uk/spud/external/Prof/research/scri/ar9477.htm.

Mackerron, D.K.L.; Young, M.W.; Davies, H.V. 1995: A critical assessment of the value of petiole sap analysis in optimizing the nitrogen nutrition of the potato crop. *Plant and Soil 172:* 247-260.

Martin, R.J. 1995a: Evaluation of rapid field methods for determining the nitrogen status of potato crops. *Proceedings of the Agronomy Society of New Zealand 25:* 91-95.

Martin, R.J. 1995b: The effect of nitrogen fertiliser on the recovery of nitrogen by a potato crop. *Proceedings of the Agronomy Society of New Zealand 25:* 97-104.

Millard, P.; Robinson, D.; Mackie-Dawson 1989: Nitrogen partitioning within the potato (*Solanum tuberosum* L.) plant in relation to nitrogen supply. *Annals of Botany 63:* 289-296.

Ojala, J.; Painter, C.G.; Augustin, J. 1976: The effect of soil moisture and nitrogen on yield and quality of the Russet Burbank potato. *American Potato Journal 53:* 275-284.

Rourke, R.V. 1985: Soil solution levels of nitrate in a potato-buckwheat rotation. *American Potato Journal 62:* 1-8.

Sylvester-Bradley, R.; Chambers, B.J. 1992: The implications of restricting fertiliser nitrogen for the productivity of arable crops, their profitability and potential pollution by nitrate. *Aspects of Applied Biology 30:* 85-94.

Tyler, K.B.; Broadbent, F.E.; Bishop, J.C. 1983: Efficiency of nitrogen uptake by potatoes. *American Potato Journal 60:* 261-269.

Vos, J.; van der Putten, P.E.L. 1998: Effect of nitrogen supply on leaf growth, leaf nitrogen economy and photosynthetic capacity in potato. *Field Crops Research 59:* 63-72.

Westermann, D.T.; Kleinkopf, G.E. 1985: Nitrogen requirements of potatoes. *Agronomy Journal 77:* 616-621.