HGCA

PROJECT REPORT No. 46

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by

I. P. McTAGGART AND K. A. SMITH

Final report of a four year project which was carried out at The Scottish Agricultural College–Edinburgh, Edinburgh School of Agriculture, West Mains Road, Edinburgh EH9 3JG. The work commenced in May 1987 and was funded by a grant of £110,238 from the Home-Grown Cereals Authority (Project No. 0021/5/87).

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EXECUTIVE SUMMARY

1. Work was carried out over a 4 year period from 1987 to 1991, to study the effect of nitrogen on the yield and grain nitrogen concentration of spring barley grown for malting. The research undertaken can be divided into two main areas:

(a) The effect of the rate, timing of application and the form in which fertiliser nitrogen was applied on nitrogen uptake and grain nitrogen content of spring barley; calcium nitrate, ammonium sulphate and ammonium nitrate fertilisers were applied at rates up to 150 kg N/ha at sowing, with some treatments split between sowing and emergence, or between sowing and tillering.

(b) The assessment of two chemical extraction techniques used to determine the potentially mineralisable native soil nitrogen, and its likely uptake into the crop.

2. The form of fertiliser nitrogen applied had little effect on grain nitrogen concentrations, except under dry soil conditions when concentrations were higher using calcium nitrate fertiliser (Section 1.1, Section 2.1).

3. Fertiliser applications in the form of calcium nitrate improved grain yields at low fertiliser rates, but at rates nearer recommended levels there was little difference in yield between fertiliser forms (Section 1.1).

4. Split or late applications of 120 kg/ha fertiliser nitrogen only improved yields when applied as calcium nitrate, and then only when early applications had been followed by heavy rain, increasing the risk of leaching losses (Section 1.1).

5. In 1989 split applications at the lower rate of 90 kg N/ha improved yields to the equivalent of those obtained with 120 kg N/ha applied at sowing. There was no increase in grain nitrogen concentrations (Section 1.1.3).

6. At low fertiliser rates, the efficiency of recovery of fertiliser nitrogen (^{15}N) in the plant shoots was greater when applied as calcium nitrate than when applied as ammonium sulphate or ammonium nitrate. Efficiency of recovery fell at higher rates in the calcium nitrate treatments, but rose in the ammonium

sulphate treatments. Under the dry soil conditions in 1989 the efficiency of recovery was significantly increased in all fertiliser treatments (Section 1.2).

7. Uptake of fertiliser nitrogen was rapid in the calcium nitrate and ammonium nitrate treatments, usually reaching a maximum by flowering. There was evidence of losses between flowering and harvest of up to 26 kg N/ha of fertiliser nitrogen previously taken up by the crop. This could have been due to gaseous losses from old plant tissue or through root exudation. There was little evidence of losses in the ammonium sulphate treatments in which plant uptake of fertiliser nitrogen was slower, but continued several weeks longer than the other fertiliser forms (Section 3.1).

8. The uptake of soil nitrogen (unlabelled N) in the calcium nitrate treatments remained constant over the range of rates and timings of fertiliser application. There was evidence of increasing uptake of soil nitrogen with increased rates of ammonium sulphate fertiliser at several sites. This appeared to be due to 'pool substitution' of ^{15}N-labelled fertiliser nitrogen with unlabelled soil nitrogen by soil micro-organisms. This required complete mixing of fertiliser and soil nitrogen which only occurred at sites with more moist soil conditions. Therefore there was no evidence of a real priming effect of fertiliser nitrogen applications increasing the rate of mineralisation of soil organic matter (Section 1.2).

9. Uptake of soil nitrogen was less rapid than fertiliser nitrogen before flowering, but continued right up to harvest in most treatments. Prior to flowering uptake was often greater in the ammonium sulphate treatments which again indicated the probable occurrence of pool substitution of ^{15}N-labelled fertiliser (Section 3.1).

10. Late uptake of soil nitrogen occurred despite the amount of mineral nitrogen in the soil having fallen to pre-fertilisation levels. This suggested the occurrence of net mineralisation of soil organic matter up to harvest (Section 5).

11. The most significant factor in determining total nitrogen uptake in the crop was the soil on which the barley was grown, rather than any of the fertiliser management treatments studied. Soil nitrogen uptake was significantly more variable between sites than fertiliser nitrogen uptake, despite the similar cropping histories at most sites (Section 1.1.4, Section 2.2).

12. The variation in soil nitrogen uptake was derived mainly from differences in the mineralisation of soil organic matter over the growing season, rather than from the amount of mineral nitrogen in the soil at sowing (Section 5).

13. Good correlations were found on all ADAS N-Index zero soils, between soil nitrogen taken up in the plant and values obtained using the chemical extraction techniques for measuring potentially mineralisable nitrogen (Section 6.2.1).

14. Soil organic matter was not a good predictor of potentially mineralisable nitrogen, but when used in conjunction with estimates from the chemical extraction techniques correlations were better than using chemical extraction predictions alone (Section 6.2.2).

15. The correlation between soil mineral nitrogen at sowing and soil nitrogen uptake was even better than that with the chemical extraction techniques; soil mineral nitrogen at sowing and extractable nitrogen were also highly correlated, but this was not so for mineral nitrogen measured in January.

16. Suggestions for future work are as follows:

(a) Validation of the initial results from the chemical extraction techniques over a wide range of soil types.

(b) Investigation of whether the time of sampling will alter the estimated potentially mineralisable nitrogen. Earlier times for sampling will be necessary if the technique is to be used to advise farmers on modifications to standard recommended rates of fertiliser application.

INTRODUCTION

This report describes work carried out over a 4 year period from 1987 to 1991, to study the effect of nitrogen on the yield and grain nitrogen concentration of spring barley grown for malting. The research undertaken can be divided into two main areas:

(a) Over the first 3 years (1987-1989), research was concentrated on the effect of the rate, timing of application and the form in which fertiliser nitrogen was applied on nitrogen uptake and grain nitrogen content of spring barley; calcium nitrate, ammonium sulphate and ammonium nitrate fertilisers were applied at rates up to 150 kg N/ha at sowing, with some treatments split between sowing and emergence, or between sowing and tillering. Trials were carried out at two sites each year, details of which are given in the next Section.

(b) In 1990 trials were undertaken on a wider range of sites with a reduced number of treatments at each site. Research was concentrated upon the assessment of two chemical extraction techniques used to determine the potentially mineralisable native soil nitrogen, and its likely uptake into the crop. Details of the trial sites are given in the next Section.

METHODS

1: Site Preparation and Fertiliser Application

1.1: Sites, 1987-1989 seasons

Two sites were selected in each of the three years 1987-1989 to study the effects of rate, form and timing of nitrogen fertiliser applied to spring barley grown for malting. Details of these sites are given in Table 1. All of these sites were located within larger main trial sites managed by the Scottish Agricultural College, Crop Production and Advisory Department (CPAD). CPAD staff were responsible for the preparation, application of basal rates of P and K fertiliser, sowing and general management of the trial plots. Their assistance is gratefully acknowledged. The trials involved three forms of nitrogen fertiliser, each applied at several different rates and timings (Table 3). The three forms of fertiliser compared contained (a) all the nitrogen in the nitrate form (as calcium nitrate), (b) all the nitrogen in the ammonium form (as ammonium sulphate), and (c) equal proportions of ammonium and nitrate (as ammonium nitrate). The experiments were laid out in a randomised block design of three replicates of eight plots, with each fertiliser form as one of three split-plots within each plot.

In 1987 and 1988, applications of 120 kg N/ha were compared under several different split-timing regimes, to assess the effect on nitrogen uptake and grain nitrogen contents. Results from 1987 and 1988 showed that split applications of 120 kg N/ha tended to raise the nitrogen content of the grain above 1.7%. Therefore it was decided that in 1989 the fertiliser rate of 90 kg N/ha would also be applied under several split-timing regimes to try to ensure a lower grain nitrogen content.

1.2: Fertiliser application procedures

The appropriate nitrogen compound labelled with ^{15}N (ca. 5 atom per cent) was mixed with unlabelled nitrogen fertiliser of the same form (containing ^{15}N at the natural isotopic abundance of 0.366 atom per cent), to dilute the ^{15}N to ca. 0.7 atom per cent, ie about twice the natural abundance. This was done for each of the microplots by dissolving the appropriate weights, corresponding to the required fertiliser rates in 500 ml of water. Small samples of each fertiliser solution were then analysed to confirm the isotopic

Table 1: Details of sites for study of N requirements for spring-sown malting barley.

	1987		1988		1989	
LOCATION	Bush Lothian	Lintlaw Borders	Bush Lothian	Middlestot Borders	Bush Lothian	Upper Cairnie Perthshire
ELEVATION (m)	180	76	205	85	195	105
SOIL SERIES	Darvel	Hobkirk	(Alluvium)	Whitsome	Easter Bush	Balrownie
TEXTURE	SCL	SL	SL	SCL	SCL	SCL
(%)						
coarse sand	26.9	15.5	28.4	18.6	29.8	28.9
fine sand	30.5	53.0	32.4	34.2	28.0	30.2
silt	24.1	21.1	23.0	28.7	27.4	25.9
clay	14.5	10.5	16.2	18.6	14.9	15.0
pH	6.1	6.5	6.5	6.7	6.4	6.7
O.M.(%)	3.8	3.0	3.7	2.3	3.4	1.8
VARIETY	Golf	Corgi	Blenheim	Sherpa	Blenheim	Blenheim
PREVIOUS CROPPING						
1988	--	--	--	--	W. barley	O. S. R.
1987	--	--	W. barley	S. barley	W. barley	W. barley
1986	W. wheat	W. barley	W. barley	W. barley	W. barley	--
1985	Potatoes	S. barley	W. barley	S. barley	W. barley	--
1984	S. barley	Swedes	W. barley	S. barley	--	--
1983	W. barley	W. wheat	--	--	--	--

Table 2: Details of 1990 sites for study of N requirements for spring-sown malting barley.

LOCATION	Manorhill Borders	Quixwood Borders	Bush Lothian (Crofts)	Bush Lothian (F. Holding)	Treaton Fife	Kettle Fife
ELEVATION (m)	105	195	190	175	90	45
SOIL SERIES	Smailholm	Ettrick	(Alluvium)	E. Bush/ Macmerry	Darvel	Eckford
TEXTURE	SL	CL	SL	SCL	SL	LS
(%)						
coarse sand	26.2	16.8	30.7	29.0	34.4	32.2
fine sand	34.4	19.4	25.8	26.6	32.3	48.6
silt	26.9	42.2	25.6	28.8	20.5	11.4
clay	12.5	21.6	18.0	15.6	12.8	6.7
pH	6.1	6.2	5.7	6.0	6.4	6.7
O.M.(%)	2.4	5.1	4.7	3.3	5.7	2.8
VARIETY	Camargue	Blenheim	Blenheim	Blenheim	Blenheim	Blenheim
PREVIOUS CROPPING						
1989	W. barley	S. barley	W. wheat	W. wheat	S. barley	Br. sprout
1988	W. wheat	W. barley	Potatoes	Potatoes	S. barley	W. barley
1987	Potatoes	S. barley	S. barley	W. barley	W. wheat	W. barley
1986	S. barley	W. wheat	W. barley	S. barley	Potatoes	Calabrese

Table 3: Nitrogen application rates and timings

1987, 1988			1989		
Sowing	Brairding (Emergence)	Tillering	Sowing	Brairding (Emergence)	Tillering
0	0	0	0	0	0
60	0	0	60	0	0
90	0	0	90	0	0
120	0	0	120	0	0
150	0	0	45	45	0
60	60	0	45	0	45
60	0	60	0	90	0
0	120	0	60	60	0

composition of the fertiliser. To each 2 m x 1.5 m microplot, this solution was applied in the form of a spray. The spray was applied by hand in a steady pattern of cross-sweeps to ensure a uniform application of fertiliser. The remainder of each split-plot received the equivalent rate of unlabelled fertiliser, hand-broadcast at the same rate. Plastic covers were placed over the ^{15}N microplots while the unlabelled fertiliser was applied, to ensure that there was no contamination with this material. On each subsequent occasion when more nitrogen fertiliser was applied, a separate microplot was treated with labelled nitrogen while the remaining area (including the microplot previously receiving labelled nitrogen) received unlabelled fertiliser.

1.3: Sites, 1990 season

In 1990 the effect of different sites on the uptake of soil nitrogen was examined more closely. Trials were set up at six sites (Table 2) with a reduced number of fertiliser rates and forms. Two sites (Crofts and Treaton) were located within larger trial sites managed by CPAD and the procedure followed was the same as in the previous three years (Section 1.1:). Three of the other sites were situated on commercial farms and the fourth was situated on the Edinburgh School of Agriculture's Bush Estate. At all four sites, the trial plot area was left unfertilised after sowing while the rest of the field was fertilised with NPK compound fertiliser by the farm staff. P and K fertiliser was hand-broadcast over the plot area at the same rate as the rest of the field. Then a single rate (120 kg N/ha) of nitrogen fertiliser was applied in only two fertiliser forms, ammonium sulphate and ammonium nitrate, together with a zero N control treatment. The trials were laid out in a randomised block design with

three replicates of two fertiliser treatments with each fertiliser form as one of two split-plots within each main plot. The ^{15}N-labelled and unlabelled fertilisers were applied to the appropriate areas as described above (Section 1.2:).

