Soil Use and Management (2000) **16**, 42–48

The effects of starter fertilizers on the growth and nitrogen use efficiency of onion and lettuce

D. A. Stone[1]

Abstract. Broadcast granular fertilizers are inefficient at supplying nitrogen (N) to wide-spaced row crops. Substantial nitrate residues can remain in the soil post-harvest, even when recommended fertilizer practices are followed. This paper explores the benefits of an alternative strategy based on targeting small amounts of liquid nitrogen starter fertilizer close to the seed at drilling to increase N use efficiency and reduce potential pollution. Bulb onion (*Allium cepa*) and crisp lettuce (*Lactuca sativa*) were grown with various rates and combinations of ammonium phosphate (AP) and urea ammonium nitrate (UAN) as 'starters', in comparison with seedbed incorporated ammonium nitrate. AP consistently improved early growth and final yield of both crops compared to broadcast ammonium nitrate, but UAN showed no additional benefits. AP in combination with broadcast N, or injected UAN, generally increased N recovery, and produced yields of marketable quality produce matched only by much higher rates of broadcast N. A reduced N input system based on starter fertilizers is likely to be acceptable to the industry, but would rely on a method to predict how much N is required to supplement that provided by the starter.

Keywords: Nitrogen fertilizers, starter dressings, liquid fertilizers, nitrogen, use efficiency, lettuces, onions

INTRODUCTION

Most vegetable crops are grown intensively with large applications of broadcast nitrogen (N) fertilizers to achieve economic yields of high quality produce. However, many wide-spaced row crops are inefficient at recovering this nitrogen (Greenwood *et al.*, 1989a). While the amounts of N required during the early stages of crop growth are small, the nitrate concentrations in the soil need to be high to ensure optimum N uptake by the developing root system. If these needs are not met, the crop can suffer a temporary N deficiency that can irreversibly depress growth and final yield (Burns, 1990). It has been suggested that N recoveries are often poor because the N fertilizer recommendations for some crops are determined more by the amount needed to satisfy this early demand, than by the needs of the crop later in the season (Greenwood *et al.*, 1989a). This can lead to large residues of mineral-N in the soil at harvest and may increase the risk of environmental pollution through leaching and denitrification.

Studies with other nutrients have shown that they can be used more effectively by targeting applications close to the plant to provide for early growth, while enabling reduced amounts to be applied to the remainder of the soil (Randell & Hoeft, 1988). The injection of small amounts of liquid 'starter' fertilizers close to the seed at drilling, or around the roots of transplants, has been shown to boost yields on soils with low to medium P and K status (Costigan, 1988; Stone, 1998). This approach offers a similar potential for increasing recoveries of N from the soil, thereby reducing the risk of pollution. In a preliminary trial, injection of 14 kg N ha^{-1} as either ammonium phosphate or ammonium nitrate gave the same yield of salad onions as the optimum broadcast ammonium nitrate rate of 80 kg N ha^{-1} (Greenwood *et al.*, 1989b). This represented an apparent increase of more than fivefold in the efficiency of N fertilizer use. While this result was encouraging, there is a need to confirm the result and evaluate the use of starter fertilizer with other crops to determine whether they offer a practical strategy for reducing N inputs which is commercially acceptable.

This paper describes a two year study to examine the effects of different N starter fertilizer solutions, application rates and position in relation to the seed (applied with and without broadcast applications), on the early growth, yield and N recovery of two contrasting vegetable crops, bulb onion and crisp lettuce. Potential osmotic effects limit the total amount of N that can be applied as a starter fertilizer. Consequently, the study also included treatments to evaluate the potential for using a nitrification inhibitor (to prolong the availability of the injected N) and a foliar application of N (to provide an alternative source of supplementary N) in an attempt to sustain any benefits from the starter through to maturity.

MATERIALS AND METHODS

Four experiments were carried out in 1990 and 1991 on a coarse sandy loam soil of the Wick series (Whitfield, 1974) at Horticulture Research International (HRI), Wellesbourne UK. The soil had previously been cropped with cereals for three years, giving a soil N index of 0 under the UK soil fertility classification system (MAFF, 1994). Soil in the plough layer (0–250 mm) was analysed in the autumn before each experiment for pH (1 : 2.5 w/v aqueous suspension), extractable P (0.5 M sodium bicarbonate, pH 8.5), and exchangeable

[1]Soil & Environment Sciences Department, Horticulture Research International, Wellesbourne, Warwick CV35 9EF, UK. Fax: 01789 470552.
E-mail: Dave.Stone@hri.ac.uk

Table 1. Soil analyses prior to application of treatments. Figures in parentheses are the MAFF indices in the UK fertility classification (MAFF, 1994).

Experiment	Year	Crop	pH	P† ($mg\,l^{-1}$)	K‡ ($mg\,l^{-1}$)	NO_3-N§ + NH_4-N§	
						0–300 mm (kg N ha^{-1})	300–600 mm (kg N ha^{-1})
1	1990	Onion	6.3	54(4)	78(1)	37	15
2		Lettuce	7.2	47(4)	119(1)	67	30
3	1991	Onion	6.6	67(4)	109(1)	34	11
4		Lettuce	6.6	67(4)	109(1)	41	14

† Extracted in 0.5 M sodium bicarbonate at pH 8.5. ‡Extracted in M ammonium nitrate. §Extracted in saturated potassium sulphate.

