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PRACTICAL SECTION FOR GROWERS

1.1 Application

The fate of ^{15}N labelled ammonium nitrate applied to an early summer cauliflower crop in that crop and in a subsequent autumn cauliflower crop was determined, in order to: (i) distinguish between soil and fertiliser derived N in the first cauliflower crop; (ii) provide an estimate of soil and fertiliser derived N returned to the soil as unharvested material; and (iii) estimate the contribution of unused fertiliser residues to succeeding crops.

There were three key results.

- Following the early summer cauliflower crop, most of the residual fertiliser remained in the 0-15 cm depth increment, suggesting that little, if any, leaching of N took place.
- However, N balance calculations indicated that there was significant loss of N from the crop-soil system. It is postulated that this occurred in gaseous form(s).
- Recovery of N applied as fertiliser to the first crop by the second crop indicated that residual fertiliser N and crop residue N are important sources of N for a subsequent crop.

The results of this study indicate that growers should attempt to include both residual fertiliser N and N derived from the mineralisation of unharvested materials in calculating fertiliser requirements in brassica rotations, using soil mineral N analyses. There may be further scope for improving the efficiency of N fertiliser use by devising and adopting strategies which minimise gaseous losses of N.

1.2 Summary

Scope and Objective of the Project

This report forms part of a contract with the Horticultural Development Council (HDC) to investigate improved methods for the prediction of the nitrogen (N) requirement for vegetables. Two previous reports have been produced, as part of this contract, which summarise two experiments carried out during 1988-1991. These were a HDC/MAFF sponsored experiment during 1988-1990 and a MAFF commissioned repeat during 1989-1991.

The cropping pattern for both experiments consisted of two cauliflower crops in the first year, followed by brussel sprouts in the following year and a spring sown cereal in the third and final year. The first report described the role of crop residues in determining the fertiliser requirement of cauliflower crops. The second report described the effect of residual N on the growth of subsequent brussel sprouts and cereal crops.

As part of the first experiment, ^{15}N labelled ammonium nitrate fertiliser was used in selected treatments of the early summer cauliflower crop. This report describes the results from these treatments, and the conclusions of the ^{15}N experiments are integrated into those of the study as a whole.

Summary of Results

The results show that N uptake by the first (early summer) cauliflower crop is increased by N application. However there was no clear cut indication that dry matter yields were increased by N application.

Fertiliser use efficiencies were calculated in two ways. Firstly, the increase in N uptake due to fertiliser application was expressed as a proportion of the fertiliser applied. Expressed in this way, fertiliser use efficiency averaged 44% for fertiliser rates of 120 and 240 kg/ha N. Secondly, the recovery of ^{15}N from labelled fertiliser by the crop was determined. This calculation indicated that fertiliser recovery averaged 35%. The differences between the two methods were statistically significant. Although there are a number of possible reasons for this, the most likely explanation is that mineralisation of native soil N through the growing season lowers the proportion of labelled N

in the soil mineral N pool. The effect of this process is to dilute the labelled N, and hence reduce the apparent recovery of fertiliser N. In reality, neither method gives an entirely satisfactory measurement of fertiliser use efficiency. N uptake by crops takes place over a finite period of time, and dynamic processes such as mineralisation and immobilisation, as well as other processes acting as inputs to or outputs from the soil mineral N pool, means that simple concepts of fertiliser derived or soil derived N become increasingly difficult to apply.

The results of soil analyses at the harvest of the early summer cauliflower crop indicated that most of the residual fertiliser remained in the 0-15 cm depth increment. Rainfall for the growing period was average, and it appears that very little, if any, leaching of N took place. However, the total recovery of ^{15}N from the soil plant system was considerably less than 100% (being 63% and 76% for the 120 and 240 kg/ha N treatments, respectively). Although some of the losses may be due to experimental error and incomplete recovery of labelled N from plant roots, it seems likely that these results indicate a real loss of N from the soil-crop system. Given that leaching losses can be considered to be negligible, gaseous losses must be the dominant mechanism.

Constructing an N balance sheet using these data, and including a contribution of 40 kg/ha N for atmospheric deposition, it is possible to calculate a daily mineralisation rate through the growing season. The value calculated is 0.18 kg/ha.day N under the conditions of the trial, compared to 0.79 kg/ha.day N at 15.9 °C in the WELL-N model which describes the response of vegetable and arable crops to N fertiliser. However, in this model no account is taken of atmospheric N deposition.

In an earlier report it had been shown that N residues from an early summer cauliflower crop were substantial, ranging between 100 and 250 kg/ha N. Soil mineral analyses, at harvest of the early summer crop and planting of a subsequent autumn cauliflower crop, indicated that a large proportion of the residue N in the first crop had mineralised during this period. The ^{15}N results support these observations; thus, very high recoveries of N remaining from the fertiliser applied to the first crop were obtained in the second crop. Where no additional fertiliser was applied, recoveries of between 80 and 88% were obtained. Where 120 kg/ha N was applied to the second crop, high recovery (77%) was maintained where 120 kg/ha was applied to the early summer crop, but a lower recovery (54%) was achieved where 240 kg/ha N was applied to the earlier crop.

Action points for growers

As a large proportion of N contained in the residues of the first cauliflower crop were utilised by the following crop, there is a need to take them into account when fertilising the second crop.

- New MAFF RB 209 recommendations (MAFF, 1994) should be followed for second crops in the same year. If more than 200 kg/ha N is applied to the first crop, the soil N index is considered to be index 1. The application of N to a second cauliflower crop should be no more than 130 kg/ha.

However, further savings in fertiliser use can be achieved if assessments of soil mineral N are made.

- Soil samples should be taken to a depth of at least 30 cm and preferably to 60 cm, as close to the planting date as possible. At least 10 cores from uniform areas of cropping within the same field should be taken. Samples should be kept cool (below 4 °C) and analysed within 24 hours. Samples should be frozen if analysis is not possible within 24 hours. The samples can be taken by the grower or by ADAS as part of the ADAS Soil Mineral Nitrogen Service.

- The results can be interpreted by using the Wellesbourne nitrogen model (WELL-N) or by adoption of the ADAS Soil Mineral Nitrogen Service.

