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Effect of the timing and rate of nitrogen fertilization on the growth and recovery of fertilizer nitrogen within the potato (*Solanum tuberosum* L.) crop

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Abstract

The effect of the timing of N fertilizer application on the uptake and partitioning of N within the crop and the yield of tubers has been studied in two experiments. In 1985 either none, 8 or 12 $g\,N\,m^{-2}$ was applied and in 1986 none, 12 or 18 $g\,N\,m^{-2}$. Fertilizer N was applied either at planting, around the time of tuber initiation or half at planting and the remainder in four foliar sprays of urea during tuber bulking. ^{15}N-labelled fertilizer was applied to measure the recovery of fertilizer N in the crops.

There was an apparent pre-emergence loss of nitrate from the soil when N was applied at planting in 1986, thereby reducing the efficiency of fertilizer use. Applying the N at tuber initiation delayed and reduced the accumulation of N in the canopy compared with crops receiving all their fertilizer at planting. Foliar sprays of urea slightly increased both tuber yields and tuber N contents when compared to a single application at planting. The proportion of the fertilizer N recovered in the crop was little affected by the rate of N application, but a greater proportion of foliar-applied N was recovered than N broadcast at planting, due partly to pre-emergence losses of nitrate in 1986. It is suggested that late applications of N was foliar sprays can be of benefit to crops with a long growing season and reduce environmental losses of N.

Introduction

There is a linear relationship between the amount of radiation intercepted by the potato crop and both total and tuber dry matter yields [10, 20]. Yield increases in response to nitrogen (N) application are due mainly to increases in radiation interception both by increased leaf area and by prolonged duration, while the efficiency of the conversion of intercepted light to dry matter is little affected [8, 13]. The maintenance of an effective canopy cover late on in the season during tuber bulking depends upon the growth of lateral branches, while main stem leaves senesce. Nitrogen fertilization stimulates the growth of lateral branches [12, 14] thereby increasing late-season light interception.

Foliar sprays of urea provide a means of fertilizing the crop late on in the season and can increase tuber yields [2, 9]. The present investigation studies the effect of the timing of N supply on N partitioning and tuber yields. Fertilizer N was applied at either planting, tuber initiation or split between planting and foliar sprays of urea during tuber bulking. In order to measure the efficiency of recovery of fertilizer N in the crop, ^{15}N-labelled fertilizer was applied at either planting or as foliar sprays.

Materials and methods

Design and husbandry

Solanum tuberosum L. cv Maris Piper was grown at Wartle, Aberdeenshire in 1985 and 1986 on a freely-drained till derived from basic igneous material (Insch series). Crops were grown in adjacent fields in the two years, which had grown winter barley for the preceding six years. Seven N treatments were randomised in blocks with four replicates in both years. Plots were 81 m^2 (12 × 6.75 m) and had nine rows, each 0.75 m wide with guard rows between the rows used for growth analysis and at either side of the plot. In addition, each plot contained a single row for use as a ^{15}N subplot (total area 12 × 0.75 m = 9 m^2), where appropriate. Plots were fertilized with 8.7 g P m^{-2} and 16.7 g K m^{-2} as potassic superphosphate before ridging. Weeds were controlled by a pre-emergence spray of paraquat and blight and aphid infestation by regular sprays thoughout the experiments. The crops were not irrigated in either year.

Nitrogen applications

Crops were fertilized with either no N, 8 or 12 g N m^{-2} in 1985 or none, 12 or 18 g N m^{-2} in 1986. Applications of N fertilizer were given either at planting (immediately before ridging), at tuber initiation or split, with half applied at planting and the remainder supplied in four foliar sprays of urea given throughout tuber bulking. The N applied to plots receiving all the fertilizer at planting was labelled with ^{15}N, as was the urea applied to plots receiving foliar sprays.

Nitrogen was applied at planting as calcium nitrate on 12 April 1985 and ammonium nitrate on 16 April 1986. Different fertilizers were used in the two years since in 1986 the only available ^{15}N-labelled form was ammonium nitrate. During application, the ^{15}N subplot in each plot was covered and then a solution of either $Ca^{15}NO_3$ or $^{15}NH_4{}^{15}NO_3$ was sprayed onto the soil surface using hand sprayers. ^{15}N was used to distinguish fertilizer N from N derived from the mineralization of native soil organic N [19]. Prior calibration of the sprayers allowed a uniform application of solution to give the appropriate rate of application of N. The N applied was enriched to 1.15 atom % ^{15}N.