K (M ammonium nitrate), see Table 1. Maintenance dressings of 100 kg P ha^{-1} and 200 kg K ha^{-1} were applied to the ploughed soil and incorporated in the seedbed. Soil mineral-N (nitrate plus ammonium-N extracted with saturated potassium sulphate solution) was measured in a bulked sample of 18 cores from the 0–300 and 300–600 mm layers immediately before drilling (Table 1).

Seeds of onion (cv. Hyton) or lettuce (cv. Saladin) were sown into 10 or 11.5 m long plots (in 1990 and 1991 respectively), each with four rows 280 mm apart in 1.52 m-wide beds, using a Stanhay precision belt seeder. Both crops were sown at 33 seeds m^{-1} of row, and the lettuce thinned to a 400 mm within-row spacing after establishment. To prevent the formation of a hard soil cap, irrigation was applied frequently during the emergence period and thereafter at a soil water deficit of 30 mm, estimated using a simple water balance model (Greenwood & Draycott, 1989). Cropping details are shown in Table 2. Seedling emergence was recorded 2–3 times a week on all four rows of a 0.5 m length of each plot. Plants were sampled 4–5 weeks after 50% emergence from a 1.6 m (lettuce) or 1 m (onion) length of plot and total above-ground dry matter determined. A second harvest was taken at commercial maturity from a 2 m (lettuce) or 4 m (onion) length, and plant stand, total above-ground fresh yield and total dry yield recorded. In Experiment 3, the numbers and total fresh weight of onion bulbs were recorded in diameter classes of 25–45, 45–55 and >55 mm. In Experiment 4, measurements were made of individual trimmed head fresh weights and a minimum weight of 450 g taken as the size criterion for marketable iceberg lettuce (Anon, 1983). Sub-samples of milled dried material were analysed for organic-N and for P content using standard procedures. Lettuce were also analysed for nitrate-N content using an HPLC method (Hunt & Seymour, 1985). Since the number of onions varied between individual plots, treatment effects were compared after adjusting for the effects of stand by covariance analysis. The apparent recovery of fertilizer N at a given rate was calculated from the uptake of N by the above-ground crop less the uptake when no fertilizer N was applied, and expressed as a percentage of the N applied.

Starter fertilizers were applied simultaneously with drilling, using the HRI injection system (Rowse *et al.*, 1988) mounted on the seeder. The original equipment was modified by replacing the coulter-mounted injector with an adjustable, backward-raked, injection tine mounted ahead of the front wheel of each drill unit (Stone, 1998). This enabled the starter fertilizer solution to be injected 30 mm below sowing depth, either directly below the seed (0/30), or 30 mm to the side of the drill line (30/30). A vertical tine mounted on one side of the drill carriage, 150 mm behind the insertion point of the seed, alternatively enabled starter solution to be injected 30 mm below and 60 mm to the side of the drill line (60/30). To eliminate any effect of the tine, the injection tines were left on the drill when sowing all treatments not receiving starter fertilizer. Broadcast N was applied by hand, as ammonium nitrate, with rates up to 80 kg ha^{-1} being incorporated in the seedbed. At higher rates, the balance was applied as a top-dressing soon after crop establishment. In the 1991 experiments, when broadcast N was used in combination with starter fertilizer, the rates were reduced to allow for the N applied in the starter solution. The treatments were arranged in a randomized block design with 3 or 4 replicates, in 1990 and 1991 respectively. Starter fertilizers were injected at 18.6 ml m^{-1} of row and N application rates varied for individual treatments by dilution with water.

Experiment 1—Onion

There were 18 fertilizer treatments, plus 5 zero N plots in each block, the latter to enable the N uptake to be calculated accurately for plants receiving no fertilizer N, see Table 3. Conventional, broadcast ammonium nitrate was applied at 6 rates between 0 and 160 kg N ha^{-1}. Two commercially available liquid fertilizers, ammonium phosphate (AP, a mix of mono and diammonium phosphates, 8% N : 24% P_2O_5) and a 1 : 1 eutectic mixture of urea and ammonium nitrate (UAN, 37% N) were used as the starter fertilizers, injected either directly below or to the side of the drill line.

Four treatments incorporating the nitrification inhibitor, nitrapyrin (2-chloro-6-(trichloromethyl) pyrydine, N-Serve 24E®, The Dow Chemical Company) were included to inves-

Table 2. Cropping details of the four experiments.

Experiment	Crop	Sowing date	50% emergence	Days from 50% emergence to		
				Thinning	Harvest 1	Harvest 2
1	Onion	23/3/90	30/4/90		37	123
2	Lettuce	16/5/90	26/5/90	31	25	67
3	Onion	26/3/91	22/4/91		45	137
4	Lettuce	12/4/91	26/4/91	33	29	80

Table 3. Nitrogen application rates in Experiment 1, onion.