- On silt soils where these experiments were carried out, more specific advice is available providing there are no adverse growing conditions:- *If the amount of soil mineral N to 60 cm is 240 kg/ha with at least 220 kg/ha in the top 30 cm, and the previous crop residues have been shallow-incorporated, the following summer cauliflower needs no further N fertiliser. Where residues have been incorporated to a depth of 20 cm or more, a fertiliser application of 30 kg/ha N should be applied to support* *early growth. Where the amounts of soil mineral N are less than the above, apply N fertiliser to top them up.*

Practical and financial anticipated benefits

With N contained in soil and crop residues after a well grown early summer cauliflower crop being *ca.* 270 kg/ha with a potential monetary value of £80/ha (using 30p/kg N), it's contribution to following crops should be taken into account. Applying excessive fertiliser to the second crop will not improve quality or yield, and it likely to lead to a poor utilisation of nitrogen from any applied fertiliser or previous crop residues.

Research carried out as part of this project has led to a revision of MAFF fertiliser recommendations RB 209 (MAFF, 1994) for a second crop from 200 kg/ha N to 130 kg/ha N, saving £21/ha. Potentially, savings of up to £60/ha in fertiliser costs could be made if the residue contribution is assessed by measuring soil mineral N.

SCIENCE SECTION

2.1 Introduction

This report forms part of a contract with the Horticultural Development Council (HDC) to investigate improved methods for the prediction of the nitrogen (N) requirement for vegetables. Two previous reports have been produced, as part of this contract, which summarise two experiments carried out during 1988-1991. These were a HDC and MAFF sponsored experiment during 1988-1990 and a MAFF commissioned repeat during 1989-1991.

The cropping pattern for both experiments consisted of two cauliflower crops in the first year, followed by brussel sprouts in the following year and a spring sown cereal in the third and final year. The first report described the role of crop residues in determining the fertiliser requirement of cauliflower crops. The second report described the effect of residual N on the growth of subsequent brussel sprouts and cereal crops.

As part of the HDC sponsored experiment, ^{15}N labelled ammonium nitrate fertiliser was used in selected treatments of the first cauliflower crop. This report describes the results from these treatments, and the conclusions of the ^{15}N experiments are integrated into those of the study as a whole.

2.2 Materials and Methods

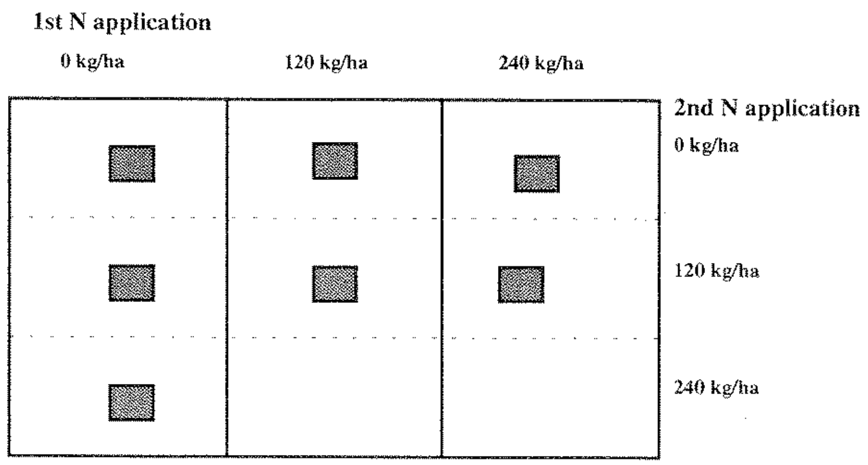
Trial Design

The HDC experiment within which ^{15}N labelled ammonium nitrate fertiliser was used was carried out at HRI Kirton.

The main experiment (in 1988) had a split-plot design, consisting of whole plots in 3 fully randomised blocks with N applied to a first (early summer) cauliflower crop at 6 levels, and split plots with N applied to a second (autumn) cauliflower crop also at 6 levels. For both applications, the rates applied were 0, 60, 120, 180, 240 and 360 kg/ha N.

For selected treatments, ^{15}N labelled ammonium nitrate solution was added to microplots within the whole plots in lieu of fertiliser addition. The whole plots to which ^{15}N was applied consisted of the 0, 120 and 240 kg/ha N treatments. Three microplots were established in each block for the 0 kg/ha N whole plot, corresponding to the 0, 120 and 240 kg/ha N second N application split plots. Two microplots were established in each block for each of the 120 and 240 kg/ha N whole plots, corresponding to the 0 and 120 kg/ha N split plots (Figure 1). Weighed quantities of unlabelled and double labelled ammonium nitrate (11.8 atom % ^{15}N) were dissolved in distilled water. Appropriate quantities of these solutions were applied evenly to the microplots. The application rates were equivalent to 131.1 and 224.2 kg/ha N.

Figure 1. Schematic diagram of one block of trial showing whole plots, split plots and microplots.



The N application to the first cauliflower crop was split 50:50, and took place on 29 March and 27 April, 1988. The ^{15}N solutions were applied to the first crop similarly. N was applied to the second crop as a single dressing on 8 August 1988.

Assessments

Soil mineral N (0-15, 15-30, 30-60, 60-90 and 90-120 cm depth increments) was determined at the beginning of the trial, and at the harvest of each crop. Determinations were carried out, using material bulked from at least 6 cores for each plot, by freezing samples within 24 hours of collection and defrosting at room temperature prior to extraction with 2 *M* KCl solution. Standard methods were used for the extraction and the analysis of extracted solutions (Anon., 1986).

Cauliflower plants were harvested at ground level to determine fresh and dry weights. On the whole plots, 30 plants were harvested and separated into marketable and unmarketable grades. The unmarketable grades were weighed whole, with subsamples taken for determination of dry matter, total N and nitrate N. Marketable plants were trimmed, allowing enough surrounding leaves to protect the curd but with the upper surface of the curd visible. Fresh weights were determined for the curds and trimmings, with subsamples taken for dry matter, total N and nitrate N analyses. Dry matter was determined after drying at 60 °C for 24 hours. Total N and nitrate N were determined on ground material by standard methods (Anon., 1986). Loose leaf samples were collected for dry matter analysis on 4 occasions (4 May, 17 May, 25 May and 1 June, 1988) from the first crop, and bulked for total N determination.