2: Plant Sampling, Preparation and Analysis

In 1987-1989, plant samples were taken from the microplots on up to five occasions during the growing season. Two 0.5 m rows were cut on each occasion to within a few mm of ground level. Larger areas (0.5 m^2) were also sampled from the unlabelled parts of the plots for dry matter determination. All plant samples were oven dried at 100°C. Dry matter yields were recorded and then the dry matter samples discarded. Samples from the ^{15}N-treated microplots were milled in a hammer mill and then sub-samples (5 g) were finely ground in an agate ball mill to produce a very fine flour-like consistency. This was necessary to achieve adequate homogeneity in the very small samples taken for ^{15}N analysis (Robinson and Smith, 1990). Samples were analysed for total nitrogen content and the $^{15}N/^{14}N$ ratio in a single determination. From this ratio the proportions of labelled and unlabelled nitrogen taken up by the crop were calculated as follows.

$$\%NDFF = \frac{x - N_0}{N_f - N_0} \times \frac{100}{1}$$

and $$\%NDFS = 100 - \%NDFF$$

where

%NDFF = % nitrogen derived from fertiliser
%NDFS = % nitrogen derived from soil
x = ^{15}N abundance of sample
N_0 = Natural background ^{15}N abundance
N_f = ^{15}N abundance of fertiliser applied

The N uptake was then calculated as follows:

Total N uptake = %N x Plant dry weight
Labelled N uptake = Total N uptake x %NDFF
Unlabelled N uptake = Total N uptake - Labelled N uptake

Fertiliser N uptake was also calculated without the need for ^{15}N data as follows:

Fertiliser N uptake = Total N uptake in the fertilised plots
- Total N uptake in the unfertilised plots

In 1990, sampling procedures were also carried out as above, except that larger samples (1 m^2) were taken for dry matter determination, and there were only four sampling dates during the growing season.

3: Soil Sampling and Analysis

3.1: Soil sampling and routine analysis

Soil samples were taken at intervals during the growing season. Samples from an area of approximately 0.5 m^2 were dug with a spade to depths of 0-20 cm and 20-40 cm, then mixed and subsampled in the field. The subsamples were stored frozen (-15^oC) until analysis could be carried out. Particle size analysis, pH and organic matter determinations were performed on bulk samples representing the complete 0-40 cm horizon. Particle size analysis was carried out by the method of Gee and Bauder (1986). Soil pH was determined in water (McLean, 1982). Soil organic matter was determined by the Walkley-Black method (Allison, 1965). Results are presented in Tables 1 and 2.

3.2: Available nitrogen analysis

Fresh soil samples from the 0-20 cm and 20-40 cm horizons were analysed for available nitrogen. They were sieved to remove stones and plant debris, and 20 g sub-samples were weighed into 250 ml conical flasks and shaken with 100 ml of 1M KCl extracting solution for one hour. The extracting

solution was then filtered (Whatman No.42 filter paper) and ammonium- and nitrate-N determined by continuous flow analysis using the methods of Crooke and Simpson (1971), and Henrikson and Selmer-Olsen (1970), respectively. In 1990 the nitrate analysis system involving copper-coated cadmium as a reducing agent, was replaced by a Chemlab Instruments Ltd. system, which used hydrazine instead.

3.3: Potentially available soil nitrogen

Potentially mineralisable nitrogen was determined on soil samples from the 0-20 cm soil horizon by two KCl hydrolysis techniques: these were slightly modified versions of those described by Whitehead (1981), and by Gianello and Bremner (1986b). In the modified Whitehead method, 12 g of fresh soil were boiled with 80 ml of 1M KCl for one hour in a 500 ml reflux flask. After cooling, the suspension was filtered (Whatman No.42) and the extract analysed for ammonium-N. A separate sub-sample of the same soil was extracted with cold 1M KCl at the same time, to measure the amount of ammonium-N present, prior to hydrolysis. The amount of potentially mineralisable nitrogen present in any soil was the difference between these two measured values. In the modified Gianello and Bremner method, 12 g of fresh soil were refluxed with 80 ml 2M KCl for four hours. Subsequent analysis was the same as for the Whitehead method.

RESULTS AND DISCUSSION

1: Nitrogen Uptake and Grain Nitrogen Content, 1987-1989

1.1: Grain nitrogen content and yield

Concentrations of nitrogen in the grain at each site 1987-1989, over a range of fertiliser nitrogen treatments are shown in Figures 1-3. The grain yields for the equivalent treatments are shown in Tables 4-6.

1.1.1: 1987

In 1987 the percentage nitrogen content in the grain increased with increasing rates of fertiliser nitrogen applied at both sites (Figure 1). There was little effect of fertiliser form except at 150 kg N/ha fertiliser nitrogen applied when the calcium nitrate treatment was significantly higher than the other fertiliser nitrogen forms giving a grain nitrogen content of 1.81% at Lintlaw. At Lintlaw split or late fertiliser nitrogen applications at the 120 kg N/ha level increased grain nitrogen contents in all treatments when applied in the form of calcium nitrate, but only the seedbed-tillering split-application treatment increased grain nitrogen concentrations for the ammonium fertiliser forms. Results presented for Bush are restricted to treatments where the fertiliser nitrogen was only applied at sowing. A mistake, when applying the later applications of unlabelled fertiliser, resulted in the contamination of split-treatment microplots which should have received only labelled nitrogen. Therefore the results presented are restricted to data calculated from the uncontaminated microplots.

At Lintlaw grain yields in response to fertiliser all applied at sowing levelled off at 90 kg N/ha and above, at approximately 7.5 t/ha, except for applications in the form of ammonium sulphate which rose linearly up to 8.3 t/ha when 150 kg N/ha was applied (Table 4). At the 120 kg N/ha level, there was a significant increase in yield of around 1 t/ha following applications split between sowing and tillering. Calcium nitrate applications also showed an increased yield when split between sowing and emergence, rising from 7.5 t/ha up to 8.9 t/ha.

At Bush, yields rose steeply in response to the lower rate of calcium nitrate but again there was no significant rise above 90 kg N/ha applied. Both of the other fertiliser forms showed a linear increase in yield up to 150 kg N/ha

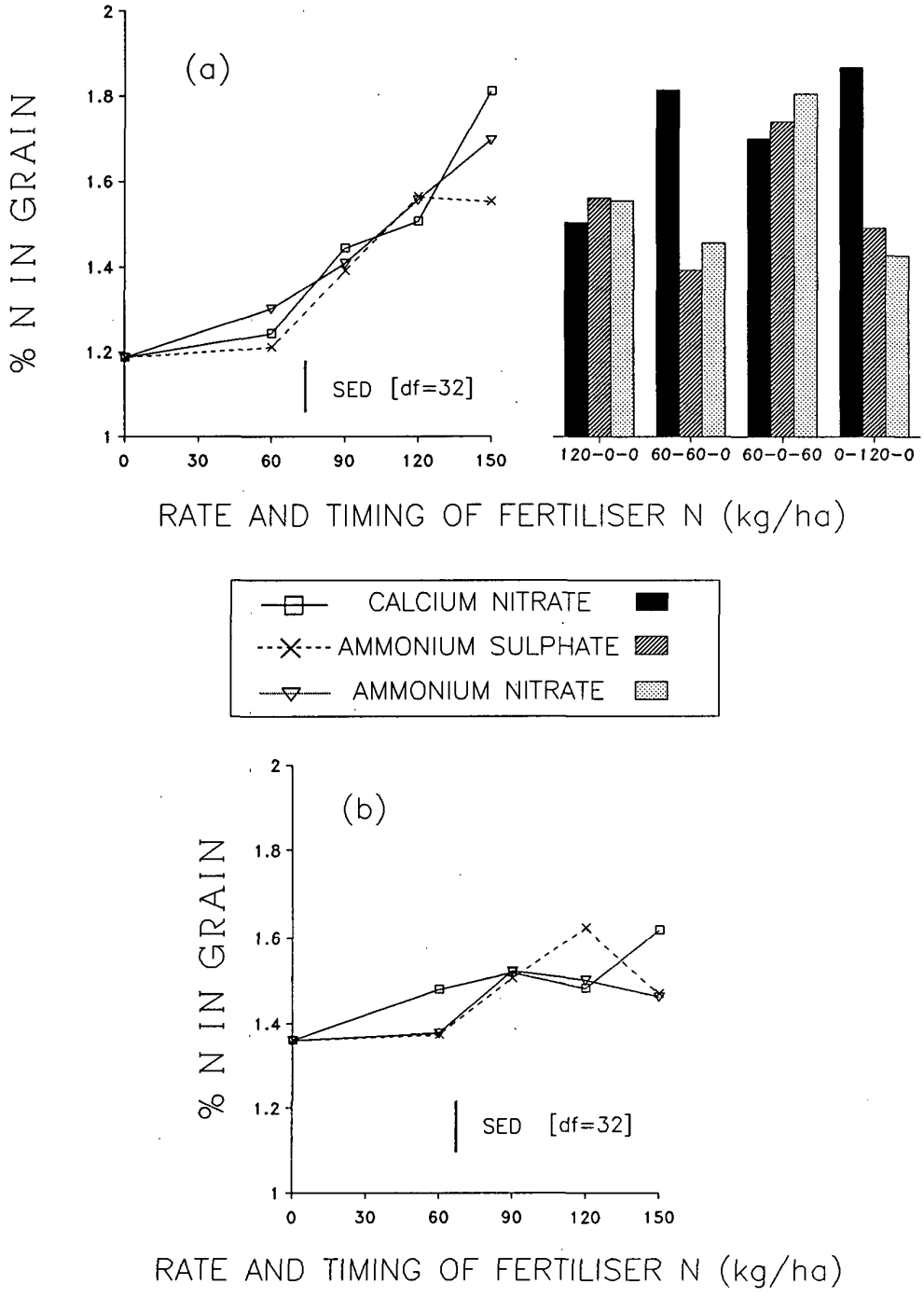


Figure 1. Nitrogen content in the grain (%) in spring barley as influenced by the rate and timing of fertiliser nitrogen applications, harvest 1987, (a) Lintlaw, (b) Bush

Table 4: Grain yields (t/ha, 15% moisture) as affected by fertiliser nitrogen applications at two sites, 1987.

N applied (kg/ha)	Bush			Lintlaw		
	CN	AS	AN	CN	AS	AN
0	4.71	4.71	4.71	3.74	3.74	3.74
60	6.60	6.10	5.10	6.01	4.86	6.29
90	6.89	8.36	6.94	7.47	6.72	7.35
120	6.51	7.04	7.67	7.48	7.28	7.21
150	7.67	7.81	8.97	6.33	8.28	7.72
60+60+0	--	--	--	8.91	6.69	7.13
60+0+60	--	--	--	8.45	8.25	8.16
0+120+0	--	--	--	6.36	7.30	7.68
	SED = 0.94 [df=8]			SED = 1.09 [df=14]		

CN: calcium nitrate; AS: ammonium sulphate; AN: ammonium nitrate

with the exception of a much higher than expected yield at 90 kg N/ha in the ammonium sulphate form.

1.1.2: 1988

In 1988 there were similar responses of grain yield to nitrogen applied at sowing to those observed in 1987 (Table 5). Calcium nitrate treatments again showed little increase in yield above 90-120 kg N/ha at either site although yields were higher at Middlestot. Both the other fertiliser forms resulted in a more gradual increase in yield up to 150 kg N/ha; yields were generally higher with ammonium sulphate than with ammonium nitrate.

Grain nitrogen contents (Figure 2) were affected little by fertiliser form; mean contents following ammonium nitrate application were lowest at all rates at Middlestot, but the differences were not statistically significant (Figure 2b). Overall, grain from Middlestot had much lower nitrogen contents than that from Bush, being under 1.6% N at all nitrogen rates up to 150 kg N/ha. There was little effect of the timing of fertiliser application at either site. The lower grain nitrogen concentrations appeared to be caused by several factors. Generally grain yields were higher at Middlestot, which meant that there was a