Fertilizer	Method	N application rate (kg ha^{-1})					
Ammonium nitrate	Broadcast	0	20	40	80	120	160
Ammonium phosphate (AP)	Injected 0/30†		20	40			
Ammonium phosphate (AP)	Injected 30/30†		20	40			
Urea/ammonium nitrate (UAN)	Injected 30/30†			40	80		
Urea/ammonium nitrate (UAN)	Injected 60/30†			40	80		160
AP + nitrapyrin @ 1.0 l ha^{-1}	Injected 30/30†			40			
AP + nitrapyrin @ 0.5 l ha^{-1}	Injected 30/30†			40			
UAN + nitrapyrin @ 1.0 l ha^{-1}	Injected 30/30†			40			
UAN + nitrapyrin @ 0.5 l ha^{-1}	Injected 30/30†			40			

† Distance below/to side of seed (mm).

Table 4. Nitrogen application rates in Experiment 2, lettuce.

Fertilizer	Method	N application rate (kg ha^{-1})				
Ammonium nitrate	Broadcast	0	30	60	120	180
Urea/ammonium nitrate (UAN)	Injected 30/30†		30	60	120	180
Urea/ammonium nitrate (UAN)	Injected 60/30†		30	60	120	180
UAN + nitrapyrin @ 1.0 l ha^{-1}	Injected 30/30†		30	60	120	180
UAN + nitrapyrin @ 1.0 l ha^{-1}	Injected 60/30†		30	60	120	180

† Distance below/to side of seed (mm).

tigate the possibility of prolonging the availability of N in the starter fertilizer. This was applied as a tank mix at two rates, 1.0 and 0.5 l of product ha^{-1}, with both the AP and UAN solutions at the 40 kg N ha^{-1} rate injected at position 30/30.

Experiment 2—Lettuce

There were 20 fertilizer treatments, plus 5 zero N plots per block, see Table 4. Ammonium nitrate was broadcast at 5 rates between 0 and 180 kg N ha^{-1}. In contrast to Experiment 1, only UAN was used as a starter fertilizer. This was injected, at the same rates as broadcast N, in positions 30/30 and 60/30, both with and without nitrapyrin at the single rate of 1.0 l ha^{-1}. An additional treatment of foliar applied urea was included to examine the feasibility of providing supplementary N to the lowest rate of starter fertilizer during the growing season. This was applied at 20 kg N ha^{-1} (in 1028 l water ha^{-1}) using a hand sprayer one week before final harvest.

Experiments 3—Onion and 4—Lettuce

Treatments for the two 1991 crops were identical, see Table 5. There were 6 rates of broadcast N to provide a conventional response and AP and UAN injected directly below the seed (0/30) at 20 kg N ha^{-1} were included to provide a direct comparison of the two starter fertilizers. AP (0/30) was also used in combination with various rates of broadcast N or side injected UAN (60/30) in an attempt to prolong any early starter boost. Two zero N plots and two plots of each starter used alone were included in each replicate.

RESULTS

No treatment had a consistent effect on percentage seedling emergence, days from sowing to 50% emergence or plant stand at maturity (data not shown). However, in Experiment 1, the spread of emergence dates of onion, as indicated by the standard deviation, was increased from 2.7 to 3.7 by the 1.0 l of nitrapyrin compared to the zero and 0.5 l ha^{-1} rate ($P < 0.01$).

Experiment 1—Onion

At the seedling harvest (3–4 true leaf stage), dry weight yield with AP injected directly below the seed (0/30) was 88% (20 kg N ha^{-1}) or 46% (40 kg N ha^{-1}) higher ($P < 0.001$) than the comparable rates broadcast (Fig. 1a). The same rates injected 30 mm to the side of the seed (30/30) were not significantly different from the broadcast rates. UAN was not significantly different from comparable broadcast rates and there was no significant effect of its injection position. Combining nitrapyrin with AP or UAN, at either rate, had no effect on early growth.

Table 5. Nitrogen application rates in Experiments 3, onion and 4, lettuce.

Fertilizer	Method	Nitrogen application rate (kg ha^{-1})					
Ammonium nitrate	Broadcast	0	20	40	80	160	240
Ammonium phosphate (AP)	Injected 0/30†		20				
Ammonium phosphate	Injected 0/30†			20	20	20	20
+ ammonium nitrate	+ broadcast			+ 20	+ 60	+ 140	+ 220
Urea/ammonium nitrate (UAN)	Injected 0/30†		20				
Ammonium phosphate	Injected 0/30†			20	20	20	20
+ Urea/ammonium nitrate	+ injected 60/30†			+ 20	+ 60	+ 140	+ 220

† Distance below/to side of seed (mm).