In addition, cauliflowers (6 plants) were harvested from the microplots for determination of fresh weight, dry matter, total N and ^{15}N content. For the first crop, plants were not separated into marketable and unmarketable parts. Loose leaf samples were also collected from the microplots on 4 occasions, but ^{15}N determinations were only carried out on samples from the final 3 sampling occasions. For the second crop, plants were separated into marketable and unmarketable parts, and the curds and trimmings were analysed separately. In addition loose leaf samples were collected on one occasion.

Soil samples (0-15, 15-30, 30-60, 60-90 and 90-120 cm depth increments) were collected from the microplots after the harvest of the first cauliflower crop for total N and ^{15}N analyses. In addition, the ^{15}N labelled ammonium nitrate solutions applied to the microplots were analysed for ^{15}N content by mass spectroscopy.

Statistical analysis

Variates relating to the first cauliflower crop were analyses by ANOVA with a single factor at 3 (N application) levels fully randomised over 3 blocks. The data from the microplots for each level were averaged, giving the same data structure as that for the whole plots. Paired t-tests were carried out to compare differences between whole plots and microplots. For the second cauliflower crop, the data were analysed as a split-plot design with 3 whole plot treatment levels and 2 split plot treatment levels (i.e. 0 and 120 kg/ha N application). Thus, data for N applied to the first crop at 0 kg/ha and to the second crop at 240 kg/ha were not included in the statistical analysis. However, these data are included in the tables (below) for completeness.

2.3 Results

2.3.1 ^{15}N analysis of the fertiliser solutions

Triplicate analyses of subsamples of the ^{15}N labelled ammonium nitrate solutions indicated that their ^{15}N contents were 2.3353 atom % and 2.3331 atom %, corresponding to the (nominal) N application rates of 120 kg/ha and 240 kg/ha, respectively.

2.3.2 Early summer cauliflower crop

The results of determinations of dry matter and N uptake for the whole plots and the microplots for the first crop are given in Table 1. Using the whole plot data, the mean dry matter yield was 3.5 t/ha, and N uptake varied between 91 kg/ha for the control (nil N application) to 164 kg/ha for the 240 kg/ha N application treatment.

Table 1. Dry matter and N uptake by the early summer cauliflower crop.

Block	N applied (nominal) *kg/ha*	DM *t/ha*		N uptake *kg/ha*	
		whole plot	microplot	whole plot	microplot
1	0	2.8	2.2	84	68
2		3.6	3.6	114	148
3		2.9	2.4	75	78
mean		*3.1*	*2.7*	*91*	*98*
1	120	3.5	3.6	133	136
2		3.5	4.2	133	171
3		3.7	4.0	141	177
mean		*3.5*	*3.9*	*136*	*161*
1	240	3.5	3.7	144	163
2		4.4	4.8	197	223
3		3.8	4.3	150	177
mean		*3.9*	*4.3*	*164*	*188*

Paired t-tests indicated that there was no significant difference ($P>0.05$) between the whole plots and microplots for dry matter yield but a significant difference ($P<0.05$) for N uptake. Analysis of variance indicated that there was a significant effect ($P<0.05$) of N application on N uptake for both whole plots and microplots.

The results of determinations of dry matter and N uptake for the whole plots and the microplots for loose leaf samples first crop are given in Table 2. Dry matter yield and N uptakes were small in comparison to the whole crop. The total N content of loose leaves was less than 2 kg/ha. In contrast to the whole crop, rate of N application had no significant effect ($P>0.05$) on dry matter yield and N uptake in both whole plots and microplots.

Table 2. Dry matter and N uptake of loose leaves from the early summer cauliflower crop.

Block	N applied (nominal) *kg/ha*	DM *kg/ha*		N uptake *kg/ha*	
		whole plot	microplot	whole plot	microplot
1	0	54	64	0.50	NA
2		111	95	1.29	1.26
3		62	61	0.64	0.73
mean		*76*	*73*	*0.81*	*0.99*
1	120	71	80	0.86	1.08
2		111	105	1.39	1.46
3		83	80	0.94	1.14
mean		*88*	*88*	*1.07*	*1.23*
1	240	90	91	1.11	1.38
2		134	154	2.05	2.55
3		96	91	1.20	1.59
mean		*106*	*112*	*1.46*	*1.84*

The ^{15}N results have been used to calculate both the proportion and quantity of N taken up by the crop, and hence the proportion of fertiliser recovered by the first cauliflower crop.