The crops emerged on 17 June in 1985 and 15 June in 1986; all subsequent dates will be referred to as the number of days from 50% emergence (DAE). Treatments receiving N fertilizer around the time of tuber initiation were fertilized 31 and 33 DAE in 1985 and 1986 respectively. Foliar sprays of urea were applied as a 15% (w/v) solution of urea to plots which had not received ^{15}N-labelled fertilizer at planting. At each application the volume of solution required to give the appropriate rate of N application was sprayed uniformly over the plots while the ^{15}N subplots were covered by an absorbant cloth. The subplots were then sprayed with a ^{15}N urea solution enriched to 1.2 atom % ^{15}N. Four equal foliar sprays of urea were applied 30, 51, 64 and 78 DAE in 1985 and 46, 60, 72 and 86 DAE in 1986.

Soil sampling

Soil samples were collected before the crop was planted and throughout the season from plots which had received fertilizer N at planting, using an auger with a 150 mm long screw. After crop emergence, 20 soil samples (to give 500 g in total) were collected immediately following the harvesting of plants from each plot, to a depth of 150 mm measured from the base of the ridge. The soil was sieved to pass through a 2 mm mesh and 10 g subsamples were taken for determination of their moisture content. The remainder was stored overnight in sealed polyethylene bags at 2°C prior to their analysis.

Plant sampling

Each plot was divided into eight sampling areas consisting of 2.0 m of two adjacent experimental rows, leaving a discard area of one row on either side of the experimental rows and at least two discard plants in each row between subplots. At each harvest a subplot was selected randomly from each plot and all the plants (typically 12) counted and lifted with a hand fork. Plants were weighed and subsampled to provide tuber, stem and leaf material for analysis, as described [13]. The ^{15}N subplots were sampled by lifting three adjacent plants chosen randomly from within the subplot, leaving at least two guard plants between successive samples. The ^{15}N contents of adjacent plants were not checked as they were not used for measurements of N uptake. Plants from the ^{15}N subplots were separated into their component tissues and subsampled as described above. When harvests coincided with the application of foliar urea sprays, plants were harvested before the urea was applied.

Chemical analysis

A 10 g subsample of sieved soil was extracted in 2.0 M KCl solution (soil:solution ratio 1:5) and then recovered from the filtered extracts after reduction to ammonium and steam distillation [11]. The distillates were evaporated to dryness at 70°C in an ammonia free atmosphere. The dry ammonium sulphate was dissolved in 50 μl of 0.01 M H_2SO_4 and 5 μl aliquots analysed for total N and ^{15}N using an ANA-SIRA mass spectrometer (VG Isogas, Middlewich, Cheshire, UK).

Total N in plant samples was measured by an automated micro-Kjeldahl method [5] using salicyclic acid-thiosulphate reduction of nitrate-N. The ^{15}N content of plant material was measured using the ANA-SIRA mass spectrometer. The weight of ^{15}N in a tissue derived from the fertilizer was calculated as described previously [14].

Rainfall

Rainfall was recorded using a tipping-bucket gauge located at a site 4 km from that used for these experiments, see [19].

Results

Soil nitrate dynamics

Throughout 1985 there was no significant difference in the concentration of nitrate recovered from the soil beneath crops fertilized with either 8 or 12 g N/m^2 at planting (Table 1). There was an overall decline in soil nitrate concentrations during the growth of the crop in both treatments. This trend was repeated in 1986, but the concentrations measured were usually lower than in the previous year. The lower soil nitrate concentration in 1986 may be due to there being less nitrate-N added as fertilizer when applied as ammonium nitrate, and ammonium-N being more liable to microbiological immobilization. However, during 1986 there were statistically significant ($P < 0.05$) increases in soil nitrate levels when fertilizer inputs were increased from 12 to 18 g N m^{-2}, these differences being found in the middle of the growing season between 34 and 72 DAE.