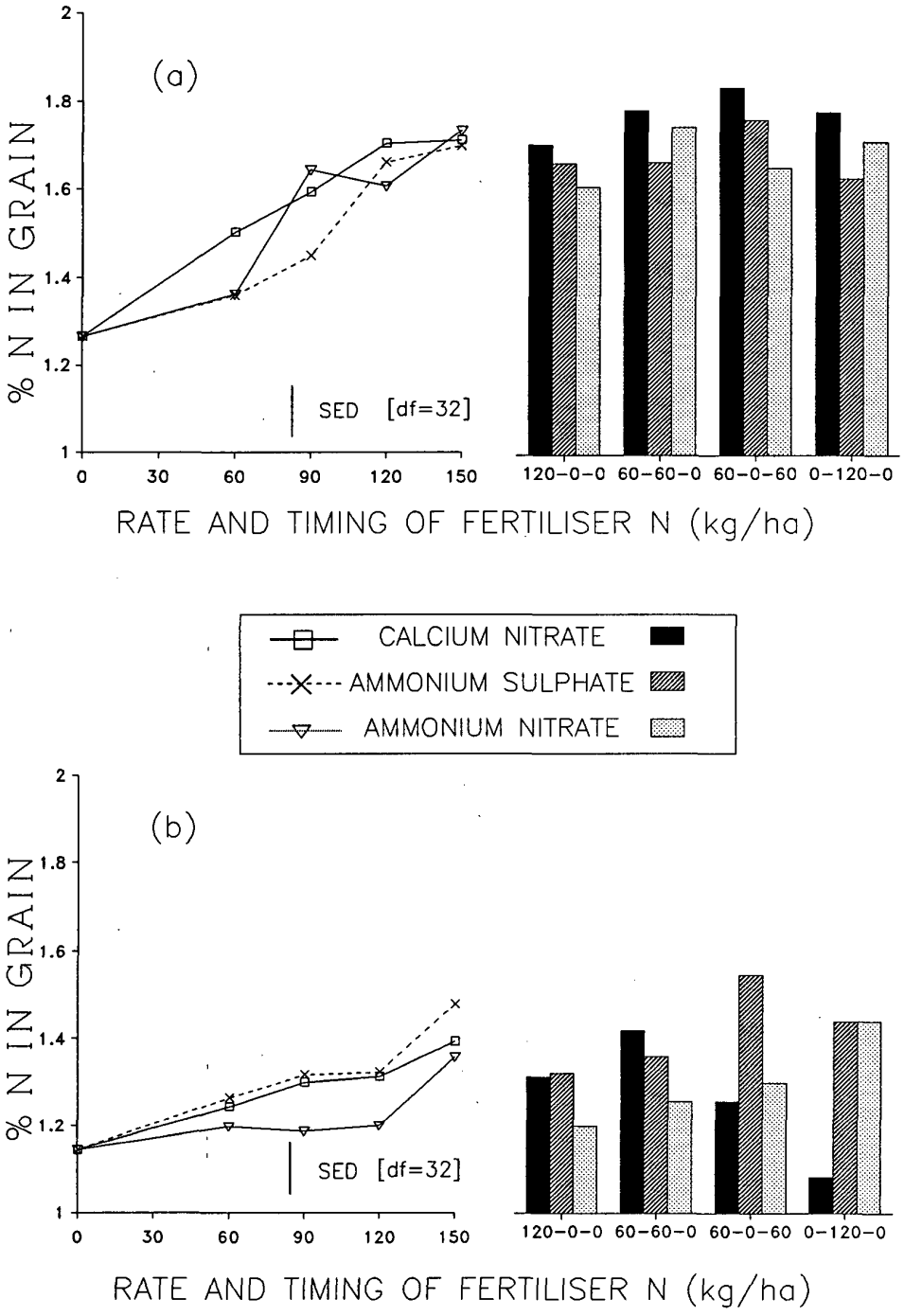


Figure 2. Nitrogen content in the grain (%) in spring barley as influenced by the rate and timing of fertiliser nitrogen applications, harvest 1988, (a) Bush, (b) Middlestot

Table 5: Grain yields (t/ha, 15% moisture) as affected by fertiliser nitrogen applications at two sites, 1988.

N applied (kg/ha)	Bush			Middlestot		
	CN	AS	AN	CN	AS	AN
0	3.21	3.21	3.21	2.23	2.23	2.23
60	4.08	4.33	4.12	7.11	3.71	4.30
90	5.38	5.68	5.20	6.40	5.40	5.33
120	5.11	5.98	5.44	7.10	5.98	5.52
150	4.86	7.18	5.52	7.28	6.98	6.30
60+60+0	5.22	5.66	6.01	6.50	6.35	6.34
60+0+60	4.88	6.07	5.28	5.91	6.13	5.91
0+120+0	6.11	6.18	5.50	6.44	6.32	7.13
	SED = 0.73 [df=14]			SED = 0.76 [df=14]		

CN: calcium nitrate; AS: ammonium sulphate; AN: ammonium nitrate

greater dilution of nitrogen in the grain by photosynthate during the grain-filling period. This was compounded by the fact that total nitrogen uptake was lower than at Bush in 1987, mainly due to a reduced uptake of unlabelled nitrogen.

Easson (1984) reported that there was little increase in the grain nitrogen contents of spring barley grown in Northern Ireland with split applications of fertiliser nitrogen up to tillering. It was reported that grain yields were increased by split applications of nitrogen only on an earlier sown crop where there had been considerable rainfall after sowing. This led to greater leaching losses of seed-bed applied nitrogen before the crop had developed sufficiently to compete for nitrogen uptake.

At Lintlaw, where there were increased yields following split applications, the crop was sown earlier than at most other trials and sowing was followed by high rainfall in late March and April. It is interesting to note that increased yields occurred both when calcium nitrate was applied at emergence and at tillering, but only at tillering with the ammonium sulphate and ammonium nitrate fertilisers. This may indicate that there was less rapid leaching losses in the treatments containing NH_4-N fertiliser compared to the more mobile NO_3-N fertiliser.

1.1.3: 1989

In 1989, concentrations of nitrogen in the grain were highest in the calcium nitrate treatments at both sites (Figure 3). Overall, values were high compared with results from the previous seasons; only the ammonium sulphate treatment at Bush produced a value of less than 1.7% N with 120 kg N/ha applied. There were no significant increases in nitrogen contents when fertiliser applications were split. This year fertiliser nitrogen was applied as a split application at the lower rate of 90 kg N/ha compared to 120 kg N/ha in the previous years. Comparing the results for these new treatments with the higher rate of 120 kg N/ha applied at sowing, it was apparent that grain nitrogen contents were generally lower in the split treatments. There was an effect of fertiliser form, however, with no significant difference between 120 kg N/ha applied at sowing and the split applications at 90 kg N/ha in the ammonium sulphate treatments at either site. Ammonium nitrate treatments also showed no significant difference at Upper Cairnie. There was no loss of grain yield using the lower split-rate of fertiliser (Table 6), with the exception of the ammonium sulphate treatment split between sowing and tillering at Bush.

Yields actually rose in the calcium nitrate and ammonium nitrate treatments at Bush. Generally, grain nitrogen contents were higher at Upper Cairnie than at Bush, apparently due to lower yields at the former site. In 1989 soil conditions were very dry, especially at Upper Cairnie (Section 5) which led to reduced grain-filling and yields, and therefore there was less dilution of the nitrogen in the grain resulting in higher grain nitrogen contents.

The form of fertiliser nitrogen applied was not significant at Bush, but calcium nitrate did increase yields at Upper Cairnie. Split applications at the 90 kg N/ha level at Upper Cairnie also increased yields.

1.1.4: Summary

Over the three seasons studied, the form in which the fertiliser was applied did not greatly influence grain nitrogen contents. When there was a significant difference, as occurred at Upper Cairnie and in some treatments at Lintlaw, it was the calcium nitrate treatments which gave the higher grain nitrogen contents. This was due to a higher nitrogen uptake in these treatments compared to the other fertiliser forms (Section 1.2). Widdowson et al (1964)

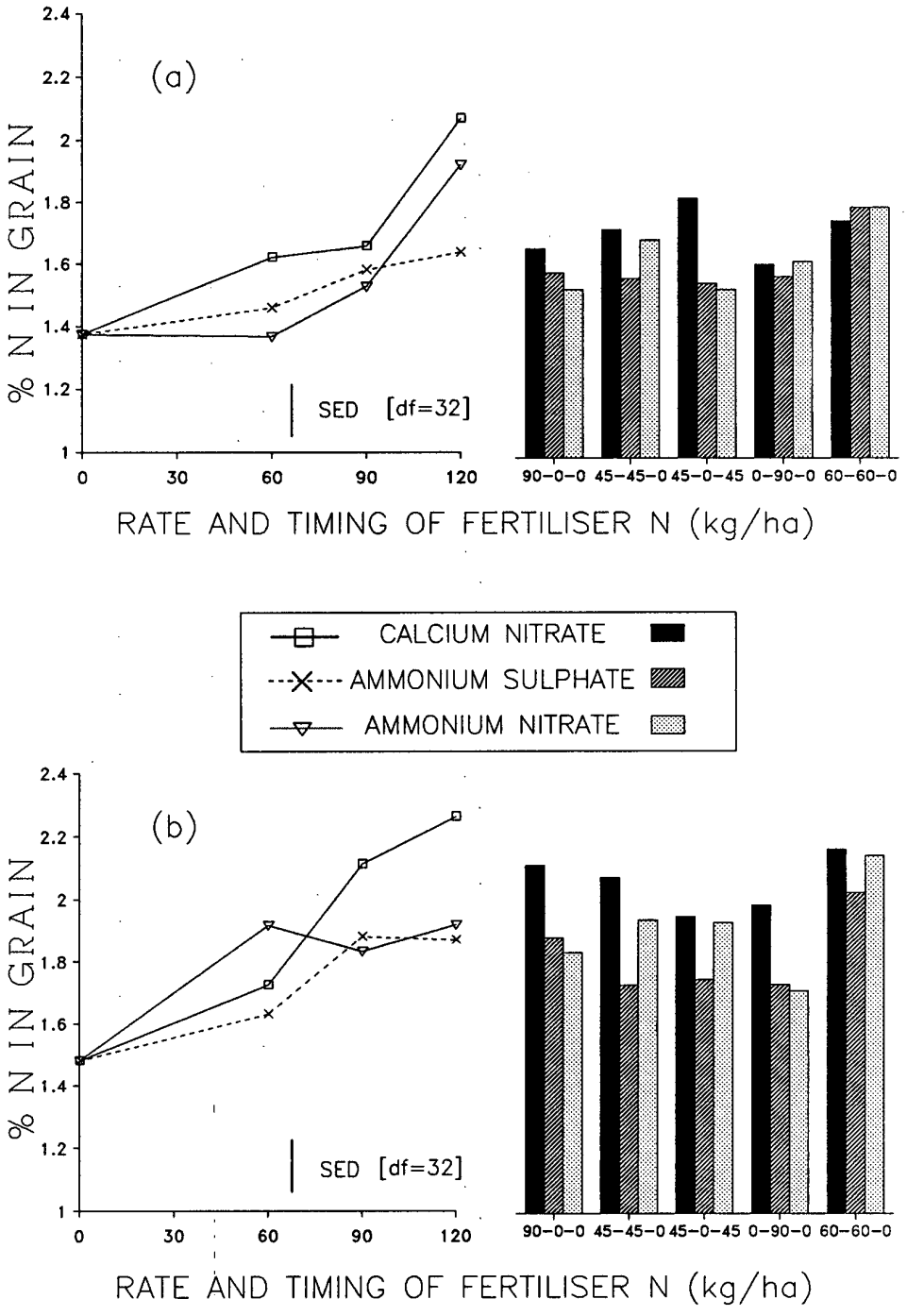


Figure 3. Nitrogen content in the grain (%) in spring barley as influenced by the rate and timing of fertiliser nitrogen applications, harvest 1989, (a) Bush, (b) Upper Cairnie

Table 6: Grain yields (t/ha, 15% moisture) as affected by fertiliser nitrogen applications at two sites, 1989.

N applied (kg/ha)	Bush			Upper Cairnie		
	CN	AS	AN	CN	AS	AN
0	2.74	2.74	2.74	3.30	3.30	3.30
60	6.46	5.88	6.67	4.31	3.94	3.52
90	6.26	6.71	6.38	3.68	3.41	3.87
120	6.65	7.18	5.91	5.22	4.78	4.27
45+45+0	6.71	7.00	7.24	5.00	4.31	4.25
45+0+45	7.53	6.10	7.09	5.10	4.57	4.12
0+90+0	6.72	6.62	6.63	4.70	4.96	3.76
60+0+60	6.03	6.59	6.36	4.79	4.42	5.08
	SED = 0.66 [df=14]			SED = 0.45 [df=14]		

CN: calcium nitrate; AS: ammonium sulphate; AN: ammonium nitrate

found with spring barley that lower grain nitrogen contents in ammonium sulphate fertilised treatments were due to a less efficient recovery of fertiliser nitrogen compared to calcium nitrate fertiliser treatments when fertiliser was broadcast onto the soil surface.

Site and season had a much greater effect on grain nitrogen contents than fertiliser form (Figure 4). Generally, at each site there was a fairly linear increase in grain nitrogen contents with increasing fertiliser application and, crucially, the relative differences in content of soil-derived nitrogen (zero fertiliser rate) were maintained over most or all of the range of fertiliser rates. These differences between sites cannot all be fully accounted for by different seasonal effects, as there were differences within each season. It must be concluded that the grain nitrogen content was significantly related to the available soil nitrogen reserves. Batey and Reynish (1976) earlier reached a similar conclusion from work in England. Results presented showing nitrogen uptake in the trials between 1987-1989 (Section 1.2) demonstrate that the uptake of soil nitrogen between sites is more variable than the uptake of fertiliser nitrogen. Climatic conditions, however, must also be taken into account and it is clear that the very high grain nitrogen contents reported for Upper Cairnie were not due to a very high soil nitrogen uptake, but rather were