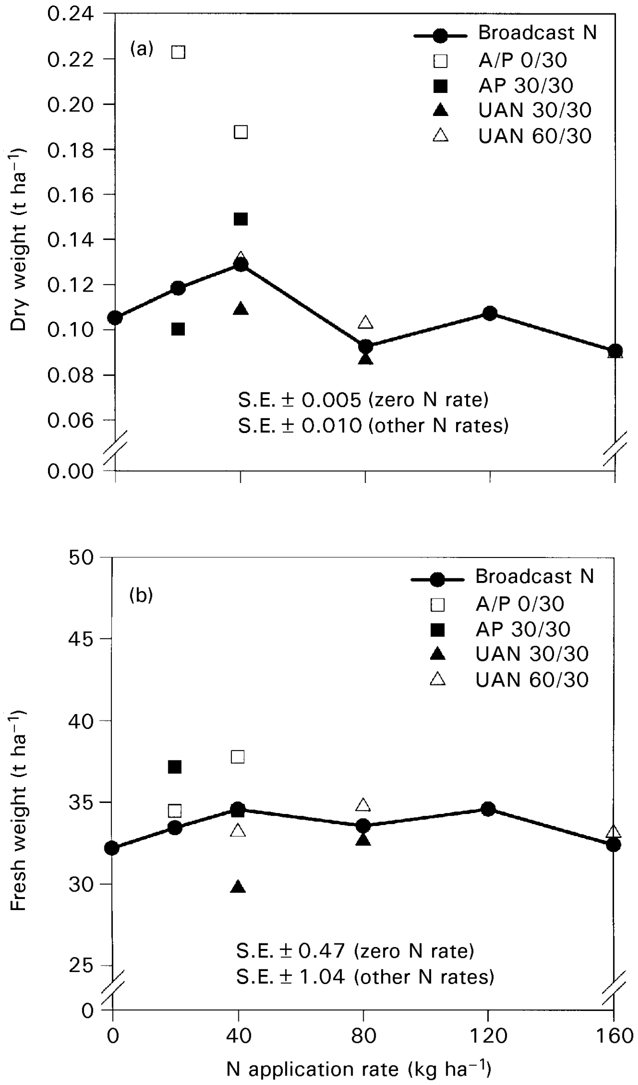

Fig. 1. Onion (Experiment 1)—Effect of N application rate and type on: (a) shoot dry weight at 5 weeks from 50% emergence and (b) bulb fresh weight at maturity. Treatment codes used in the keys are given in Table 3. S.E. = Standard error of the mean (d.f. 43). For clarity, the nitrapyrin treatments are not shown.

The benefits of AP declined towards maturity (Fig. 1b), and the effects of injection position disappeared. However, averaged across rates and position, a modest, but significant ($P < 0.05$), yield advantage of 4% over the best broadcast rate remained. The high rate of nitrapyrin gave higher yields ($P < 0.05$) than the low rate, and when combined with AP increased the benefit over broadcast to 12% (34.6 to 38.6 t ha^{-1}). In combination with UAN, the benefits of nitrapyrin were similar but marginally not significant.

Response to broadcast application of N was small, with maximum final bulb yield being obtained with just 40 kg N ha^{-1}. Apparent recovery of broadcast N declined from 91% at 20 kg N ha^{-1} to 20% at 160 kg N ha^{-1}. There was no significant difference in the recovery of N between types or injection positions of starter fertilizer. However, at 40 kg N ha^{-1}, starter fertilizers, averaged across treatments, increased ($P < 0.001$) the recovery of N from 30% to 47% compared with the same rate broadcast.

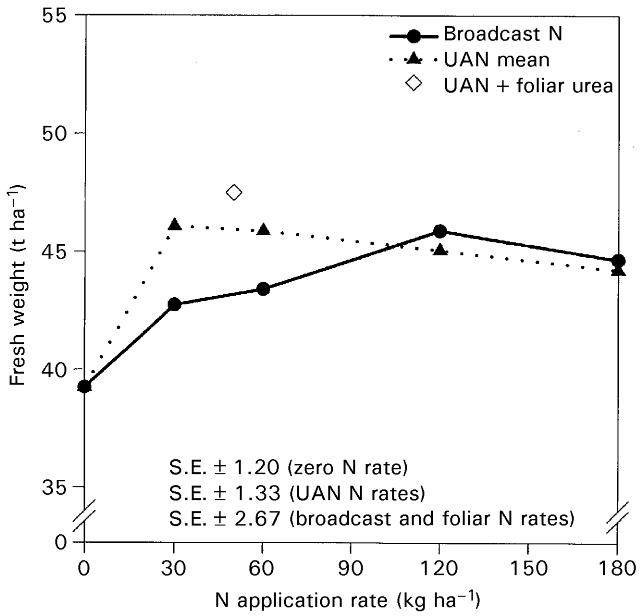

Fig. 2. Lettuce (Experiment 2)—Effect of N rate and type on total fresh weight of lettuce at maturity, with ...... and ——— without UAN starter (UAN data points are means of with and without nitrapyrin). S.E. = Standard error of the mean (d.f. 50).