Only 0.65 g N m^{-2} was present in the soil as nitrate in 1985 before planting. Application of 8 or 12 g nitrate-N m^{-2} could have produced concentrations of up to 8.6 and 12.6 g nitrate-N m^{-2}, respectively assuming an instantaneous incorporation of the fertilizer into the soil nitrate pool and that there was no 'added nitrogen interaction' between fertilizer and soil nitrate [21]. In the absence of soil samples collected prior to emergence, making these assumptions allows an estimate of the apparent net 'losses' of nitrate from the seed bed between planting and emergence to be made. Only apparent losses could be estimated as no collections of drainage water were made to assess leaching losses, and measurements of denitrification or the mineralization-immobilization turnover of soil N were not made. At the time of the first harvest in 1985, 24 DAE, some 10.5 g N m^{-2} was measured in the soil as nitrate, implying net changes in the

Table 1. Soil nitrate (g N m^{-2}) recovered from beneath crops receiving 8 or 12 g N m^{-2} at planting in 1985, and 12 or 18 g N m^{-2} at planting in 1986

Date (DAE)	1985 8 g N m^{-2}	12 g N m^{-2}	Date (DAE)	1986 12 g N m^{-2}	18 g N m^{-2}
−55*	0.6(0.11	0.6(0.11)	−43*	1.3(0.22)	1.3(0.01)
24	10.5(0.69)	10.8(0.84)	−36*	5.0(0.22)	9.4(0.47)
37	6.1(0.62)	5.9(0.12)	19	3.8(0.11)	3.8(0.74)
51	8.1(0.52)	7.0(0.27)	34	1.8(0.10)	2.4(0.35)
64	6.1(0.59)	6.6(0.30)	46	2.3(0.49)	5.5(0.94)
78	6.5(0.84)	7.4(0.78)	60	1.9(0.29)	3.9(0.69)
92	3.0(0.01)	3.2(0.12)	72	0.8(0.14)	1.9(0.56)
106	3.2(0.12)	3.4(0.16)	86	1.4(0.11)	1.2(0.22)
			103	1.6(0.99)	2.5(0.32)

Values are the mean (and standard error) of four replicates.
* Samples taken pre emergence

treatments receiving 8 or 12 g N m^{-2} of about +1.9 and −2.1 g N m^{-2}, respectively. These amounts are small and it can be assumed that any losses of nitrate from the soil before emergence were negligible.

Greater apparent losses of nitrate were detected in 1986. A more reliable assessment of these losses was possible than in 1985, since soil samples were collected after planting and prior to crop emergence. Maximal concentrations of nitrate before emergence were 5.0 ± 0.22 and 9.4 ± 0.47 g N m^{-2} in treatments receiving 6 and 9 g nitrate-N m^{-2}, respectively since half of the N applied in each treatment was ammonium-N. By the time of the first sampling post emergence (19 DAE), these concentrations had decreased by 1.2 and 5.6 g N/m^2 for the treatments receiving 6 and 9 g nitrate-N m^{-2} respectively (Table 1). Therefore, there were apparent losses of 20% and 62% of the respective application rates of nitrate-N despite the fertilizer N being applied as ammonium nitrate in 1986, as opposed to calcium nitrate in 1985.

Uptake and recovery of fertilizer nitrogen

When N fertilizer was applied at planting, the pattern of N uptake throughout the season was similar to that reported previously [7, 13]. Initially N was taken up into the canopy (Fig. 1), but the rate of N uptake by the crops decreased substantially after 37 DAE in 1985 and 46 DAE in 1986 (Fig. 2). Thereafter there was a loss of N from the canopy due to the retranslocation of N to the growing tubers, and leaf abscission during canopy senescence (Fig. 1). Withholding all the fertilizer N until tuber initiation, 31 or 33 DAE, reduced the N uptake by the canopy during the first half of the growing season in both years (Fig. 1). Compared with the crops receiving fertilizer N at planting, the maximum N content of the canopy was measured later on in the season and the N content of the whole crop was significantly ($P < 0.05$) less until 64 DAE in 1985 and 72 DAE in 1986 when N fertilizer was withheld until tuber initiation.

The application of ^{15}N-labelled fertilizer at planting or as foliar sprays allowed the apparent recovery of fertilizer N within the crops to be calculated. Recovery is used here to mean the amount of fertilizer N (as indicated by ^{15}N) measured in the harvested plants compared with the amount of fertilizer applied. Because of the possibility of 'added nitrogen interactions' [21], the true recovery of N can not be determined, and our values represent the apparent recovery of N [21]. When the N was applied at planting the recovery of fertilizer N was a lower proportion of the total crop N content in 1986 than 1985. After the initial rapid uptake of N, 37 DAE in 1985 and 46 DAE in 1986, fertilizer N accounted for 17% and 30% of crop N, for applications of 12 and 18 g N m^{-2} in 1986, compared with 49 and 55% for fertilizer with 8 and 12 g N m^{-2} respectively in 1985. After 37 DAE in 1985 there was no further uptake of fertilizer N, although the N content of the crop continued to increase. In contrast, fertilizer N uptake in 1986 continued for as long as the N content of the crop increased (Fig. 2).