The proportion of crop N derived from the ^{15}N labelled fertiliser is given by:

```
Crop N dff (%) =  {(c-b)/(a-b)}.100          ... 1
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where, c is the ^{15}N content (atom %) of the crop material from plots receiving labelled fertiliser,
a is the ^{15}N content (atom %) of the labelled fertiliser solution, and
b is the ^{15}N content (atom %) of crop material from plots not receiving labelled fertiliser.

The quantity of crop N derived from the ^{15}N labelled fertiliser is given by:

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Crop N dff (kg/ha) =  {(c-b)/(a-b)}.P        ... 2
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where, P is the crop N uptake (kg/ha) from plots receiving labelled fertiliser.

Table 3 shows both the proportion and quantity of N derived from fertiliser calculated using the ^{15}N results for the first cauliflower crop. Because N uptake differed significantly between whole plots and microplots, the calculation of the quantity of N derived from fertiliser is based on N uptake values for the microplots. Additional N uptake due to fertiliser application, calculated as the difference in N uptake between fertilised and (unfertilised) control plots, is also given. In this case, results from both whole plots and microplots are given for comparison.

There were significant differences ($P<0.05$) for additional N uptake due to fertiliser application calculated by the difference method (N applied - no N applied) between whole plots and microplots, with generally greater values from the microplots. Values varied between 45 kg/ha N for the 120 kg/ha N treatment on whole plots, to 90 kg/ha N for the 240 kg/ha N treatment on microplots. However, crop N derived from fertiliser for the microplots calculated by ^{15}N is not significantly different ($P>0.05$) to that calculated by difference. For the 120 kg/ha N treatment, values were 52 and 63 kg/ha N for the ^{15}N and difference methods, respectively. For the 240 kg/ha treatment, values were 67 and 90 kg/ha N. Analysis of variance indicates no significant differences ($P>0.05$) between N application rates for crop N derived from fertiliser, irrespective of plot size and method of calculation, expressed either as a proportion of total crop N or on a kg/ha basis.

Table 3. N derived from fertiliser for the early summer cauliflower crop.

Block	N applied (nominal)	Crop N dff by ^{15}N		Fertiliser crop N by difference	
	kg/ha	*%*	*kg/ha*	*kg/ha* whole plot	*kg/ha* microplot
1	120	31	42	49	68
2		25	42	19	24
3		40	71	66	99
mean		*32*	*52*	*45*	*63*
1	240	44	71	60	95
2		36	80	83	75
3		28	49	74	98
mean		*36*	*67*	*73*	*90*

The percentage recovery of the ^{15}N labelled fertiliser by the crop is given by:

$$\text{Fert. Rec. (\%)} = \{(c-b)/(a-b)\}.(P/F).100 \quad \ldots 3$$

where, F is the fertiliser application rate (kg/ha) of plots receiving labelled fertiliser.

Table 4 shows the recovery of ^{15}N labelled fertiliser, again calculated using the application rate corresponding to the microplots. The average recovery was 35% of applied fertiliser. Analysis of variance indicates no significant difference (P>0.05) between N application rates.

For the loose leaf samples, the proportion of their N content derived from the ^{15}N labelled fertiliser has been calculated. Taking an average of the results over the 3 sampling dates and using the N uptake data presented in Table 2, it is also possible to calculate the total quantity of N in loose leaves which is derived from the fertiliser (Table 5). The fact that the proportion of N in the loose leaves derived from fertiliser tends to increase with time is likely to introduce a slight error into this calculation. However, although the proportion on N in the loose leaves derived from fertiliser is comparable to that in the crop itself (Table 3), the amount is very small, averaging 0.5 kg/ha N.

Table 4. N derived from fertiliser for the early summer cauliflower crop.

Block	N applied (nominal) *kg/ha*	Fertiliser recovery *%*
1	120	32
2		32
3		54
mean		*39*
1	240	32
2		36
3		22
mean		*30*

Table 5. Loose leaf N derived from labelled fertiliser for the early summer cauliflower crop.

Block	N applied (nominal)	Loose leaf N dff by ^{15}N			
	kg/ha		*%*		*kg/ha*
		17 May	25 May	1 June	
1	120	13	11	19	0.2
2		15	27	20	0.3
3		20	22	28	0.3
mean		*16*	*20*	*22*	*0.2*
1	240	28	24	37	0.4
2		28	34	39	0.9
3		30	39	41	0.6
mean		*29*	*32*	*39*	*0.6*

For the soil samples, the total N and ^{15}N contents in each depth increment were used to calculate the percentage of soil N derived from the labelled fertiliser at the harvest of the first cauliflower crop. An assumed value of 1.33

g/cm^3 for soil bulk density was used in order to calculate the quantity of soil N derived from the fertiliser and the percentage of the fertiliser remaining in the soil (Table 6a-e).

Table 6a. Labelled fertiliser remaining in soil (0-15 cm) at harvest of early summer cauliflowers.

Block	N applied (nominal)	Soil N dff		Fertiliser remaining in soil
	kg/ha	%	*kg/ha*	%
1	120	1.21	41	31
2		0.91	34	26
3		0.55	18	13
mean		*0.89*	*31*	*23*
1	240	3.01	104	47
2		1.28	44	20
3		4.35	136	61
mean		*2.88*	*95*	*42*

Table 6b. Labelled fertiliser remaining in soil (15-30 cm) at harvest of early summer cauliflowers.

Block	N applied (nominal)	Soil N dff		Fertiliser remaining in soil
	kg/ha	%	*kg/ha*	%
1	120	0.06	2	1
2		0.06	2	2
3		NA	NA	NA
mean		*0.06*	*2*	*2*
1	240	0.17	6	3
2		0.07	3	1
3		0.41	12	6
mean		*0.22*	*7*	*3*

Table 6c. Labelled fertiliser remaining in soil (30-60 cm) at harvest of early summer cauliflowers.

Block	N applied (nominal)	Soil N dff		Fertiliser remaining in soil
	kg/ha	%	*kg/ha*	%
1	120	0.05	2	1
2		-0.03	-1	0
3		0.01	0	0
mean		*0.01*	*0*	*0*
1	240	-0.08	-2	-1
2		-0.03	-1	0
3		0.14	3	1
mean		*0.01*	*0*	*0*

Table 6d. Labelled fertiliser remaining in soil (60-90 cm) at harvest of early summer cauliflowers.

Block	N applied (nominal)	Soil N dff		Fertiliser remaining in soil
	kg/ha	%	*kg/ha*	%
1	120	0.07	1	1
2		-0.01	0	0
3		-0.03	0	0
mean		*0.01*	*0*	*0*
1	240	-0.08	-1	0
2		0.15	2	1
3		0.05	1	0
mean		*0.04*	*0*	*0*