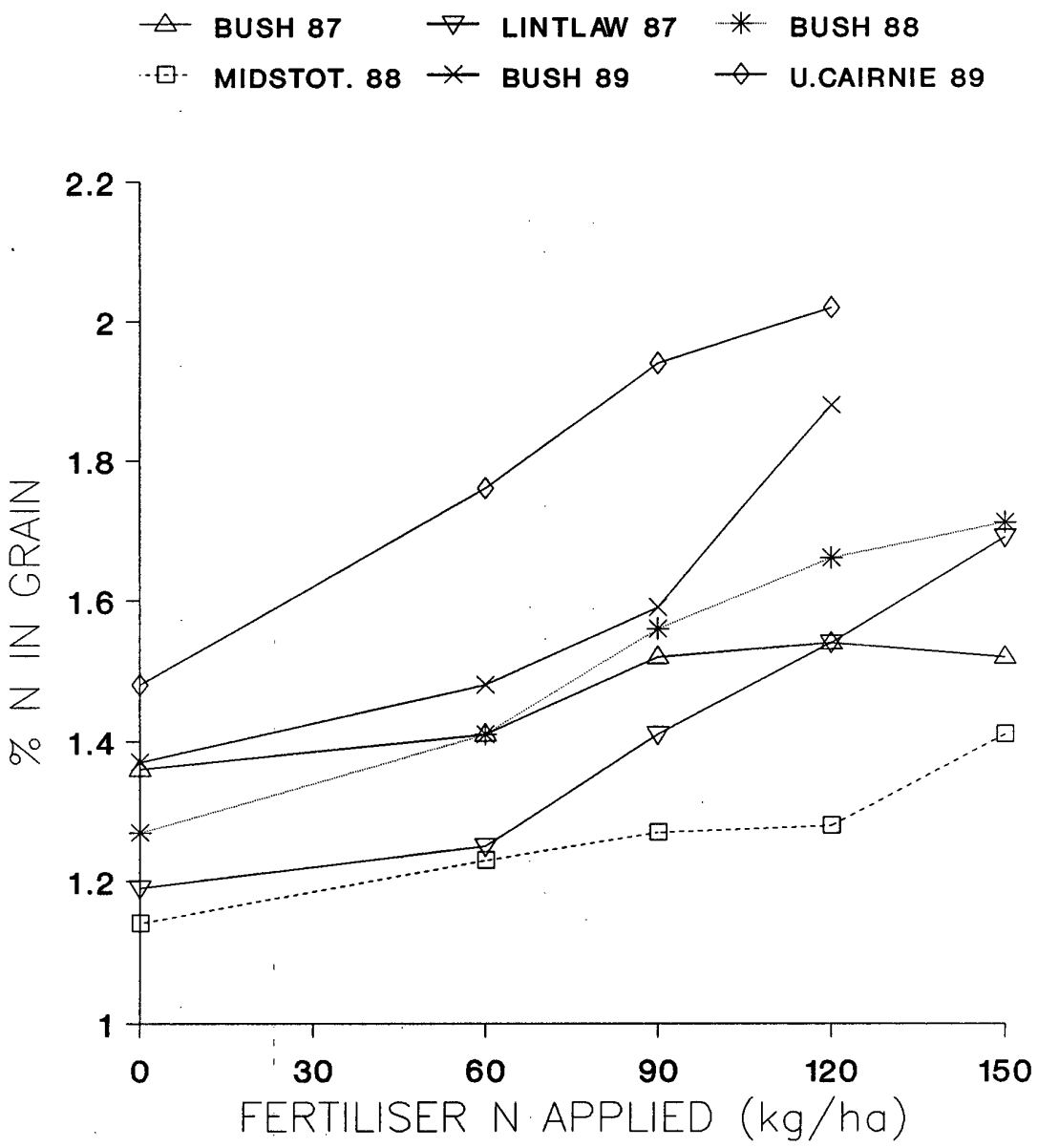


Figure 4. Mean nitrogen content in the grain (%) in spring barley as influenced by the rate of fertiliser nitrogen applied at sowing over 6 sites, harvest 1987-1989

a result of low grain yields due to the very dry soil conditions limiting the grain filling period.

1.2: Uptake of labelled and unlabelled nitrogen in plant shoots at harvest

The uptake of labelled and unlabelled nitrogen is shown for each site in Figures 5-10. The uptake of labelled nitrogen generally rose linearly with increased fertiliser nitrogen applied. Overall, the ammonium sulphate treatments resulted in lower labelled nitrogen uptake. At both Bush (Figure 5) and Lintlaw (Figure 6) in 1987, ammonium nitrate fertiliser applications resulted in significantly greater uptake of labelled nitrogen at the highest fertiliser nitrogen rates than when the other fertiliser forms were applied. At Lintlaw split applications increased the uptake of labelled ammonium sulphate, whilst the uptake of calcium nitrate was only increased when it was all applied at the time of crop emergence. Shortly after the second split application (55 - 83 days after sowing) the rate of crop uptake increased dramatically. This was during the period of stem elongation (Section 3.1). This reduced the length of time in which the more mobile nitrate had to remain in the soil before rapid plant uptake began, thus it reduced the risk of losses from leaching and denitrification. The reason for the increased uptake when the ammonium sulphate fertiliser was split could also be due to areduction in the length of time which the fertiliser lay in the soil, but in this case it is likely that reduction in competition from soil micro-organisms was the key factor. Therefore, by delaying the application of some of the NH_4-N fertiliser until tillering meant that there was more competition from the better developed plant roots reducing the availability of the fertiliser nitrogen for immobilisation. This was confirmed by the fact that there was a greater uptake of labelled nitrogen at harvest from the second ammonium split application (Section 3.1).

The percentage recovery of fertiliser nitrogen applied is shown in Table 7. At both Bush and Lintlaw the recovery of ammonium sulphate rose with increased fertiliser applications. Ammonium nitrate remained generally constant with only a slight rise in efficiency at high fertiliser rates. Recoveries of calcium nitrate fell as fertiliser rates were increased at Bush, but remained constant at Lintlaw. Split applications gave the greatest improvement in uptake efficiency when applied in the ammonium nitrate form.

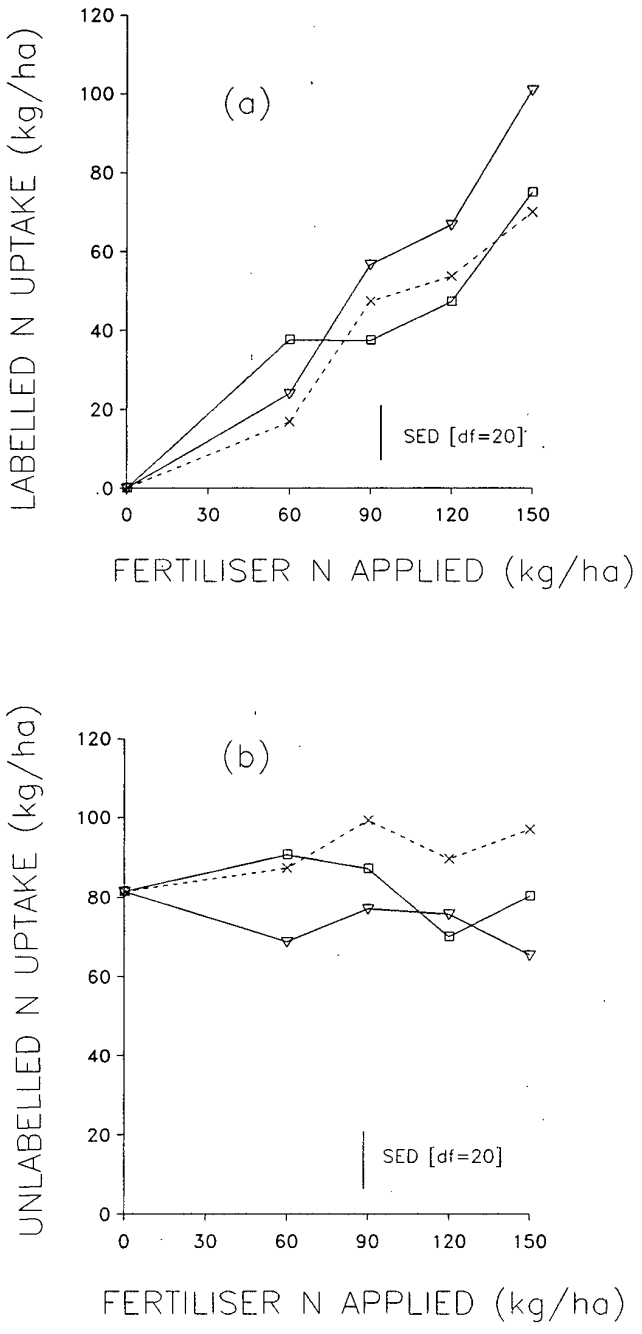


Figure 5. Uptake of (a) labelled and (b) unlabelled nitrogen in above ground plant tissue by spring barley as influenced by the rate of fertiliser nitrogen applications, harvest, Bush 1987

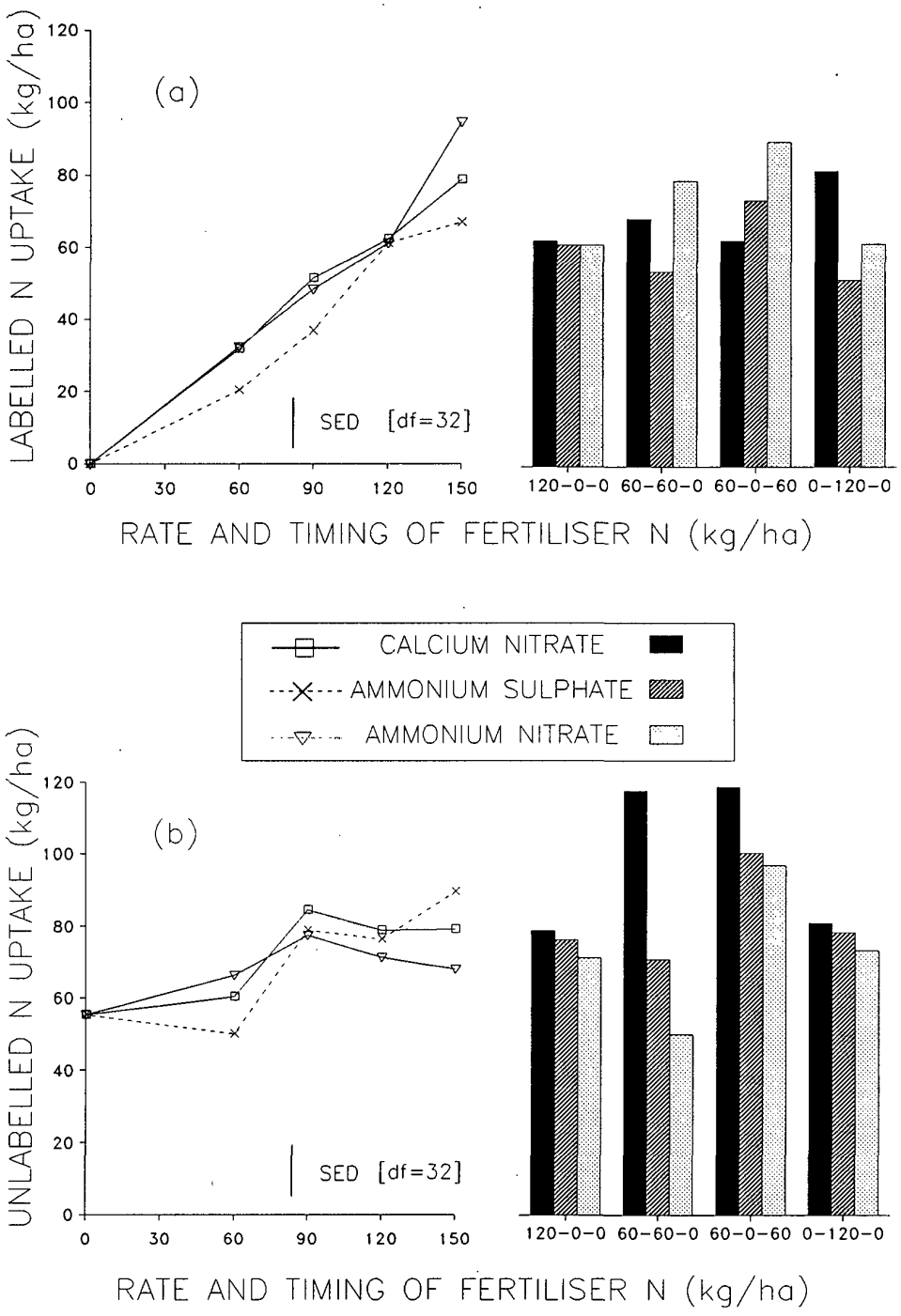


Figure 6. Uptake of (a) labelled and (b) unlabelled nitrogen in above ground plant tissue by spring barley as influenced by the rate and timing of fertiliser nitrogen applied, harvest, Lintlaw 1987

At Bush 1988 (Figure 7), labelled nitrogen uptake levelled off at 120 kg N/ha when applied in the form of calcium nitrate, but continued to rise in the other two treatments. In contrast, at Middlestot (Figure 8) labelled nitrogen uptake rose linearly with the rate of fertiliser nitrogen applied for all fertiliser forms. Calcium nitrate produced significantly greater uptake at all rates. Split applications tended to increase the uptake of ammonium nitrate and ammonium sulphate at Middlestot, but at Bush only the ammonium nitrate split between sowing and emergence, and calcium nitrate at 120 kg N/ha all applied at emergence showed greater uptake. The percentage recovery of fertiliser nitrogen applied as calcium nitrate fell at the higher fertiliser rates at both Bush and Middlestot (Table 8). This was similar to the results found at Bush the previous year. This suggested that at the higher fertiliser rates the plant was unable to utilise all the available nitrogen immediately. Losses probably occurred via denitrification or leaching. Leaching losses over the 1988 growing season, on a heavier clay loam soil at a nearby site, were measured at approximately 10 kg N/ha out of 120 kg N/ha ammonium nitrate applied (Vinten et al, 1991). However, this was measured under winter barley which would have a better developed root system at the time of fertiliser application, and so could take up the applied fertiliser more rapidly. Also, 50% of the nitrogen applied was in the NH_4-N form and this would also reduce the risks from leaching.