Experiment 2—Lettuce

There was little response to broadcast N at the first harvest. Dry matter yield increased from 11.6–12.2 kg ha^{-1} between zero and 30 kg N ha^{-1}, but then declined linearly at higher rates of N, to a minimum of 9.5 kg ha^{-1} at 180 kg N ha^{-1}. There was no significant effect of any of the UAN treatments (data not presented). By maturity, total fresh yield showed a response up to a maximum at 120 kg N ha^{-1} (Fig. 2). While there was no significant increase in yield or apparent recovery of applied N from using UAN in either injection position or addition of nitrapyrin, UAN was always as effective as broadcast N. Similarly, UAN plus foliar urea supplying a total of 50 kg N ha^{-1} gave a comparable yield to that estimated for the same rate of broadcast N or injected UAN.

Experiment 3—Onion

At the seedling harvest, prior to application of broadcast N rates above 80 kg N ha^{-1}, there was a small response to broadcast fertilizer up to 40 kg N ha^{-1}. However, AP alone gave a 24% increase in above-ground dry matter and an increase ($P < 0.001$) in % P in the plant from 0.44% to 0.58%. UAN starter fertilizer did not increase yield above the same broadcast rate and did not affect plant % P. An additional dry matter harvest was taken 10 weeks after emergence when individual plants were about the size of salad onions and all the broadcast N had been applied (Fig. 3a). The early growth benefit of AP starter fertilizer had persisted, with AP increasing dry matter yields by 50% ($P < 0.001$). There were no significant additional effects of combining AP with broadcast or injected UAN. UAN alone was not as effective as AP, and was not significantly different from the same rate of N broadcast.

By maturity (Fig. 3b), yield of bulbs increased with N application rates up to 160 kg ha^{-1}. Although the early AP starter effect had diminished, and supplementary N was required to achieve maximum yield, AP averaged across rates

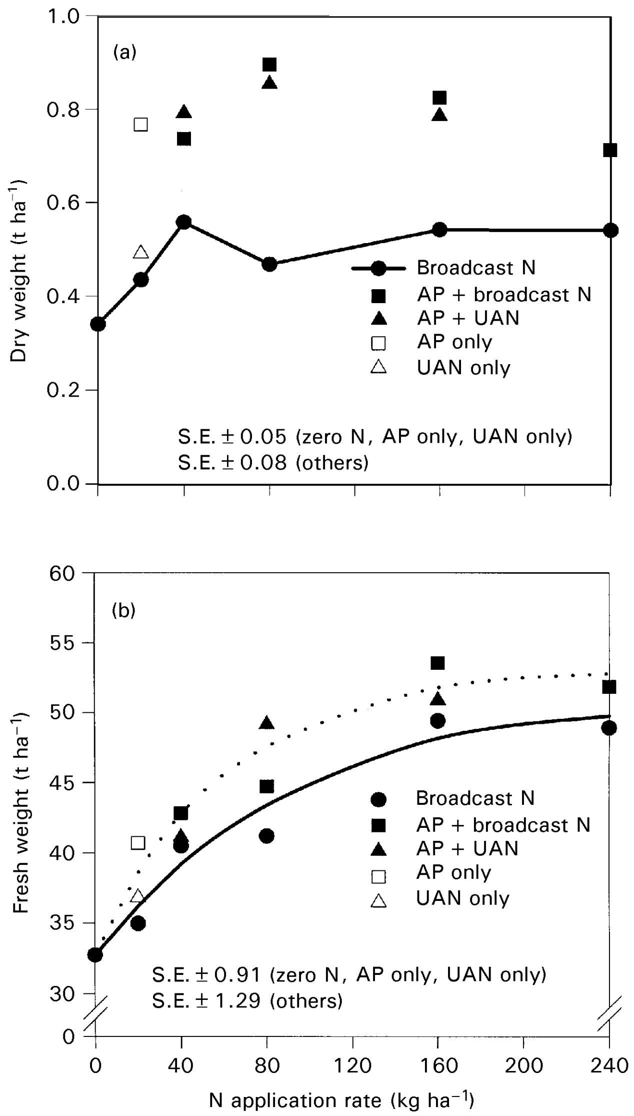

Fig. 3. Onion (Experiment 3)—Effect of N application rate and type on: (a) shoot dry weight at 10 weeks from 50% emergence and (b) bulb fresh weight at maturity (modified from Stone & Rowse, 1992), broadcast N, with ...... and ——— without ammonium phosphate starter. Fitted curves are of the form a + br^x. S.E. = Standard error of the mean (d.f. 51).

of N still produced a 7% increase ($P < 0.001$) in total fresh yield of bulbs. More importantly for commercial production, AP gave a 31% increase ($P < 0.001$) in bulbs in the largest, >55 mm, size grade. UAN alone was not as effective as AP but had an equivalent beneficial effect to broadcast N when used in combination with AP. The apparent recovery of N by the onion bulbs decreased at high rates of N, irrespective of how it was applied. However, although apparent N recovery appeared to increase from 33% for broadcast treatments to 49% in the presence of AP, this was marginally not significant because of considerable plot to plot variability. N recovery from AP alone (62%) was higher ($P < 0.05$) than from the comparable broadcast (21%) or UAN rate (39%).