N derived from fertiliser in the soil was concentrated in the 0-15 cm depth increment, being 31 and 95 kg/ha in the 120 and 240 kg/ha N treatments, respectively. For the 15-30 cm depth increment, the values were 2 and 7 kg/ha N, respectively, and below 30 cm were essentially negligible.

Table 6e. Labelled fertiliser remaining in soil (90-120 cm) at harvest of early summer cauliflowers.

Block	N applied (nominal)	Soil N dff		Fertiliser remaining in soil
	kg/ha	*%*	*kg/ha*	*%*
1	120	-0.10	-1	-1
2		0.09	1	1
3		-0.11	1	1
mean		*0.03*	*0*	*0*
1	240	0.05	1	0
2		0.01	0	0
3		0.13	1	1
mean		*0.04*	*1*	*0*

Using the data from Tables 3, 5 and 6, it is possible to calculate the total applied N recovered in the soil-plant system at the harvest of the early summer cauliflowers. These results are shown in Table 7. Total recovery of fertiliser N was 82 kg/ha for the nominally 120 kg/ha N (actual 131 kg/ha N) treatment, and 170 kg/ha for the nominally 240 kg/ha N (actual 224 kg/ha N) treatment.

Table 7. N recovered in the soil-plant system at harvest of the early summer cauliflower crop.

Block	N applied (nominal)	N recovered
	kg/ha	*kg/ha*
1	120	85
2		79
3		NA
mean		*82*
1	240	179
2		130
3		202
mean		*170*

2.3.3 Autumn cauliflower crop

Table 8. Dry matter and N uptake by the autumn cauliflower crop.

Block	1st N (nominal)	2nd N	DM		N uptake	
	kg/ha		*t/ha*		*kg/ha*	
			split plot	microplot	split plot	microplot
1	0	0	4.3	4.1	119	133
2			5.1	5.1	104	133
3			4.1	7.2	105	322
mean			*4.5*	*5.5*	*109*	*196*
1	0	120	5.8	6.2	185	242
2			6.1	6.1	191	242
3			6.1	6.4	196	173
mean			*6.0*	*6.2*	*191*	*219*
1	0	240	5.8	6.4	189	266
2			6.1	6.5	217	278
3			6.2	7.4	207	254
mean			*6.0*	*6.8*	*204*	*266*
1	120	0	6.0	5.7	205	228
2			6.0	5.9	193	275
3			5.9	6.4	192	210
mean			*6.0*	*6.0*	*196*	*238*
1	120	120	6.1	6.4	223	279
2			6.3	6.1	198	254
3			6.3	7.3	268	315
mean			*6.2*	*6.6*	*229*	*283*
1	240	0	6.1	6.7	213	293
2			6.7	7.0	227	313
3			6.4	12.2	212	476
mean			*6.4*	*8.6*	*217*	*361*
1	240	120	6.8	6.7	265	225
2			6.8	6.8	252	318
3			6.8	8.0	240	361
mean			*6.8*	*7.2*	*252*	*301*

The results of determinations of dry matter and N uptake for the split plots and the microplots for the second crop are given in Table 8.

Paired t-tests indicated significant differences ($P<0.05$) between split plots and microplots for N uptake, with N uptake being greater in the microplots. Analysis of variance (0 and 120 kg/ha second N application, only) indicated that there was a significant ($P<0.05$) response of N uptake to N application for the split plots but not for the microplots. Mean values for the split plots were 174 and 224 kg/ha N, for the 0 and 120 kg/ha N applications, respectively, compared to 265 and 268 kg/ha N for the microplots. It is also apparent that there is an anomalously large result for dry matter uptake from one of the microplots: in block 3 for the 240+0 kg/ha N treatment.

Table 9. N in autumn cauliflower crop derived from fertiliser applied to early summer crop.

Block	1st N (nominal)	2nd N	Crop N dff by ^{15}N		Crop N from fertiliser by difference	
	kg/ha		%	kg/ha	kg/ha split plot	kg/ha microplot
1	120	0	22	50	86	95
2			23	62	90	141
3			16	34	87	-111
mean			*20*	*49*	*87*	*42*
1	120	120	24	68	37	37
2			13	33	7	12
3			12	39	72	141
mean			*17*	*47*	*38*	*63*
1	240	0	34	101	94	161
2			31	96	123	180
3			36	170	107	154
mean			*34*	*122*	*108*	*165*
1	240	120	15	35	79	-18
2			26	84	61	76
3			30	107	44	187
mean			*24*	*75*	*61*	*82*

Table 9 shows both the proportion and quantity of N derived from the fertiliser applied to the early summer crop taken up by the autumn crop. As in Table 3, the calculations are based on N uptake values for the microplots only. For both crop N derived from fertiliser by ^{15}N and by difference, the control plots in each block are those corresponding to the nil fertiliser applied to the second crop but the same rate of fertiliser applied to first crop. Thus, for example, the control plot for the 120+120 kg/ha N treatment is 0+120 kg/ha N.

Analysis of variance indicated that crop N from fertiliser by difference in the split plots was significantly ($P<0.05$) less in the 120 kg/ha N second application treatment than in the 0 kg/ha N second application treatment. However, in the microplots there were no significant differences ($P>0.05$) between the second fertiliser application treatments for N derived from fertiliser expressed either as proportion or on a kg/ha basis, or for crop N from fertiliser by difference. A paired t-test indicated no significant difference ($P>0.05$) between the methods of calculation of fertiliser recovery for microplots.

Table 10. Recovery of residue and fertiliser N applied to the first crop by the second crop.

1st N (nominal)	2nd N	1st crop N residue dff	Soil N at 1st crop harvest dff	2nd crop N recovery	
kg/ha	*kg/ha*	*kg/ha*	*kg/ha*	*kg/ha*	*%*
120	0	28	33	49	80
120	120	28	33	47	77
240	0	36	103	122	88
240	120	36	103	75	54

Calculation of the proportion of fertiliser N added to the first crop and remaining after harvest (either as crop residue or in the soil) which was taken up by the second crop is shown in Table 10. Fertiliser derived residue N returned to the soil after harvest of the first crop has been calculated using a N harvest index of 0.47 (the average for the 120 and 240 kg/ha N treatments). Where no N had been added to the second crop, recovery of N derived from fertiliser applied to the first crop amounted to 80% and 88%, for the 120 and

240 kg/ha N treatments respectively. Where 120 kg/ha N was added to the second crop, recovery was reduced, particularly for the 240 kg/ha N application to the first crop (Table 10).

2.3.4 Nitrogen offtake in marketable cauliflower curds

Table 11. N offtake and N derived from first N application fertiliser for marketable curds.

Block	1st N (nominal)	2nd N	N offtake by marketable curds	N dff in marketable curds
	kg/ha		*kg/ha*	*kg/ha*
1	0	0	108	
2			94	
3			252	
mean			*151*	
1	0	120	169	
2			154	
3			127	
mean			*150*	
1	0	240	167	
2			195	
3			181	
mean			*181*	
1	120	0	198	43
2			252	46
3			203	51
mean			*217*	*47*
1	120	120	210	55
2			218	37
3			240	56
mean			*222*	*49*
1	240	0	229	87
2			297	80
3			357	99
mean			*293*	*89*
1	240	120	191	56
2			268	84
3			270	78
mean			*243*	*73*