At Bush the recovery of calcium nitrate N was improved when fertiliser nitrogen was split between sowing and tillering. This would allow a readily available supply of nitrogen just at the time of rapid vegetative growth and nutrient uptake. Recovery of ammonium nitrate remained constant over the range of fertiliser rates, but split applications improved recovery, especially when split between sowing and emergence. The efficiency of recovery of ammonium sulphate improved as fertiliser rates increased. This also occurred in 1987, and could be due to the lower mobility of NH_4-N in the soil. This would reduce the movement of nutrients down the soil profile with surface applied fertiliser (Section 5). Therefore fertiliser nitrogen would still be accumulated near the soil surface and not well distributed near the developing roots. At higher fertiliser rates sufficient NH_4-N may be present to at least partially offset the reduced mobility.

Another possible explanation for the reduced recovery of ammonium sulphate fertiliser at low application rates is that the recovery of fertiliser

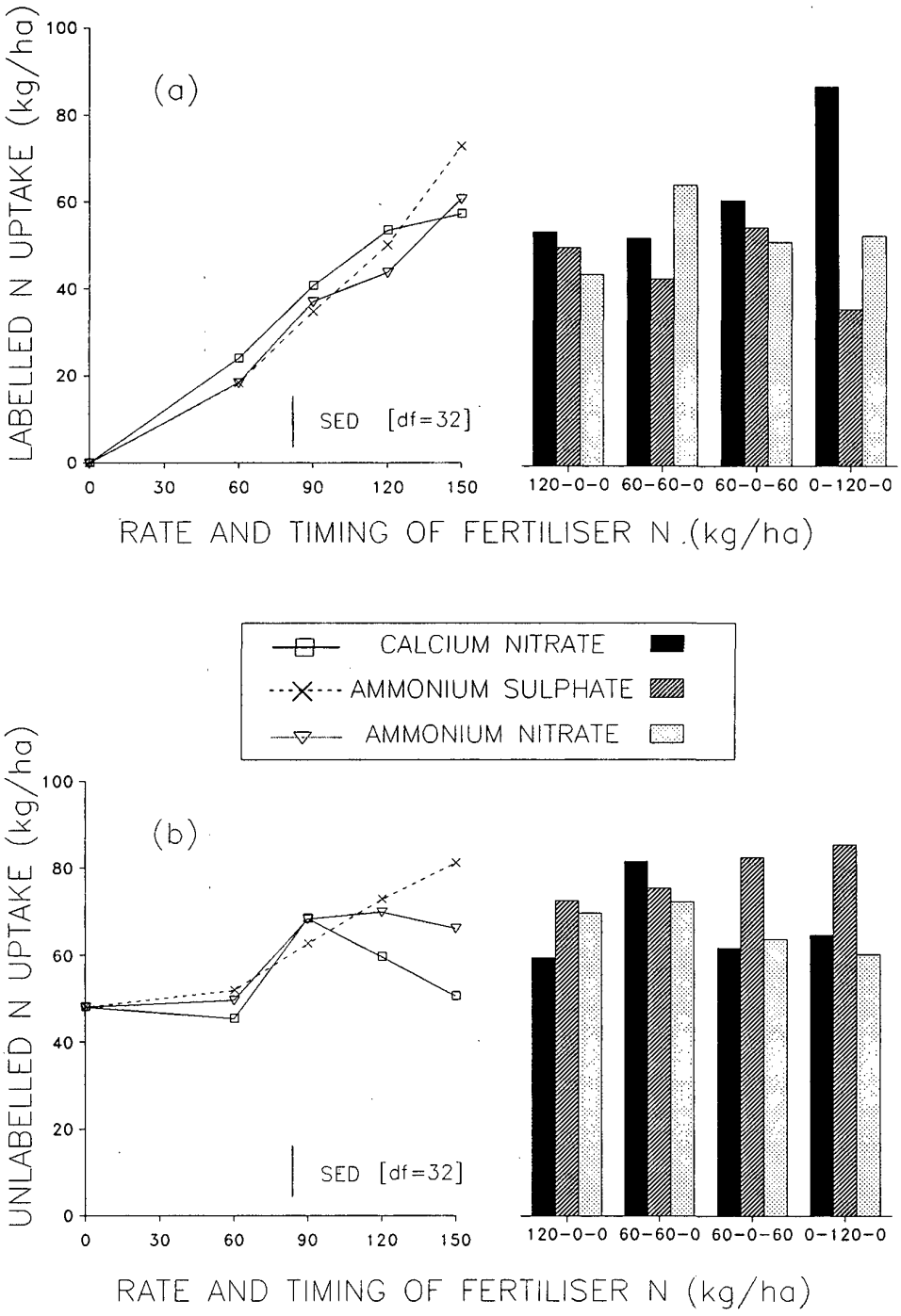


Figure 7. Uptake of (a) labelled and (b) unlabelled nitrogen in above ground plant tissue by spring barley as influenced by the rate and timing of fertiliser nitrogen applied, harvest, Bush 1988

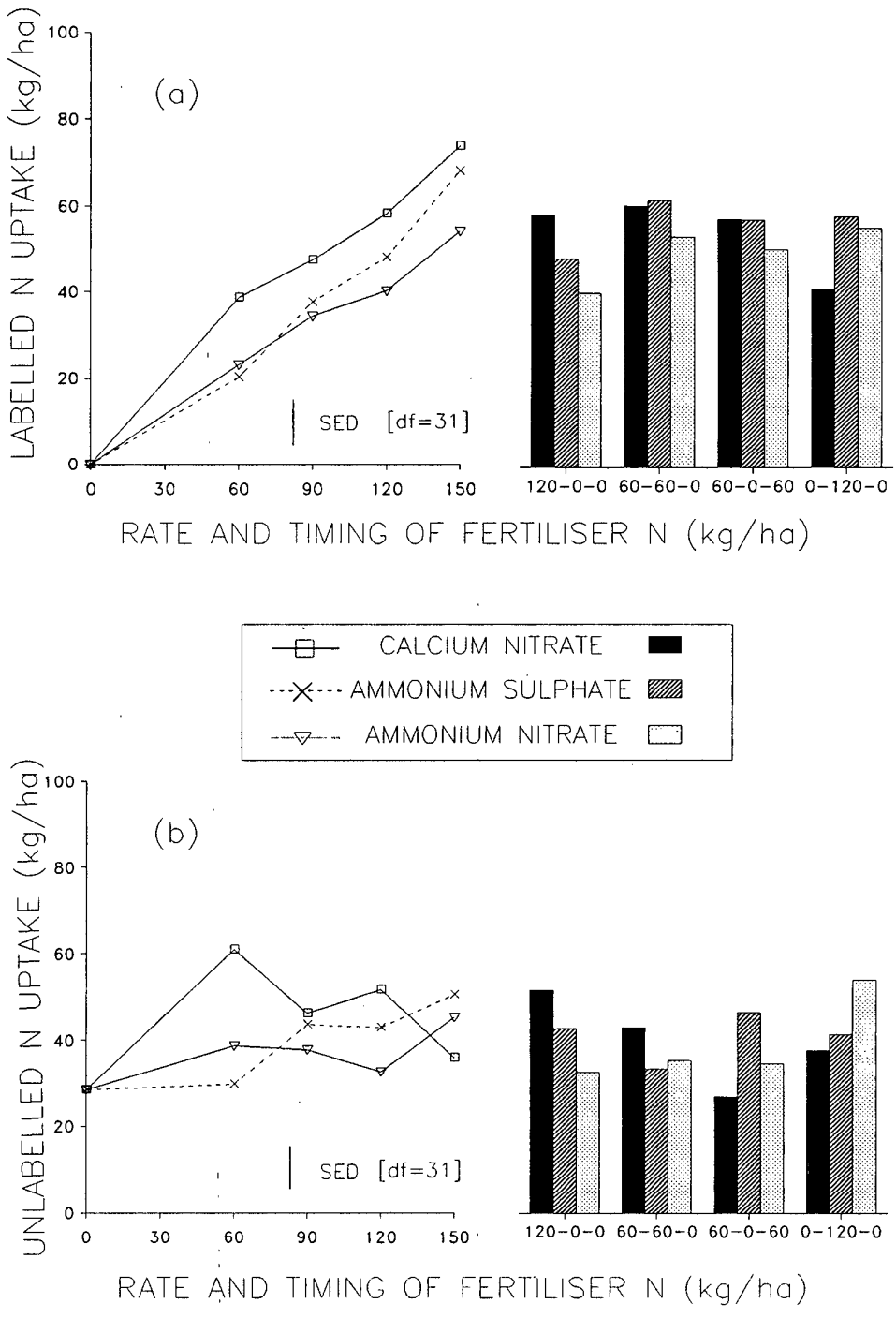


Figure 8. Uptake of (a) labelled and (b) unlabelled nitrogen in above ground plant tissue by spring barley as influenced by the rate and timing of fertiliser nitrogen applied, harvest, Middlestot 1988

Table 7: Percent labelled N recovery in plant shoots at two sites, 1987

N applied (kg/ha)	Lintlaw			Bush		
	CN	AS	AN	CN	AS	AN
60	53.2	33.9	54.2	62.6	28.2	40.0
90	57.1	40.9	53.7	41.7	52.6	63.0
120	51.8	51.0	51.0	39.4	44.7	55.6
150	52.5	44.6	63.0	50.0	46.7	67.3
60+60+0	56.8	44.7	65.7	--	--	--
60+0+60	51.9	61.2	74.5	--	--	--
0+120+0	68.0	42.8	51.1	--	--	--
	SED = 13.5 [df=27]			SED = 12.8 [df=16]		

CN: calcium nitrate; AS: ammonium sulphate; AN: ammonium nitrate

Table 8: Percent labelled N recovery in plant shoots at two sites, 1988

N applied (kg/ha)	Middlestot			Bush		
	CN	AS	AN	CN	AS	AN
60	64.3	33.9	38.6	40.0	30.5	30.7
90	52.8	41.8	38.1	45.3	38.6	41.2
120	48.5	40.1	33.5	44.6	41.7	36.6
150	49.2	45.4	36.1	38.1	48.5	40.4
60+60+0	50.3	51.4	44.4	43.4	35.7	53.5
60+0+60	47.7	47.7	41.9	50.6	45.5	42.7
0+120+0	34.3	48.3	46.1	72.4	29.9	43.9
	SED = 7.3 [df=27]			SED = 10.2 [df=28]		

CN: calcium nitrate; AS: ammonium sulphate; AN: ammonium nitrate

nitrogen, as determined by ^{15}N, was reduced by 'pool substitution' (Jenkinson et al, 1985; Hart et al, 1986). Pool substitution has been shown to have a proportionately greater effect on low fertiliser ^{15}N additions compared to higher application rates (Jenkinson et al, 1985). They also showed that a delay in the uptake of nitrogen after application would enhance the effect of pool substitution. For the first few weeks after sowing there was little uptake of

nitrogen in the plant as there was not yet a sufficiently developed root system in the young barley plants. Therefore, there was more time for the ^{15}N-labelled fertiliser to be immobilised and replaced with mineralised ^{14}N from the soil organic nitrogen pool before it was taken up by the plant. Other research has shown that the effect of pool substitution is greater when working with $^{15}NH_4$-N rather than $^{15}NO_3$-N (Kowalenko and Cameron, 1978; Steele et al, 1980). This is because the pool substitution is regulated by the rate of immobilisation by micro-organisms in the soil (Jenkinson et al, 1985) whose preference for NH_4-N as a substrate is well documented.

In 1989 the recovery of labelled nitrogen was significantly influenced by the form in which the fertiliser was applied (Figures 9 and 10). At both sites uptake was lower when applied in the ammonium form compared to the nitrate form. Splitting the fertiliser application increased the uptake of labelled nitrogen in the calcium nitrate treatments at Upper Cairnie. The efficiency of recovery was generally high (Table 9), especially at the Bush site. At Bush the nitrate fertiliser treatments gave the highest recoveries, with the greatest efficiency at 60 kg N/ha fertiliser applied. At all rates above this, whether applied as a single or split treatment, percentage recovery did not vary significantly. At Upper Cairnie split applications applied as calcium nitrate improved efficiency. This season was generally warm and dry, which led to very dry soil conditions during the growing season (Section 5). Such conditions would greatly reduce risks of losses via leaching or denitrification. This increased both the overall effective quantity of available N and the length of time that it remained available in the soil for plant uptake (Section 5). However, these conditions would also reduce the mobility of the nitrogen in the soil, especially that in the less mobile ammonium form, which could explain the lower recoveries from the ammonium fertiliser treatments.