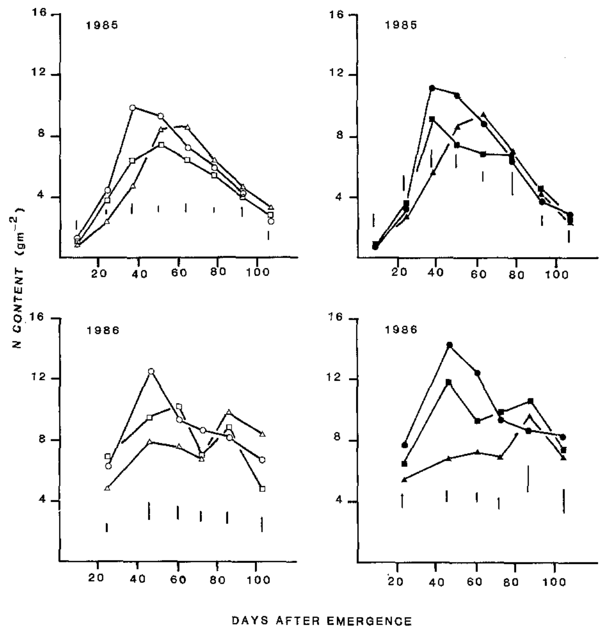

Fig. 1. The effect of the timing and rate of N application on the N content of the canopy. Data are the means of four replicates for crops growing with 8 g N m^{-2} (open symbols) and 12 g N m^{-2} (closed symbols) in 1985, and 12 g N m^{-2} (open symbols) and 18 g N m^{-2} (closed symbols) in 1986, applied either at planting (○), at tuber initiation (△) or half at planting and the remainder in a foliar spray of urea during tuber bulking (□). Bars represent the standard error of the difference between means (9DF).

Recovery of foliar applied N was less in 1986 than in the previous year, as well as that applied at planting (Table 2). The recovery in the whole plant

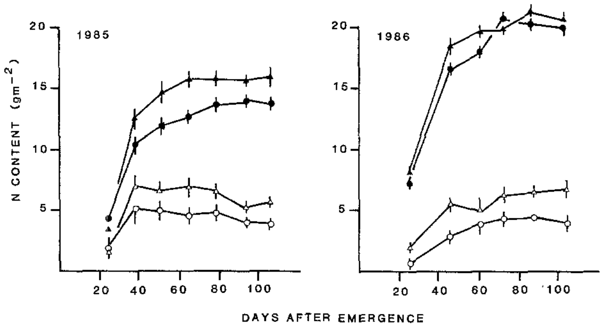

Fig. 2. The N content (closed symbols) and recovery of fertilizer N (open symbols) in the total crop when receiving 8 g N m^{-2} (○) or 12 g N m^{-2} (△) at planting in 1985 and 12 g N m^{-2} (○) and 18 g N m^{-2} (△) at planting in 1986. Data are the mean (and standard errors) of four replicates.

of 6 g N m^{-2} applied as a foliar spray was 52% in 1985, compared with only 36% in 1986. However, in both years the proportion of the foliar applied N recovered was greater than that of the soil application. The proportion of the fertilizer N in the crop that was recovered in the tubers was not affected by the mode of application. Increasing the amount of N fertilizer applied, either at planting or as foliar sprays, had no significant effect on the proportion of fertilizer recovered in the crop, except for those foliar sprays applied in 1985 (Table 2). This suggests that any 'added nitrogen' interactions such as isotope exchange between soil and fertilizer N pools was negligible, since the percentage recoveries of soil-applied fertilizer and that applied to foliage were similar. Recovery of the foliar fertilizer fell from 70% to 52% by increasing the rate of application from 4 to 6 g N m^{-2} in 1985.