The total N offtakes in marketable curds and the quantities derived from ^{15}N labelled fertiliser applied to the early summer crop are given in Table 11. The values are calculated using the N harvest indices for the whole plots of the first crop and the split plots of the second crop, and the respective N uptakes for the microplots.

2.4 Discussion and Conclusions

Response to N application

The results from the microplots for N uptake by the first (early summer) cauliflower crop (Table 1) are consistent with those presented for the trial as a whole (Rahn, 1993) in that N uptake is significantly increased ($P<0.05$) by N application. For dry matter yield, however, the microplots showed a significant response ($P<0.05$) to N application, whereas whole plots did not. Previously reported results (Rahn, 1993) showed no consistent effect of N application on dry matter yield: in the first HDC sponsored trial there was no effect in the trial as a whole, while in the second MAFF sponsored trial there was a response in dry matter yield. For the second (autumn) cauliflower crop, previous results had indicated that N uptake responded to both the first and second applications of N (Rahn, 1993). However, this was not the case for the microplots (Table 8) which showed no significant response to the second N application.

In addition, there were consistent differences between whole/split plots and microplots (Tables 1, 2 and 8) with microplots giving generally greater N uptakes for all treatments. It is tempting to suggest that this reflects the slight differences in N applied to whole plots and microplots, but N was applied at higher and lower rates to the nominal 120 kg/ha and 240 kg/ha treatments, respectively, and in any case differences are also apparent in the control (0 kg/ha N) treatments. It is likely, therefore, that the differences are due to errors in the factors used to convert the raw data to an area basis. The lack of a significant response in microplots to the second N application can probably be ascribed to greater variability among replicates due to their small size compared to the split plots.

Recovery of N fertiliser

Analysis of variance indicated no significant differences ($P>0.05$) between N treatments for both cauliflower crops for N derived from fertiliser expressed either on a proportion of total crop N or a kg/ha basis (Tables 3 and 9). Logically, if there is no difference in the proportion of crop N for different N application rates then there should be a difference on a kg/ha basis, and *vice versa*. The variance associated with these measurements is large, so that difference between treatments, if they exist, are masked. For both cauliflower crops, average values for crop N derived from fertiliser as a proportion of total crop N and on a kg/ha basis are greater for the 240 kg/ha N first application than for the 120 kg/ha first application. Greenwood and Draycott (1988) found that N recovery from fertiliser expressed as a proportion and determined by the difference between fertiliser treatments and a (no fertiliser) control decreased linearly with fertiliser application rate for a range of vegetable crops. Expressed on a kg/ha basis, fertiliser recovery was related to application rate by a negative quadratic function.

Of more interest is the comparison between crop N derived from fertiliser as determined by ^{15}N and that by the difference in N uptake between fertilised and control plots (Table 3 and 9). If the crop exploits soil and fertiliser N in proportion to their relative amounts in the soil, uptake from fertiliser and native soil sources will be proportional to their relative contributions to the mineral N pool, averaged over the growing season (Barraclough *et al.*, 1985). These contributions are primarily affected by the magnitude of mineralisation/immobilisation turnover cycles (MIT), in which (labelled) fertiliser and soil nitrogen removed from the mineral N pool by immobilisation is replaced by unlabelled mineralised soil nitrogen. This process, known as pool substitution (Jenkinson *et al.*, 1985), lowers the proportion of the mineral N pool composed of labelled fertiliser. The results for the first cauliflower crop (Table 3) are consistent with such a process since crop N uptake derived from fertiliser as determined by ^{15}N is less than the difference in N uptake between fertilised and control plots. It is possible that this may represent a real increase in crop N uptake from native soil sources due to fertiliser addition, if for example fertiliser N increased the volume of soil explored by roots. However, such positive added nitrogen interactions (ANIs) have been observed in many other studies, and have usually been ascribed to pool substitution driven by MIT. The calculated fertiliser recovery values (Table 4) are therefore lower than the 'true' fertiliser efficiencies. For the first cauliflower crop, fertiliser recovery of ^{15}N averages 35%, whereas the fertiliser efficiency calculated by the difference in N uptake between fertilised and control plots averages 44%. For the second cauliflower crop, there was no significant difference between crop N derived from fertiliser determined by ^{15}N and that determined by the difference between fertilised and control plots

(Table 9). However the variance associated with (in particular) the latter measurement was very large.

N balance for the early summer cauliflower crop

The results of the soil analyses taken at the harvest of the first (early summer) cauliflower crop indicated that most of the residual fertiliser remained in the 0-15 cm depth increment. Very little of the fertiliser N had moved below this depth. Rainfall for the growing period of this crop was average (Rahn, 1993), and it is not surprising that very little leaching of N took place.

However, when the total recovery of fertiliser N in the soil-plant system is calculated (Table 7), a sizeable proportion is unaccounted for. Recoveries of less than 100% of labelled fertiliser N are commonly reported in the literature, and are usually ascribed to gaseous loss (Vos *et al.*, 1993). Gaseous losses due to denitrification are considered to be the major pathway (Powlson *et al.*, 1992), while losses in the form of ammonia are generally thought to be relatively small (Schjorring *et al.*, 1989).