Experiment 4—Lettuce

Figure 4a shows that the early pattern of response by lettuce was similar to that of onion. AP starter fertilizer gave a 39% increase ($P < 0.001$) in early dry matter yield, which was not enhanced by combination with additional N. UAN alone produced a small ($P < 0.05$) yield increase above the same rate (20 kg N ha^{-1}) broadcast, but was less effective than AP alone. P concentration in the plants was increased by AP ($P < 0.001$), from 0.43% to 0.48%, averaged across N application rates, but was unaffected by UAN.

The effect of AP starter on growth persisted until final harvest when, averaged across rates of N, total fresh yield was 45% greater ($P < 0.001$) than with broadcast N (results not shown). A similar increase in fresh yield of heads marketable as iceberg lettuce, attributable to AP, is shown in Figure 4b. The effect of UAN alone diminished by maturity, but it was still as effective as broadcast N in supplementing AP. There was no effect of starter fertilizer on crop uniformity as indicated by the log(variance) of individual plant trimmed or untrimmed weights. Averaged across rates of N, AP starter increased ($P < 0.001$) apparent recovery in the harvestable part of the crop from 19.6% to 29.5%. As with onions, yield was maintained with reduced overall levels of applied N. Nitrate-N in the dry matter of trimmed heads at maturity increased with increasing rates of N, irrespective of the method of application (Fig. 5).

DISCUSSION AND CONCLUSIONS

The experiments support earlier findings (Costigan, 1988; Stone, 1998) that starter fertilizers can be successful in increasing the early growth of onion and lettuce and that these effects can persist to maturity. AP starter fertilizer used alone gave large boosts to early growth of onions (Figs 1a and 3a), but the effects tended to decline as the crop matured, even when supplemented with additional broadcast N or injected UAN (Figs. 1b and 3b). Nevertheless, AP increased final bulb yields, particularly of the larger bulb sizes, when used in combination with supplemental N. Early growth of lettuce (Fig. 4a) was also increased by AP alone. The effect persisted to maturity (Fig. 4b) with AP supplying just 20 kg N ha^{-1} giving the same marketable yield as very much higher rates of broadcast N. It is possible that the broadcast treatments might have given larger yields if they had been harvested later. However, it was shown by Burns (1996) that delayed lettuce maturity following short periods of N deficiency allowed only partial recovery of yield loss. It was also found in starter fertilizer experiments with lettuce on peat soils (Stone *et al.*, 1999) that while plants matured earlier with starter fertilizers, non-starter treatments did not completely catch up at a later harvest.

Of the two starter solutions tested, AP was consistently superior to UAN, which lends support to the suggestion by Costigan & Heavyside (1988) that the response is mainly attributable to P. In Experiments 3 and 4, AP at 20 kg N ha^{-1} (also supplying 60 kg P_2O_5 ha^{-1}) increased P concentration in the plant dry matter at the early harvests, whereas UAN did not. In the early stages of growth, crops are particularly sensitive to P deficiency which diminishes as the plants get bigger because of an increased ratio of root absorbing surface to crop demand (Scaife, 1994). It is likely that, following the boost to early growth provided by a high P starter fertilizer, the root systems of the larger plants can extract mineral N from a larger volume of soil and consequently the requirement for fertilizer N is likely to be less.