Normally, increasing fertiliser rates up to rates achieving maximum yields has little effect on percent fertiliser recoveries (Broadbent and Carlton, 1978). However, Greenwood and Draycott (1988) found in vegetable crops that recoveries fell at higher fertiliser rates and attributed this to poorly developed root systems in early growth which were able to explore only very limited volumes of the soil. Spring barley would also have a small root system at this time and so the higher recoveries of calcium nitrate at the lowest rates could be explained by the greater mobility of nitrate ions in the soil compared to ammonium. At the higher rates this mobility became a liability as the roots

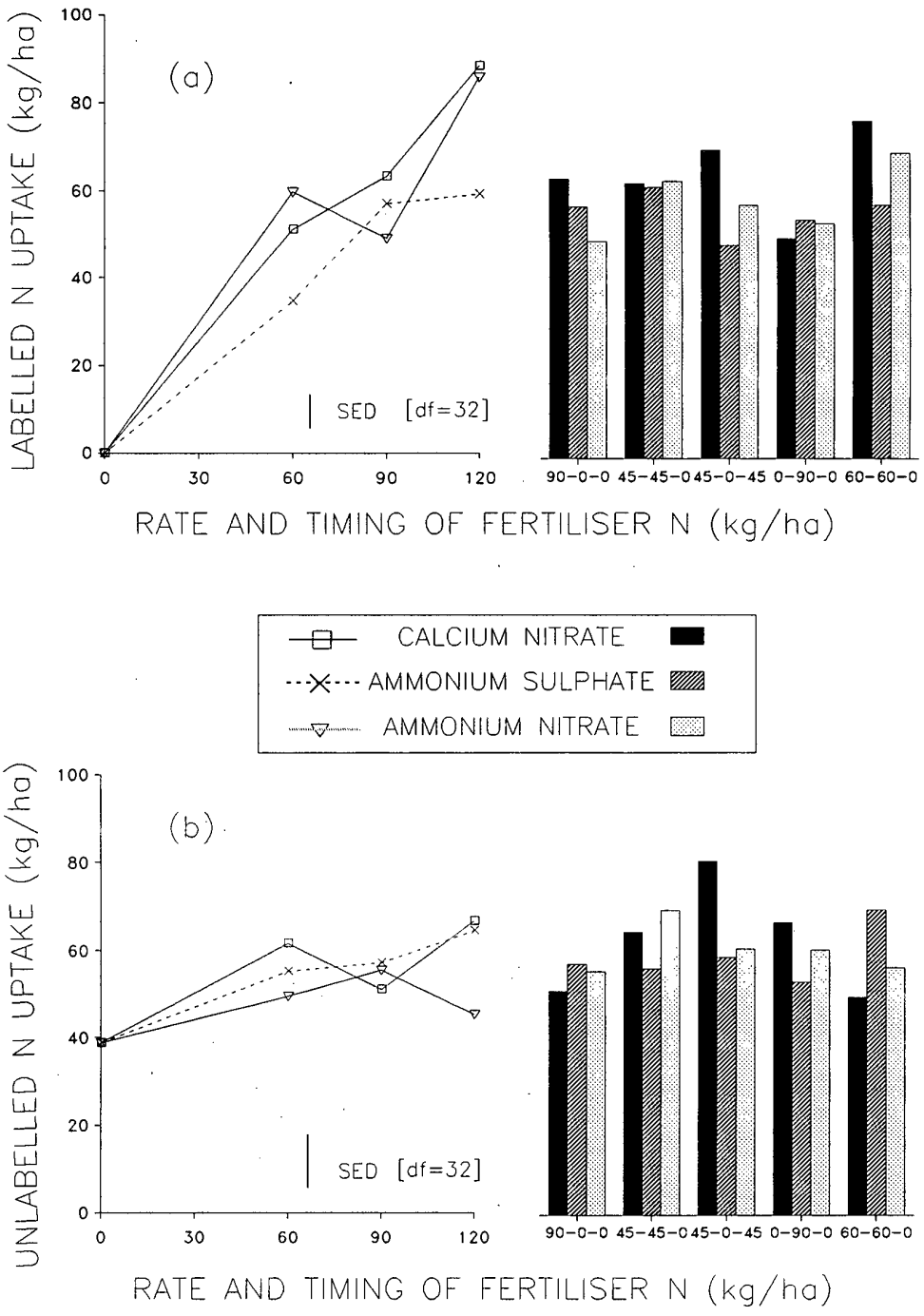


Figure 9. Uptake of (a) labelled and (b) unlabelled nitrogen in above ground plant tissue by spring barley as influenced by the rate and timing of fertiliser nitrogen applied, harvest, Bush 1989

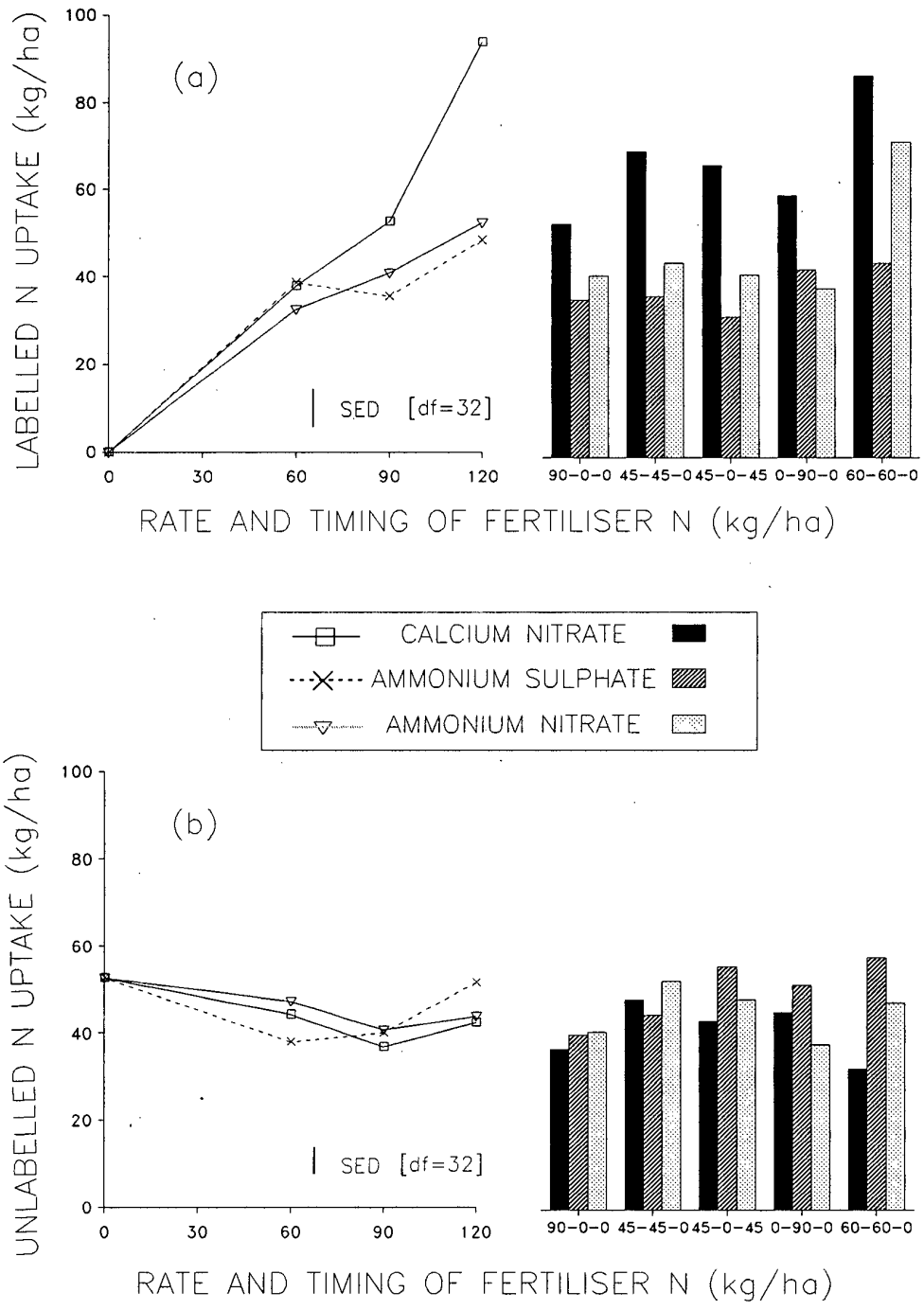


Figure 10. Uptake of (a) labelled and (b) unlabelled nitrogen in above ground plant tissue by spring barley influenced by the rate and timing of fertiliser nitrogen applied, harvest, Upper Cairnie 1989

Table 9: Percent labelled N recovery in plant shoots at two sites, 1989

N applied (kg/ha)	Upper Cairnie			Bush		
	CN	AS	AN	CN	AS	AN
60	63.0	64.4	54.3	85.4	58.0	82.9
90	58.6	39.5	45.4	70.4	63.4	54.7
120	78.1	40.2	43.7	73.5	49.4	71.6
45+45+0	76.8	40.4	48.8	69.2	68.1	69.6
45+0+45	73.3	35.3	45.8	77.5	53.6	63.7
0+90+0	65.7	47.1	42.4	55.4	59.9	59.2
60+60+0	71.9	36.6	59.5	63.5	47.7	57.5
	SED = 9.7 [df=28]			SED = 11.4 [df=28]		

CN: calcium nitrate; AS: ammonium sulphate; AN: ammonium nitrate

could not utilise all the available nitrate and so there was a greater potential for leaching and denitrification. In winter cereals this does not occur due to an already well established root system able to utilise immediately much more of the fertiliser nitrogen applied. Another possible explanation for the increased recovery at higher fertiliser rates of ammonium sulphate could be the immobilisation of NH4-N initially into the biomass from where it is quite quickly released again (Bristow et al, 1987), but which would allow the crop sufficient time to develop a more extensive root system.

The uptake of unlabelled nitrogen did not show the same linear rise as the uptake of labelled nitrogen at any of the sites. At Bush 1987 (Figure 5) both calcium nitrate and ammonium nitrate fertiliser forms showed a constant uptake of between 70 kg N/ha and 80 kg N/ha at all rates of fertiliser applied. There was a slight rise in the uptake of unlabelled nitrogen when the fertiliser was applied in the form of ammonium sulphate. There was a similar rise in uptake from treatments when ammonium sulphate fertiliser was applied at Lintlaw 1987 (Figure 6). Unlabelled nitrogen uptake was also greater in the calcium nitrate treatments at fertiliser rates of 90 kg N/ha and above. Split applications also increased unlabelled nitrogen uptake in the calcium nitrate treatments.

In 1988 the uptake of unlabelled nitrogen in the calcium nitrate and ammonium nitrate treatments remained constant at all rates above 60 kg N/ha

at Bush (Figure 7), and at all rates above zero at Middlestot (Figure 8). The uptake of unlabelled nitrogen in the ammonium sulphate treatments increased steadily with increased fertiliser applications at Bush. Splitting fertiliser applications had little effect on the uptake of un labelled nitrogen.

In 1989, uptake remained constant at all fertiliser rates except for the zero application rate at Bush (Figure 9). Once again split fertiliser applications had little effect with the exception of the calcium nitrate treatment splitting 90 kg N/ha between sowing and tillering at Bush.

In general, the lack of evidence of a steady increase in the uptake of unlabelled nitrogen with increased fertiliser applications, for most treatments, suggested that there was no real "priming" effect as had been proposed by previous research (Broadbent and Nakashima, 1971; Westerman and Kurtz, 1974). The only real evidence of any effect occurred with the ammonium sulphate treatments. Another explanation put forward to explain increases in the uptake of unlabelled nitrogen measured in some trials, is that it is only an apparent effect (Jenkinson et al, 1985). This effect, called the "added nitrogen interaction" (ANI) occurs in trials using ^{15}N-labelled fertiliser, and is caused by the continuous mineralisation-immobilisation turnover of nitrogen in the soil. Research carried out under field conditions (Jansson, 1958; Aulakh and Rennie, 1984; Recous et al, 1988a) and in the laboratory (Okereke and Meints, 1985) has shown that there is preferential immobilisation of NH_4-N by soil micro-organisms. Thus the greater uptake of unlabelled nitrogen at the higher rates of ammonium sulphate fertiliser applications may be attributable to the greater likelihood of immobilisation of NH_4-N than NO_3-N by the soil microbes, resulting in a greater pool-substitution effect on the ^{15}N fertiliser added. The fact that there was no such effect with the ammonium sulphate treatment at Upper Cairnie could be explained by the fact that the ANI effect requires good interaction between the ^{15}N fertiliser applied and the unlabelled inorganic nitrogen already present in the soil (Jenkinson et al, 1985). Soil conditions were very dry at Upper Cairnie; this would have had the effect of reducing the mobility of the NH_4-N and preventing a complete interaction with the unlabelled nitrogen in the soil, thus reducing any ANI effect. The lack of an ANI due to a lack of interaction between the two nitrogen pools has also been observed by other workers (Hart et al, 1986; Nielsen et al, 1988; Recous et al, 1988b).

The data for the calcium nitrate and ammonium nitrate treatments showed that uptake remained constant at all rates of applied fertiliser, but that uptake was slightly lower when no fertiliser nitrogen was applied. This could have been caused by a stimulation in plant growth, including roots, by the lowest rate of fertiliser which would allow greater exploration of the soil and greater uptake of unlabelled nitrogen, as proposed by Sorensen (1982). Under field conditions in Scotland (Smith et al, 1984) it was concluded that the constant uptake of soil nitrogen with increasing fertiliser rates was due to efficient root exploration at the lower fertiliser rates in spring barley grown on a loamy sand soil. This was in contrast to results from a heavier badly structured soil, where the lower uptake of soil nitrogen at low fertiliser rates was attributed to restricted root growth at these lower rates, observed earlier at this site (Holmes, 1976; Pidgeon, 1980).

A study of the uptake of both labelled and unlabelled nitrogen at all six sites studied between 1987 and 1989 showed that there was considerable variation in the uptake of unlabelled nitrogen (Figure 11). Average uptake ranged from 40 kg N/ha at Middlestot to 82 kg N/ha at Bush in 1987. Even in the same season there were considerable differences. This variation in the uptake of unlabelled nitrogen was much greater than the variation in the efficiency of uptake of labelled nitrogen, which ranged from 43% at Bush in 1988 to 61% at Bush in 1989.

The variation in the uptake of unlabelled nitrogen occurred on soils which, with the exception of Upper Cairnie, were all classed as low nitrogen soils (N-Index = 0) on the basis of previous cropping. From these results it appeared that changes in fertiliser form, or timing of application, had relatively little effect on overall nitrogen uptake compared to the variation due to the uptake of native soil nitrogen between different sites.