Four possible reasons may account for the low recovery of labelled fertiliser N at harvest of the first cauliflower crop: (i) an error in the amount of labelled fertiliser added to the microplots; (ii) invalid assumptions used in calculating fertiliser recovery; (iii) N in roots is not accounted for; and (iv) real loss of fertiliser N from the crop-plant system.

The amount of labelled fertiliser applied to the microplots was determined using gravimetric and volumetric analytical procedures, and it is unlikely that this could account for the low recovery. More likely is an error in the area of the microplots. Consistent differences between whole plots and microplots with respect to N uptake might suggest that microplots were actually larger than has been assumed in the calculations. However, use of a larger area for the microplots in the calculations would tend to decrease N derived from fertiliser for the crop, and increase it for the soil. The effect on total recovery in the soil-plant system is uncertain, but would probably not be large.

A major assumption used in calculating the N derived from fertiliser in the soil is the value of the soil bulk density. The value of 1.333 g/cm^3 is probably an overestimate, particularly for the topsoil where the major proportion of the fertiliser derived N is found. This error would overestimate N derived from fertiliser in the soil, and hence increase apparent fertiliser recovered in the soil-plant system.

Other workers have suggested that recoveries of less than 100% of N derived from fertiliser in the soil-plant system may in part be ascribed to the fact that root N is not included in calculations of total recovery (Vos *et al.*, 1993). At harvest, however, with a dispersed root system, part of the root N will be included in the soil organic fraction.

It seems likely, therefore, that the less than 100% recovery of fertiliser derived N represents a real loss from the soil-crop system. Given the time of year and the distribution of fertiliser derived N in the soil profile (Tables 6a-e) losses by leaching can be considered to be negligible. Gaseous losses must therefore be the dominant mechanism.

N balance calculations for the first (early summer) cauliflower crop reported previously (Rahn, 1993) suggested that net mineralisation of organic N occurred where no fertiliser N had been applied, and that this decreased with increasing quantity of applied fertiliser N, such that where greater than 180 kg/ha N was applied net immobilisation took place. These calculations are reproduced in Table 12. Data for the whole plots are used.

The balance term represents the net change in the soil-crop system after accounting for inputs (transplanted crop, fertiliser), outputs (harvested crop) and the net change in the soil mineral nitrogen pool between planting and harvest. Therefore, it actually represents the net effect of mineralisation-immobilisation, leaching and gaseous exchange. Gaseous exchange components may be positive (wet and dry deposition) and negative (nitrification, denitrification, ammonia volatilisation). As indicated above, leaching losses can probably be neglected in this study, so that the balance term represents the combined effect of mineralisation-immobilisation and gaseous exchange.

The term 'Fertiliser N lost' has been calculated from Table 7 by expressing the N not recovered as a percentage of the actual fertiliser N rates applied to the microplots (131 and 224 kg/ha N), and using this percentage to calculate fertiliser not recovered for the rates used on the whole plots. Assuming that the unaccounted for N derived from fertiliser is a loss by gaseous exchange, adding in a term for N deposition from the atmosphere will give a recalulated balance which represents mineralisation-immobilisation. In fact, if the gaseous loss is dominantly via the plant, using the value for unaccounted for N derived from fertiliser will underestimate the total loss, because plant uptake will be from both fertiliser and soil sources. However, the assumption serves as a good first approximation. Ammonia dry deposition is believed to dominate total N deposition. It is not possible to give a reliable estimate because dry deposition depends on factors such as ambient ammonia concentration, the interaction with other (particularly S) species in the atmosphere, atmospheric stability and the crop compensation point, all of which show strong diurnal and seasonal variations. Given the extent of the uncertainties, a figure of 40 kg/ha N has been assumed (Goulding, 1990). The recalculated N balance now indicates only a small contribution from net mineralisation, although the value is crucially dependent on the value used for atmospheric N deposition.

Table 12. N balance calculation for the early summer cauliflower crop.

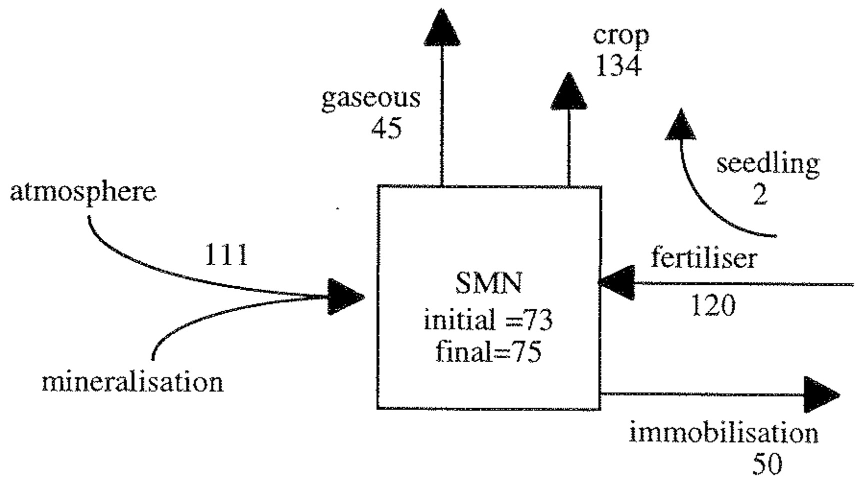
Term	Treatment		
	0 kg/ha N	120 kg/ha N	240 kg/ha N
Transplanted crop N	-2	-2	-2
Soil mineral N at planting	-73	-73	-73
Fertiliser N	0	-120	-240
Crop N harvested	91	136	164
Soil mineral N at harvest	37	75	147
Balance at harvest	**53**	**16**	**-4**
Fertiliser N lost	0	45	58
Atmospheric N deposition	-40	-40	-40
Recalculated balance	**15**	**21**	**14**

These data apply to a 92 day period, and hence an average net mineralisation rate can be calculated of *ca.* 0.18 kg/ha.day N. This compares to a default value of 0.79 kg/ha.day N for a season in the WELL-N model (Greenwood and Draycott, 1989) which describes the response of vegetable and arable crops to N fertiliser. However, in this model no account is taken of atmospheric N deposition. If this contribution is excluded from the data of Table 12, an average mineralisation rate of *ca.* 0.61 kg/ha.day N is suggested.

N cycle for the early summer cauliflower crop