Tuber yields and nitrogen contents

Application of up to 12 g N m^{-2} significantly ($P < 0.05$) increased the fresh yield of tubers at the final harvest in both years (Table 3). Although increasing the N supply from 12 to 18 g N m^{-2} in 1986 increased tuber yields, the differences were not statistically significant. Delaying the application of N until tuber initiation decreased the yield of tubers in both years, except when 8 g N m^{-2} was applied in 1985. In contrast, supplying half the fertilizer N as foliar sprays of urea increased tuber yields in both years, giving a significant increase ($P < 0.05$) when 8 g N m^{-2} was applied in 1985, compared with applying all the N at planting. The pattern of N application also changed the N content of the tubers at the final harvest. Fertilization with N at tuber initiation decreased the N contents of tubers in both years, although these changes were not statistically significant. Applying half the fertilizer as foliar sprays increased both the concentration and contents of tuber N. In 1986 the concentration of tuber N rose from 1.19% to 1.23% and 1.4% to 1.63% of the dry matter when application of 12 and 18 g N m^{-2}, respectively, was split between planting and foliar sprays.

Discussion

The sites on which the experiments were conducted were very fertile. This is indicated by the low apparent recovery of fertilizer N in the crops, the small yield responses obtained by increasing fertilizer inputs and the high concentrations of nitrate in the soil before planting. The progressive, if variable, decline in soil nitrate concentration during the growth of a crop has been well documented for many arable crops, including the potato [1]. The potential extent of the decline before crop emergence has, in contrast, not been fully appreciated. While no such decline occurred in 1985, it was

Table 2. The effect of the timing and rate of N application on the recovery of fetilizer N (g m^{-2}) in the tubers and whole crop at the final harvests, 106 DAE in 1985 and 103 DAE in 1986

	1985		1986	
Application of ^{15}N fertiliser	Tuber	Total	Tuber	Total
8 g N m^{-2} at planting	3.3(0.20)	3.9(0.24)	–	–
12 g N m^{-2} at planting	4.6(0.47)	5.6(0.42)	2.9(0.15)	6.6(0.88)
18 g N m^{-2} at planting	–	–	4.1(0.53)	6.6(0.88)
4 g N m^{-2} foliar spray	2.4(0.21)	2.8(0.28)	–	–
6 g N m^{-2} foliar spray	2.5(0.23)	3.1(0.25)	1.5(0.11)	2.1(0.15)
9 g N m^{-2} foliar spray	–	–	2.4(0.14)	3.8(0.09)

Values are the mean (and standard error) of four replicates.

Table 3. The effect of the timing and rate of N application on the yield of fresh tubers ($kg\,m^{-2}$) and their N contents ($g\,m^{-2}$) at the final harvest, 106 DAE in 1985 and 103 DAE in 1986

Treatment	1985 Yield	1985 N content	1986 Yield	1986 N content
No N applied	4.8	8.7	5.0	9.0
$8\,g\,N\,m^{-2}$ at planting	5.7	11.7	–	–
$12\,g\,N\,m^{-2}$ at planting	6.6	13.8	6.1	13.0
$18\,g\,N\,m^{-2}$ at planting	–	–	6.5	15.1
$8\,g\,N\,m^{-2}$ at tuber initiation	6.0	10.9	–	–
$12\,g\,N\,m^{-2}$ at tuber initiation	6.3	13.0	5.7	11.2
$18\,g\,N\,m^{-2}$ at tuber initiation	–	–	6.1	13.9
$4\,g\,N\,m^{-2}$ at planting + $4\,g\,N\,m^{-2}$ as foliar spray	6.3	12.6	–	–
$6\,g\,N\,m^{-2}$ at planting + $6\,g\,N\,m^{-2}$ as foliar spray	6.8	15.6	6.2	14.2
$9\,g\,N\,m^{-2}$ at planting + $9\,g\,N\,m^{-2}$ as foliar spray	–	–	6.6	17.4
SE (18 df)	0.26	1.21	0.24	1.11

substantial in 1986 and probably contributed to the lower proportion of fertilizer recovered in the crops compared with 1985. Pre-emergence losses of soil nitrate can not be due to uptake by the crop, which is the chief cause later in the season [9]. In the absence of an active root system, the apparent losses of nitrate must be due to leaching, denitrification or immobilization in the microbial biomass. Although no direct measurements of these processes were made, it is possible to estimate their likely magnitudes in the 1986 experiment.