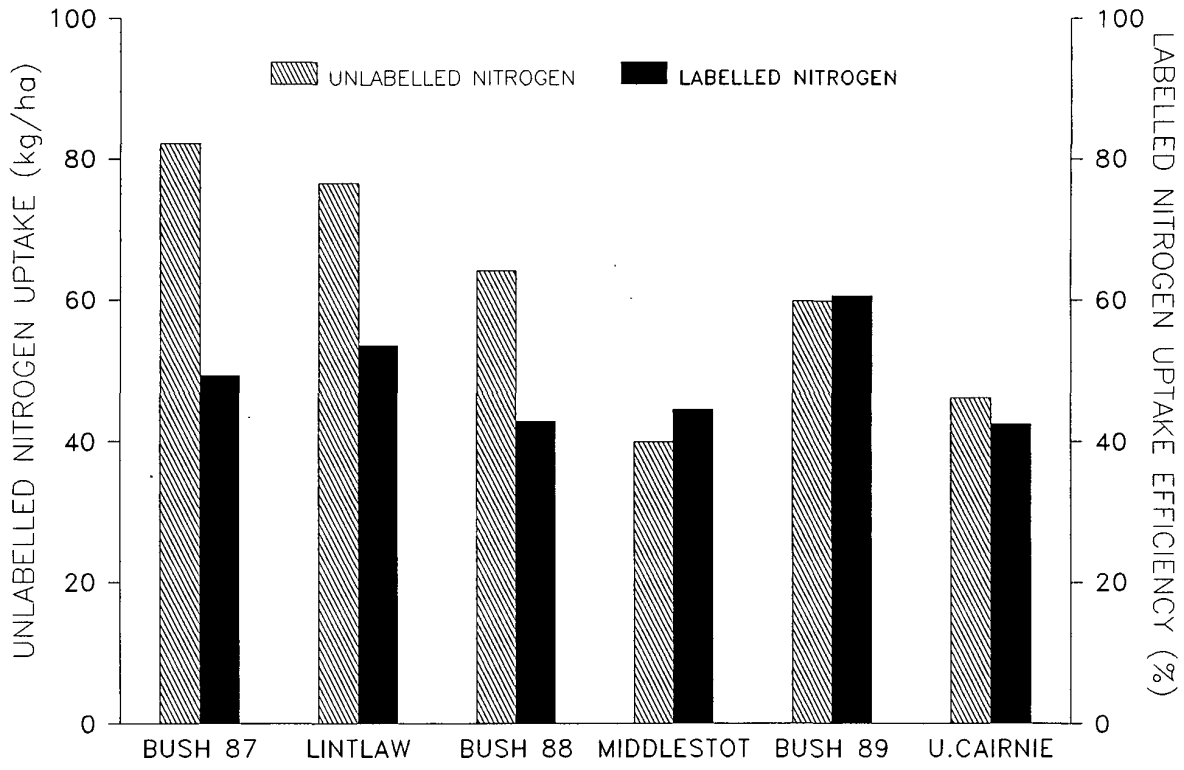


Figure 11. Mean uptake of labelled and unlabelled nitrogen in above ground plant tissue in spring barley over a range of fertiliser nitrogen applications at 6 sites, harvest, 1987-1989

2: Nitrogen Uptake and Grain Nitrogen Content, 1990

2.1: Grain nitrogen contents and yields

In 1990 the site effect was further investigated with trials laid out at six different sites. Details of the sites are given in Table 2. Figure 12 shows the grain nitrogen contents for each fertiliser nitrogen treatment applied at each site. All the sites, with the exception of Kettle, had been previously cropped with cereals and yet grain nitrogen contents still ranged from 1.4% to 1.8% N with 120 kg N/ha fertiliser applied at sowing. Once again site had a much greater effect than the form of fertiliser applied.

Grain yields also showed no significant variation with fertiliser form except at Manorhill, where ammonium sulphate produced lower yields than the ammonium nitrate treatment (Table 10). Yields in the unfertilised treatment at Kettle were very much higher than at any other site, due to a very large uptake of soil nitrogen (Section 2.2).

2.2: Uptake of labelled and unlabelled nitrogen in plant shoots at harvest

Across the range of the six sites studied in 1990 there was little difference in the uptake of labelled nitrogen fertiliser applied in the form of either ammonium sulphate or ammonium nitrate (Figure 13). The uptake of labelled nitrogen was slightly higher in the ammonium nitrate treatment at only two sites, Manorhill and Kettle. Average uptake at each site ranged from 46 kg N/ha at Quixwood to 73 kg N/ha at Kettle. These values were similar to the uptake of labelled nitrogen in the same treatments in the previous seasons.

Unlabelled nitrogen uptake in 1990 showed no effect of fertiliser form, except at Manorhill, where uptake was greater in the ammonium nitrate fertiliser treatment (Figure 14). Uptake was significantly lower at all sites when no fertiliser was applied with the exception of Kettle where uptake was higher in the unfertilised treatments. This site differed from the other sites that year in that the previous crop was brussels sprouts rather than a cereal, and thus the soil was categorised as N-Index = 1 (MAFF, 1985). Total uptake of unlabelled nitrogen was much higher than any of the other sites with an average uptake of 123 kg N/ha. Grain yields were also significantly higher at Kettle, with the greatest increase compared to other sites being found in zero nitrogen

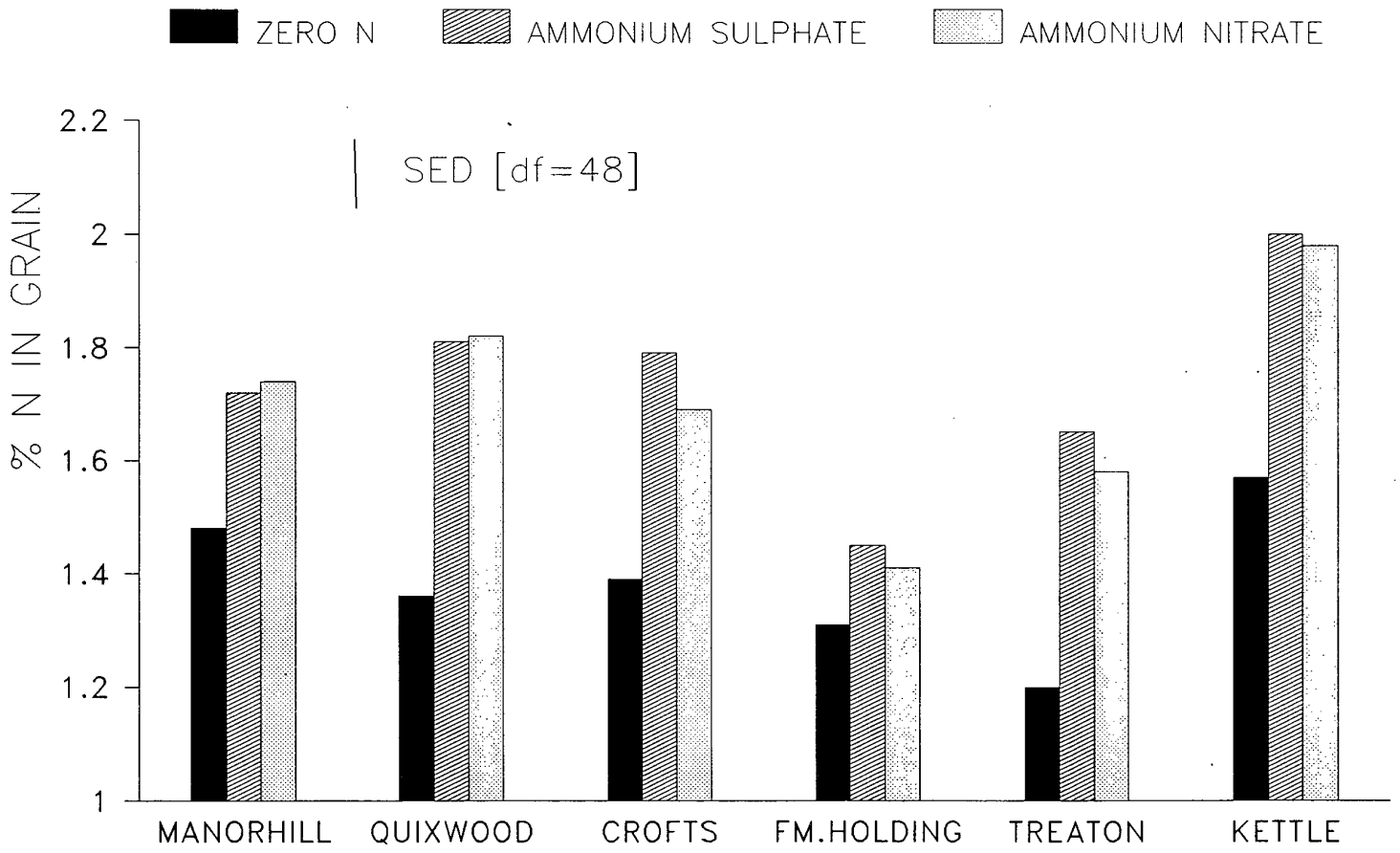


Figure 12. Nitrogen concentration in the grain (%) in spring barley at fertiliser rates of zero and 120 kg N/ha at six sites, harvest, 1990

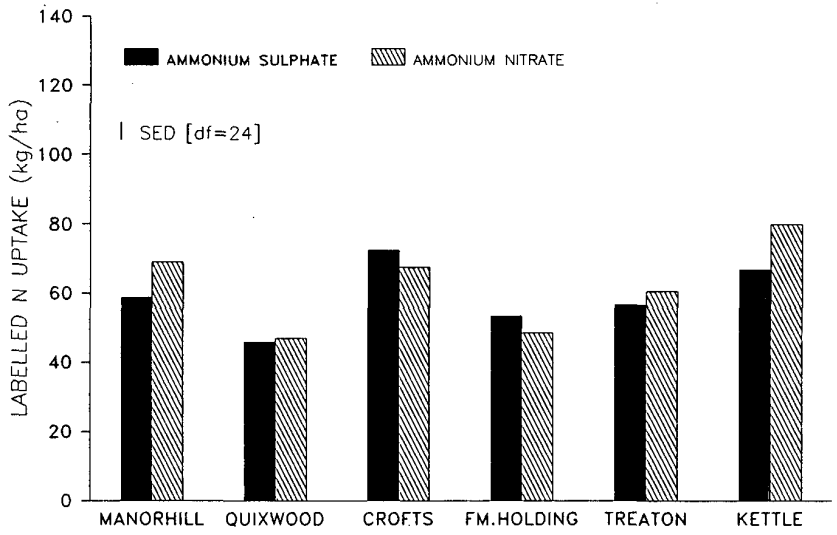


Figure 13. Uptake of labelled nitrogen in above ground plant tissue in spring barley after 120 kg/ha fertiliser nitrogen applied, at 6 sites, harvest, 1990

Figure 14. Uptake of unlabelled nitrogen in above ground plant tissue in spring barley after zero or 120 kg/ha fertiliser nitrogen applied, at 6 sites, harvest, 1990

Table 10: Grain yields (t/ha, 15% moisture) as affected by fertiliser nitrogen application at two sites, 1990

Site	Fertiliser applied (kg N/ha)		
	Zero	120	
		AS	AN
Manorhill	2.45	4.85	6.09
Quixwood	4.31	6.13	6.19
Bush (Crofts)	4.60	7.38	7.76
Bush (Fm. Holding)	3.33	6.78	7.10
Treaton	2.87	5.82	6.19
Kettle	6.68	7.30	7.35

SED = 0.52 [df=5]

AS: ammonium sulphate; AN: ammonium nitrate

treatments (Section 2.1). This indicated that there was a plentiful supply of native soil nitrogen which the crop could take up. The main source of this soil nitrogen was likely to be from the mineralisation of the residues of the previous crop rather than from older soil organic matter fractions; the soil had, in fact a low organic matter content of 2.8% (Table 8). The soil was also light in texture, allowing easier exploration by the plant roots and thus reducing the relative benefit gained by fertilised crops in terms of greater root growth.

The other five sites had all been previously cropped with a cereal, and yet the average unlabelled nitrogen uptake at each site ranged from 41 kg N/ha at Treaton to 79 kg N/ha at Quixwood (Figure 15). This variation between sites was greater than the variation in labelled nitrogen uptake which ranged from 48 kg N/ha at Quixwood to 70 kg N/ha at Crofts. At Kettle, where grain yields and unlabelled nitrogen uptake were much higher than the other sites, labelled nitrogen uptake was only slightly higher at 73 kg N/ha. These results confirmed findings from the previous seasons.