In addition to using the ^{15}N data to estimate N balances for the fertilised treatments, and hence net mineralisation/immobilisation, it is also possible to estimate gross mineralisation and immobilisation rates by invoking the process of pool substitution (discussed above). Thus, processes which remove N from the labelled (mineral N), pool do not alter the $^{15}N/^{14}N$ ratio of that pool, whereas those which contribute N to the pool lower the $^{15}N/^{14}N$ ratio. Barraclough *et al.* (1985) have derived equations for the average composition over time of a mineral N pool to which labelled N is added at zero time, into which mineralisation introduces N at a constant rate and at natural ^{15}N abundance, and from which plant uptake and/or denitrification, leaching, etc. may remove N, again at a constant rate (see their equation A9). The average ^{15}N composition of the mineral N pool is, of course, a function of both the inputs to and outputs from that pool, so that in order to solve the equation for both of these unknowns a second independent equation is required. In this study this is provided by soil mineral N analysis at the beginning and end of the period (i.e. the change in soil mineral N is simply the arithmetic difference between total inputs and total outputs). It is possible to solve these simultaneous equations using numerical methods. The results of this analysis, combined with the N balance calculations, are illustrated in Figure 2.

These results seem to suggest that MIT in the 120 kg/ha N treatment is approximately 50 kg/ha N over the 92 day period, but is about ten times greater in the 240 kg/ha N treatment. Although it is possible that there are differences in gross rates of mineralisation and immobilisation due to differences in fertiliser applications rates, it seems unlikely that they could be of this magnitude. A sensitivity analysis for the 240 kg/ha N treatment indicated that the numerical solution for gross mineralisation was not greatly sensitive to the input value of the time average ^{15}N composition. The most likely explanation for the large discrepancy between treatments, is that the assumption of constant rates of inputs to and outputs from the mineral N pool is not valid. There is a body of evidence which suggests that application of fertiliser leads to short-term immobilisation of N by the microbial biomass followed by a slower mineralisation phase. The effect of this of the average composition of ^{15}N labelled mineral N pool is probably to reduce it below that which would have pertained had gross rates of inputs to and outputs from the pool remained constant in time. Under this scenario, gross rates for inputs and outputs would be over estimated if they were calculated using the assumption that they were constant in time.



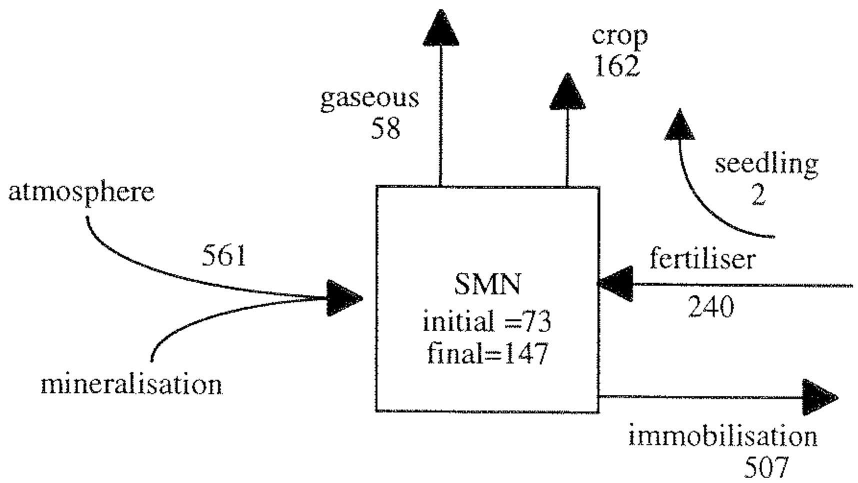


Figure 2. Calculated N cycle for the early summer cauliflower crop at two fertiliser rates, assuming constant rates for all processes.

N balance for the autumn cauliflower crop

It has previously be reported (Rahn, 1993) that N residues from the first (early summer) cauliflower crop were substantial, ranging between 100 and 250 kg/ha N. Soil mineral analyses at harvest of the first, and at planting of the second cauliflower crop, indicated that a large proportion of the residue N in the first crop had mineralised during this period. The ^{15}N results tend to support these observations (Table 10); thus, very high recoveries of N remaining from the fertiliser applied to first crop were obtained in the second crop. Where no additional fertiliser was applied, recoveries of between 80 and 88% were obtained. Where 120 kg/ha N was applied to the second crop, high recovery (77%) was maintained in the 120 kg/ha first application N, but was somewhat reduced (54%) in the 240 kg/ha first application N.

Table 13. "Available" (i.e. soil mineral + fertiliser + crop residue) N and N uptake in total and derived from labelled fertiliser.

1st N (nominal)	2nd N	"Available" N	N uptake	"Available" N	N uptake
		(total)		(dff)	
kg/ha		*kg/ha*		*kg/ha*	
120	-	204	161	131	52
240	-	297	188	224	67
120	0	103	238	61	49
120	120	223	283	61	47
240	0	183	361	139	122
240	120	303	301	139	75

In addition, in the first HDC sponsored trial, fertiliser N applied to the first crop increased N uptake by the second crop by approximately the same increment as freshly applied N. N uptake by the second crop of fertiliser applied to the first crop expressed as a proportion of the total available (i.e. fertiliser remaining in the soil plus that in the first crop residue) is strongly correlated with total N uptake by the second crop as a portion of total N available (Table 13) ($P<0.001$, $n=6$). This also suggests that residual fertiliser N either in the soil or as crop residue has the same effect in increasing N uptake as other N (fresh fertiliser, soil) sources.

Conclusions

Results reported previously (Rahn, 1993) have shown that large responses in marketable yield of cauliflowers and N offtake can be expected to N fertiliser application in N index 0 situations. However, responses to subsequent applications depended on the previous application. The results suggested that the contribution of brassica residues to the nutrition of subsequent crops has in the past been underestimated, and that soil mineral nitrogen analyses would provide an adequate method of taking these into account.

This ^{15}N study fully supports this conclusion. In particular, the high recoveries obtained of fertiliser applied to the first (early summer) cauliflower crop by the second (autumn) crop indicate the necessity to take into account both residual fertiliser and crop residue N when determining fertiliser recommendations.

The ^{15}N study, however, has provided some additional insights into the N cycling processes controlling N nutrition in these crops. Firstly, in this study at least, it is apparent that residual fertiliser and crop residue N have as much value to a following crop as other forms of N (including freshly applied fertiliser N). Secondly, fertiliser N applied to an early summer cauliflower crop does not seem to move to any great extent below 15 cm. Thirdly, there seems to be a significant gaseous N loss mechanism, which has not been properly accounted for in the past, possibly because these losses have been more or less balanced by atmospheric inputs. In addition, the ^{15}N study has indicated the dynamic nature of the mineralisation - immobilisation process, and the results suggest that the net effect may be similar irrespective of fertiliser rate, contrary to previous conclusions drawn solely from soil mineral N analyses (Rahn, 1993).

2.5 References

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