For leaching to occur, rainfall and/or irrigation must exceed evaporation. Between April and June 1986, only one significant rain event was recorded, a fall of 19.6 mm two days before emergence. The *maximum* fraction, f, of fertilizer nitrate that this rainstorm could have leached below the sampling depth, x (150 mm), can be estimated using Burns' simple model (see [19]). $f = [Q/(Q + \theta)]^x$, where Q is the drainage volume (19.6 mm) and θ is the volumetric water constant of the soil (0.3 + 0.02 throughout the experiment). On this basis, $f = 10.2\%$ of the nitrate present in the soil two days before emergence. Therefore, losses of nitrate by leaching alone cannot account for the pre-emergence decline in soil nitrate measured in 1986.

Potential losses by denitrification are less easy to estimate. If such losses are to be significant, extensive zones of anoxia must be present in the soil, which is more likely to be the case when drainage is poor. As we saw no evidence of impeded drainage, we conclude that denitrification losses were unlikely to be large.

Immobilization of nitrate by the microbial biomass can proceed simultaneously with the re-mineralization of a proportion of the immobilized nitrogen: the large peak in soil nitrate 46 DAE in 1986 in plots to which $18\,g\,N/m^2$ had been applied is possibly indicative of this. Ritz and Griffiths' work [18] suggests that a figure of c. 33% of immobilized N can readily be re-mineralized is not unrealistic. Assuming this to be the case, we can construct a crude balance sheet for nitrate in the $18\,g\,N\,m^{-2}$ treatment. $9\,g\,N\,m^{-2}$ were added as nitrate to soil containing $1.3\,g\,N\,m^{-2}$ nitrate. Of this $10.3\,g\,N\,m^{-2}$, some 10% ($1.03\,g\,N\,m^{-2}$) might have been leached below 150 mm before emergence. At 19 DAE, $3.8\,g\,N\,m^{-2}$ nitrate were measured in the soil, indicating a possible immobilization of $10.3 - (3.8 + 1.03) = 5.47\,g\,N\,m^{-2}$. If 33% ($1.81\,g\,N\,m^{-2}$) of this amount was re-mineralized, $1.81 + 3.8 = 5.6\,g\,N\,m^{-2}$ nitrate should have been left in the soil. This amount is remarkably close to that which was actually measured 46 DAE (Table 1). The amount of nitrate remaining immobilized (i.e. $5.47 - 1.81 = 3.66\,g\,N\,m^{-2}$) represents a 'loss' before emergence of up to 41% of *nitrate* applied as fertilizer. The precise figure will be less than this, depending on the relative amounts of native soil nitrate and fertilizer nitrate being immobilized, and on the extent to which fertilizer *ammonium* is immobilized or nitrified in the soil.

Application of nitrate fertilizer can, therefore, lead to a low recovery in the crop due to pre-emergence losses. However, even when no apparent losses of nitrate were found from the soil before emergence in 1985, the proportion of soil-applied fertilizer recovered in the crop was low compared with those reported for cereal crops [17].

The amount of fertilizer N needed by the potato crop depends upon the length of the growing season. Increased tuber yields in response to applied N are due to both increased light interception during the first part of the season, and a reduced rate of the decline in canopy photosynthesis during the later part, due to continued leaf growth [13]. As a consequence, the influence of N application on tuber yield is dependant on the date of harvest, with later harvested crops responding to larger applications of N [4, 7, 13].

In contrast to applying N to the soil, late application of a foliar spray of urea increased both tuber yields and tuber N contents when compared to a single application at planting. Yield responses to foliar urea sprays can be variable, with beneficial [2, 3, 9] and no effects [6] reported. It is likely that yield responses will only be found with late foliar applications to crops with a long growing season. In addition, it is necessary to supply N at planting to ensure rapid canopy development early in the season. It has been shown that application of foliar urea to winter wheat can give a similar or greater recovery of fertilizer N in the crop than when N is applied to the soil in spring [16]. In the present study the proportion of foliar-applied N recovered in both tubers and the whole crop at the end of the season was higher than that of N applied to the soil at planting. It appears, therefore, that dividing the application of N and providing half as a foliar spray can increase the overall efficiency of fertilizer recovery, thereby reducing environmental losses of N. An alternative strategy to reduce early season losses of N by applying slow release fertilizers has been found unsatisfactory, as the rates of N release were inadequate to meet the demands for canopy growth [15].

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