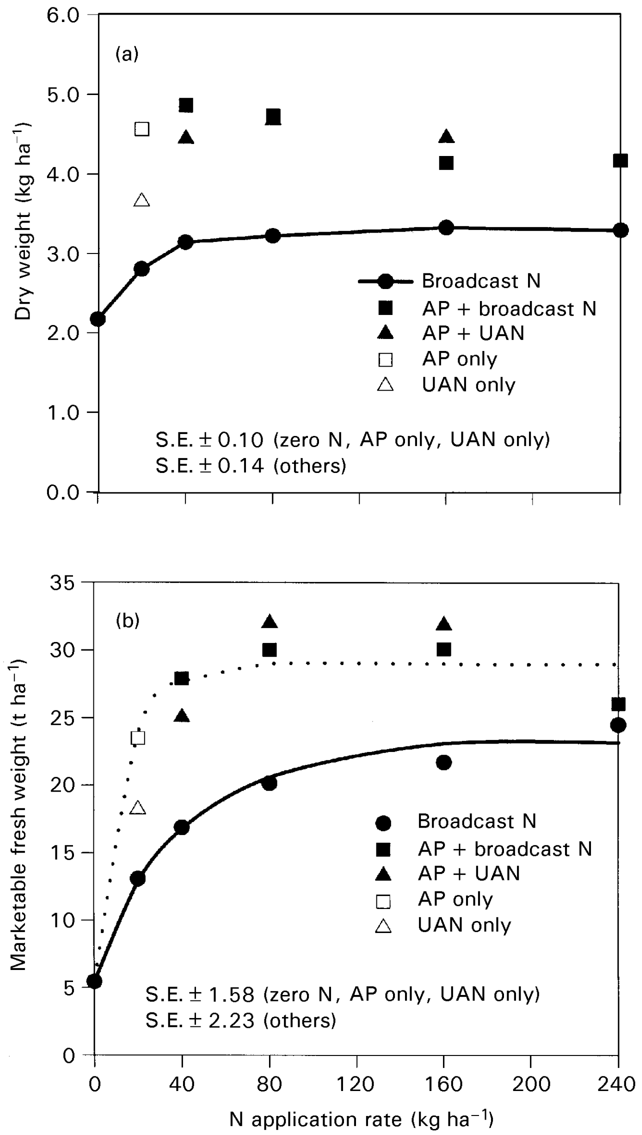

Fig. 4. Lettuce (Experiment 4)—Effect of N application rate and type on: (a) shoot dry weight at 4 weeks from 50% emergence and (b) fresh weight as marketable heads >450 g (modified from Stone & Rowse, 1992); broadcast N, with ...... and ——— without ammonium phosphate starter. Fitted curves are of the form $a + br^x$. S.E. = Standard error of the mean (d.f. 51).

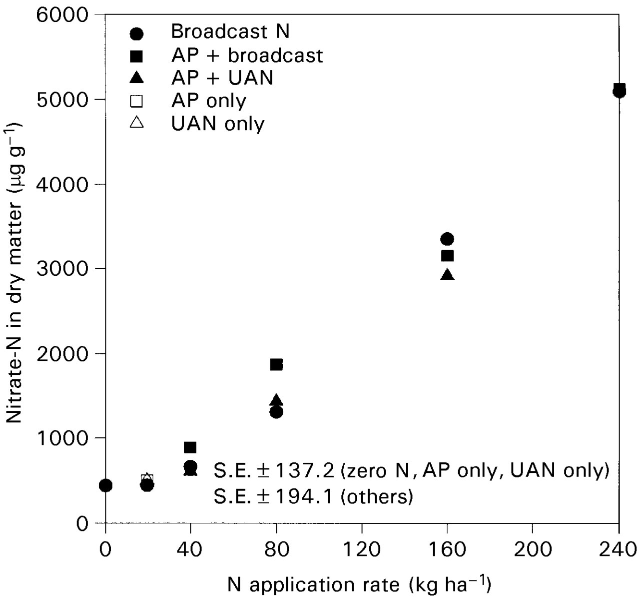

Fig. 5. Lettuce (Experiment 4)—Relationship between N application rate and nitrate-N content in the dry matter of trimmed, marketable heads.

It is evident from the fitted response curves for onion (Fig. 3b) that AP would enable comparable yields to be achieved with approximately half the application rate of broadcast N. For example, a yield of 48 t ha^{-1} was obtainable with either 160 kg N ha^{-1} broadcast or 85 kg N ha^{-1} as AP plus broadcast N or UAN. Similarly (Fig. 4b), the yield of iceberg lettuce heads with AP starter alone (20 kg N ha^{-1}) was virtually identical to the very much higher rate of broadcast N (240 kg N ha^{-1}) required for maximum yield. Clearly, N was used more efficiently in the presence of starter fertilizer. The apparent recovery of applied N in the harvestable part of the crop decreased linearly with increasing N rate, irrespective of how it was applied. Recovery from AP starter fertilizer used alone was higher than from the comparable broadcast rate (Experiments 1, 3 and 4). In combination with broadcast N or injected UAN, apparent recovery by lettuce was increased by 50% (Experiment 4), although a similar percentage increase with onion was marginally not significant (Experiment 3). UAN alone did not improve apparent N recovery (Experiments 1–4). Since AP starter fertilizer alone produced high yields, it implies that AP, in addition to improving recovery of applied fertilizer N also improved utilization of soil N.

In each experiment, the benefits of starter fertilizer diminished with time. In part, this may have been due to water limitations as the model used to monitor irrigation need underestimated water requirement as crop cover increased. It is known for some crops that irrigation can enhance the effects of starter fertilizer (Rahn *et al.*, 1996). Field to field variability in mineral N will mean that starter fertilizer alone is unlikely to provide sufficient N to sustain the early growth benefits to maturity. Uncertainties remain, however, in estimating how much additional N is required to maximise the starter benefits. Work is continuing to examine the practicality of applying supplementary N as a mid-season top-dressing, at rates based on simple soil nitrate tests or computer model predictions.

It is an open question whether a nitrification inhibitor, such as nitrapyrin, would be as effective as supplementary N in prolonging the starter effect unless tested under high rainfall, or irrigation, situations. In the present work, nitrapyrin, was used at rates lower than those known to adversely effect onion and lettuce (Goring, 1962). Nevertheless, at the highest rate, a significant increase in the spread of emergence dates of onion (Experiment 1) was found. There was no effect on early growth of onion, but there was some evidence that nitrapyrin, particularly at the highest rate, increased the final fresh yield obtained with AP starter fertilizer used alone (Experiment 1). No benefits were found from combining nitrapyrin with UAN with either onion or lettuce (Experiments 1 & 2).

Overall, the results presented support the view that starter fertilizers offer considerable scope for maintaining commercial yields with reduced inputs of applied nitrogen. In addition there can be crop quality advantages in terms of size distribution, earlier maturity and lower nitrate-N contents. While the injection of AP directly below the seed (0/30) was better than side injection (30/30) in achieving maximum early growth of onion, final yield was unaffected by this difference in injection position (Figs. la and b). This suggests that crops that are commercially drilled in twin lines 75 mm apart could still benefit from starter fertilizer injected centrally between the two lines. Starter fertilizers are finding increasing acceptance in the UK horticultural industry and, for example, are used with about 50% of the UK area of seeded bulb onions, some 2500 ha (D. Martin pers. comm.).

There is public concern over the possible health risks posed by high nitrate levels in some crops, although this is generally not a problem in field grown lettuce. As the nitrate-N content of lettuce increased with N application rate (Fig. 5), it follows that producing high yields with less N using AP starter fertilizer should enable plants to be grown with lower nitrate-N contents.

ACKNOWLEDGEMENTS

This work formed part of a research programme commissioned by the Ministry of Agriculture, Fisheries and Food. The author is grateful to Hydro-Chafer for donating the starter fertilizers used and gratefully acknowledges the technical assistance provided by Kim Niendorf and Mary Turner.

REFERENCES

ANON. 1983. Can we grow really good iceberg in the UK? *Grower* **100**, 17–18.

BURNS, I.G. 1990. The effects of continuity of early nitrogen nutrition on growth and development of *Lactuca sativa*. In: *Plant nutrition—Physiology and Applications* (ed. van Beusichem) Kluwer Academic Publishers, Dordrecht, pp. 545–549.

BURNS, I.G. 1996. Nitrogen supply, growth and development. *Acta Horticulturae*. **428**, 21–30.

COSTIGAN, P.A. 1988. The placement of starter fertilizers to improve early growth of drilled and transplanted vegetable crops. *Proceedings of the Fertilizer Society*, London, No. 274.

COSTIGAN, P.A. & HEAVYSIDE, M. 1988. The effects of starter fertilizer on the early growth and yield of transplanted crisp lettuce on fertile soils. *Journal of Horticultural Science* **63**, 247–253.

GORING, C.A.I. 1962. Control of nitrification by 2-chloro-6-(trichloromethyl) pyridine. *Soil Science* **93**, 211–218.

GREENWOOD, D.J. & DRAYCOTT, A. 1989. Experimental validation of an N-response model for widely different crops. *Fertilizer Research* **18**, 153–174.

GREENWOOD, D.J. KUBO, K. BURNS, I.G. & DRAYCOTT, A. 1989a. Apparent recovery of fertilizer N by vegetable crops. *Soil Science and Plant Nutrition* **35**, 367–381.

GREENWOOD, D.J. STONE, D.A. BURNS, I.G. & ROWSE, H.R. 1989b. Improving the efficiency of N-fertilizer use for vegetable crops. *Journal of the Science of Food and Agriculture* **48**, 125–127.

HUNT, J. & SEYMOUR, D.J. 1985. Method for measuring nitrate–nitrogen in vegetables using anion-exchange high-performance liquid chromatography. *Analyst* **110**, 131–133.

MAFF. 1994. *Fertilizer recommendations for Agricultural and Horticultural Crops*. Reference Book 209, HMSO, London.

RANDELL, G.W. & HOEFT, R.G. 1988. Placement methods for improved efficiency of P and K fertilizers: a review. *Journal of Production Agriculture* **1**, 70–79.

RAHN, C.R. SHEPHERD, M.A. & HIRONS, R.W.P. 1996. The effect of water supply on the response of onions and calabrese to starter solutions. *Acta Horticulturae* **428**, 141–150.

ROWSE, H.R. COSTIGAN, P.A. & THOMPSON, A.R. 1988. Sub-seed injection of fertilizers and pesticides—equipment and preliminary results. In: *Proceedings of 11th Conference of the International Soil & Tillage Research Organization*, Edinburgh, pp. 845–850.

SCAIFE, A. 1994. Fall in nutrient demand per unit root length during the linear phase of plant growth. *Plant and Soil* **164**, 315–317.

STONE, D.A. 1998. The effects of 'starter' fertilizer injection on the growth and yield of drilled vegetable crops in relation to soil nutrient status. *Journal of Horticultural Science & Biotechnology* **73**, 441–451.

STONE, D.A. TYLER, F.T. & RUNHAM, S. 1999. Effect of starter fertilizers on the yield and quality of lettuce grown on peaty soils. *Soil Use and Management* **15**, 128–132.

STONE, D.A. & ROWSE, H.R. 1992. Reducing the nitrogen requirement of vegetable crops by precision fertilizer injection. *Aspects of Applied Biology* **30**, 339–402.

WHITFIELD, W.A.D. 1974. The soils of the National Vegetable Research Station, Wellesbourne. In: *Report of the National Vegetable Research Station for 1973*, pp. 21–30.

Received August, 1999, accepted after revision November, 1999.