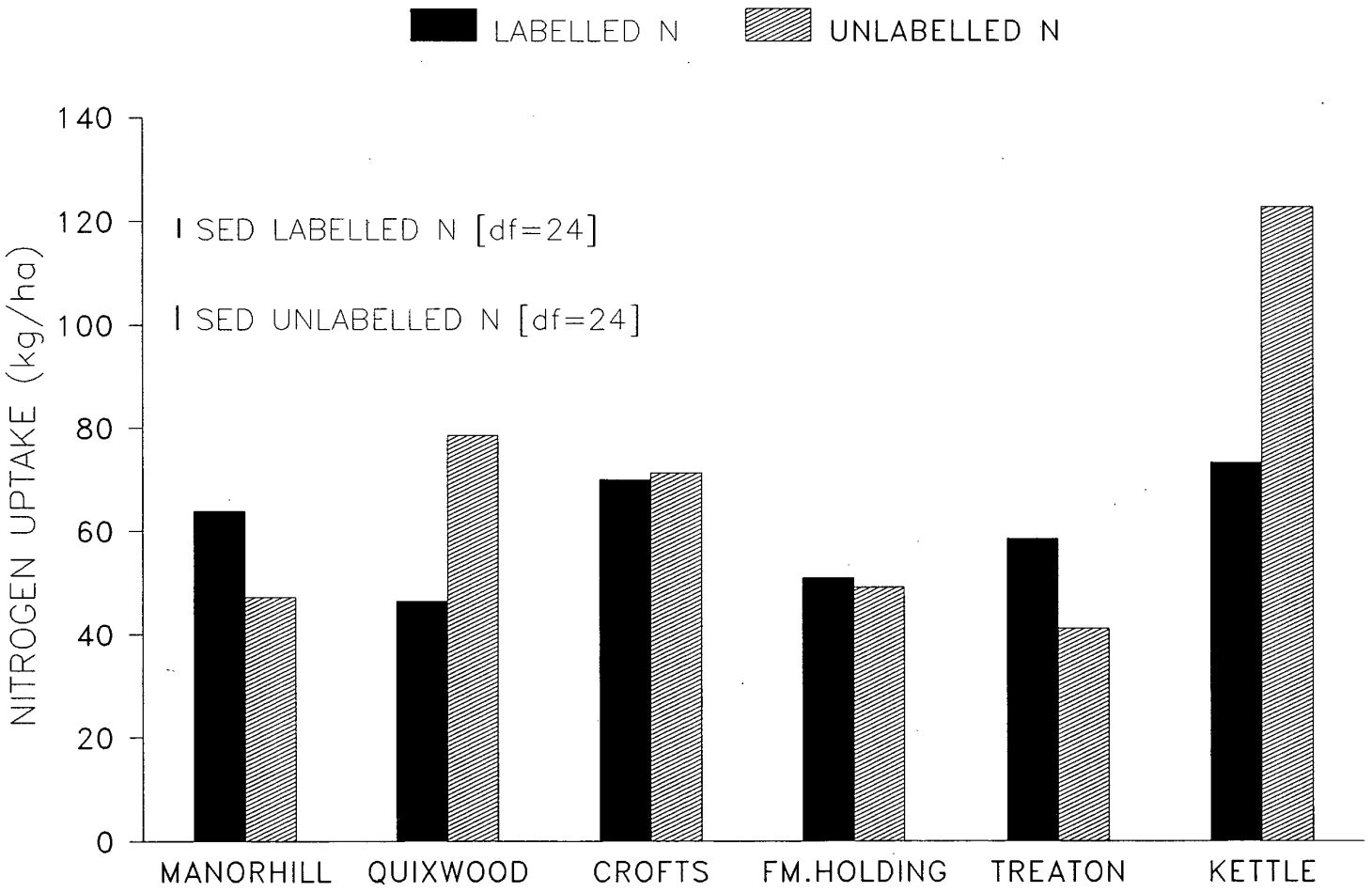


Figure 15. Mean uptake of labelled and unlabelled nitrogen in above ground plant tissue in spring barley at six sites, harvest, 1990

3: Uptake of Labelled and Unlabelled Nitrogen in Plant Shoots Over the Growing Season

In the following section the uptake of labelled and unlabelled nitrogen in plant shoots over the growing season is discussed. Representative diagrams are presented in the main text, with the remaining diagrams to be found in the appendix.

3.1: 1987-1989 seasons

3.1.1: Bush 1987

At this site, the uptake of labelled nitrogen, applied at a rate of 120 kg N/ha as either calcium nitrate or ammonium nitrate, rose steadily from 47 to 75 days after sowing during the period of stem elongation, reaching a maximum amount before anthesis of 70 kg N/ha and 78 kg N/ha respectively. When applied in the form of ammonium sulphate, uptake continued to rise for a further two weeks. However, maximum uptake of labelled nitrogen in the ammonium sulphate treatment, at 65 kg N/ha was still lower than in the other treatments, due to a less steep rise in uptake during stem elongation. In all three treatments the amount of labelled nitrogen in the plant tissues fell by harvest, most notably in the calcium nitrate treatment, falling from 70 kg N/ha after 75 days to 47 kg N/ha at harvest. The uptake of unlabelled nitrogen was much lower than labelled nitrogen prior to anthesis, but continued to rise until the plants were harvested at the end of the growing season. These effects were comparable with the results reported for spring barley grown in Scotland in similar environmental conditions by Smith et al (1984).

3.1.2: Lintlaw 1987

Here, the uptake of labelled nitrogen, with 120 kg N/ha fertiliser applied at sowing, followed a similar pattern to the Bush site, except that in the ammonium sulphate and calcium nitrate treatments there were no significant losses of labelled nitrogen between anthesis and harvest. Also, there was no difference in the uptake of labelled nitrogen between the fertiliser forms prior to anthesis. Unlabelled nitrogen rose continuously until harvest for all fertiliser forms.

When applied as a split-application the uptake of labelled nitrogen rose more slowly with no evidence of any decline before harvest. The uptake of labelled nitrogen from the first and second split applications had reached

similar levels within a few weeks of application, and this was maintained up to harvest in the calcium nitrate and ammonium nitrate treatments. In the ammonium sulphate treatment, uptake of labelled nitrogen derived from the first application was significantly lower than that derived from the second application applied at either emergence or tillering. The uptake of unlabelled nitrogen, prior to anthesis, was greater in the ammonium sulphate treatments. When fertiliser nitrogen was applied all at emergence, the uptake of labelled nitrogen was significantly slower in the ammonium sulphate treatments. Once again, however, this was accompanied by a greater uptake of unlabelled nitrogen over the same period, but overall nitrogen uptake was still lower than in the other treatments.

3.1.3: Bush 1988

At this site, with 120 kg N/ha fertiliser applied at sowing (Figure 16) labelled nitrogen uptake in the ammonium sulphate treatment was slow, reaching a maximum uptake of 64 kg N/ha several weeks after anthesis and then falling to 50 kg N/ha at harvest. In the calcium nitrate and ammonium nitrate treatments maximum uptake of labelled nitrogen occurred before anthesis, however once again there were losses of more than 25 kg N/ha of labelled nitrogen by harvest. Uptake of unlabelled nitrogen stopped rising after anthesis, remaining constant thereafter in the calcium nitrate and ammonium nitrate treatments. In the ammonium sulphate treatment uptake rose until considerably after anthesis.

Even though there was no observed drop in the amount of unlabelled nitrogen in the plants, taking into account the losses of labelled nitrogen, it is probable that losses did occur. Therefore it is likely that there was continued uptake of unlabelled nitrogen in all three treatments, but that these were balanced by losses, resulting in no net change in the calcium nitrate and ammonium nitrate treatments. The reason for the reduced losses of labelled nitrogen, and late rise in unlabelled nitrogen in the ammonium sulphatetreatment appears to have been due to a lower nitrogen concentration in the crop (Section 1.2).

3.1.3.1: Possible Mechanisms Recous et al (1988b) found that losses of labelled nitrogen occurred with $^{15}NO_3$ fertiliser, but not with $^{15}NH_4$ fertiliser. These losses were later accounted for in the soil organic matter. It was concluded that these losses were due to exudation of plant compounds, the rate of which was possibly determined by the concentration of the plant nitrate pool

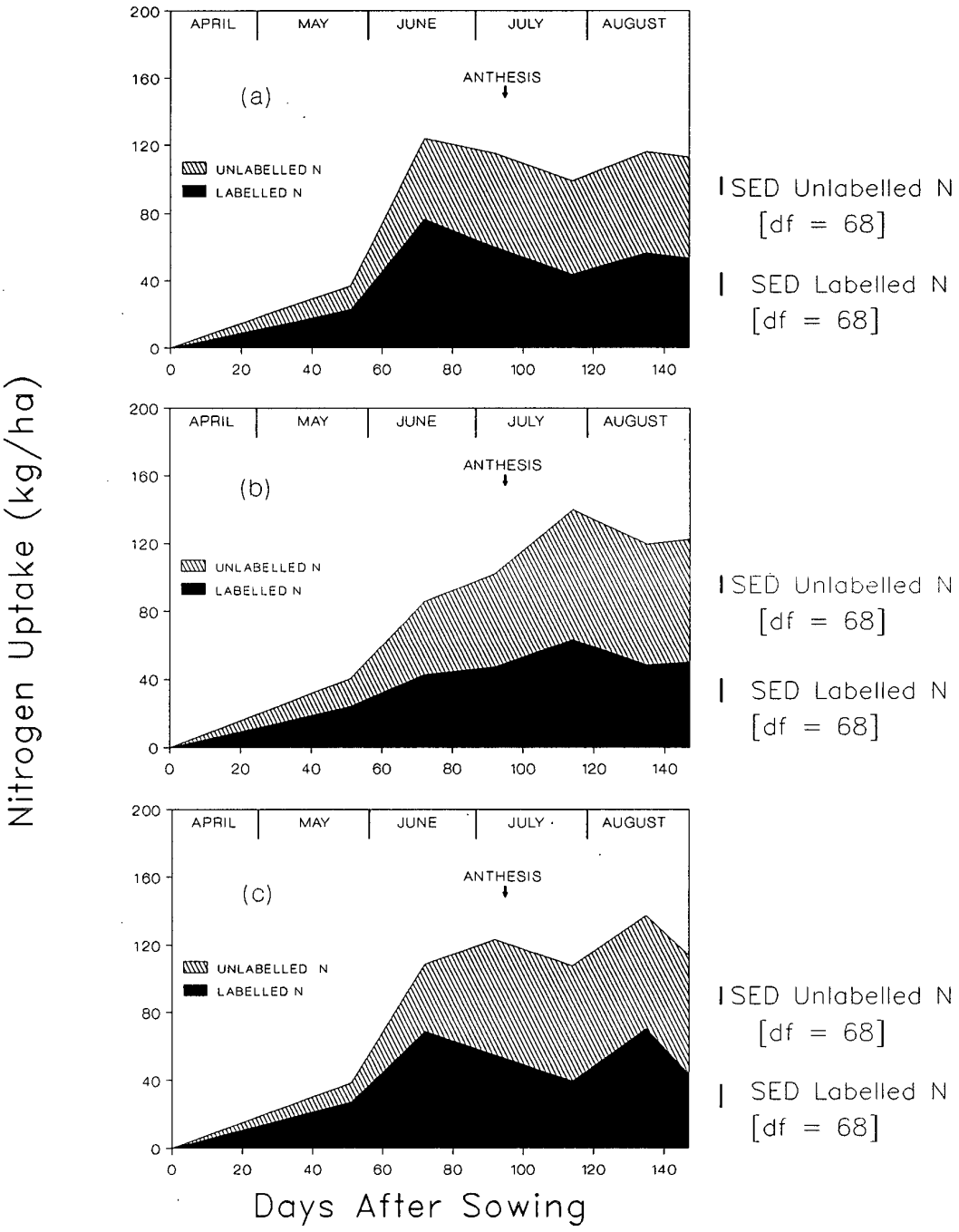


Figure 16. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen applications of 120 kg/ha at sowing in the form of (a) calcium nitrate, (b) ammonium sulphate and (c) ammonium nitrate, Bush 1988

as this was directly determined by the amount of nitrogen taken up in the nitrate form. Mary et al (1988) also showed that losses of labelled nitrogen re-appeared in the soil organic matter suggesting that translocation to the roots followed by root exudation was the probable pathway. However, these findings were limited to losses prior to anthesis when uptake had been very rapid. Losses of labelled nitrogen after anthesis were not detected in the soil organic matter, and it was suggested that these later losses were due to ammonia volatilisation from senescing plant tissue. Losses via volatilisation of 7 kg N/ha have been measured during senescence in wheat (Harper et al, 1987).

Overall uptake of unlabelled nitrogen was greatest for the ammonium sulphate treatment. During the early part of stem elongation, between 51 and 72 days after sowing, the lower rate of labelled nitrogen uptake was offset by a more rapid uptake of unlabelled nitrogen compared to the other treatments. This may have been due to uptake of more mobile unlabelled soil nitrate at a time of high demand, or it could have been as a result of pool-substitution of applied $^{15}NH_4$-N reducing the apparent fertiliser uptake. Results showing the relative amounts of NH_4-N and NO_3-N in the soil 51 days after sowing (Section 5) showed that there was still 68 kg N/ha NH_4-N present in the soil, indicating that there was considerable scope for pool substitution. There was also a significant amount of NO_3-N present, which indicated that this supply was not limiting. Therefore it would appear that pool substitution was significant.

3.1.3.2: Effect of Splitting When fertiliser applications were split the uptake of unlabelled nitrogen continued to rise until harvest (Figure 17). In the ammonium sulphate treatments, uptake of labelled nitrogen from the first application remained constant after about 70 days, but uptake from the second application continued to rise until shortly before harvest. There was a greater final recovery of labelled nitrogen from the second application. When all the fertiliser was applied at emergence there was a very rapid uptake of labelled nitrogen in the calcium nitrate and ammonium nitrate treatments between 51 and 72 days after sowing. This period of uptake coincided with the start of stem elongation and a large demand for nutrients by the rapidly growing crop. During this period, however, the uptake of unlabelled nitrogen was low and only increased significantly around the time of booting and ear emergence. This coincided with the end of the fall in soil mineral nitrogen suggesting that the plants had used up all the available fertiliser nitrogen by this time. Uptake of labelled nitrogen in the ammonium sulphate treatment was less rapid, but

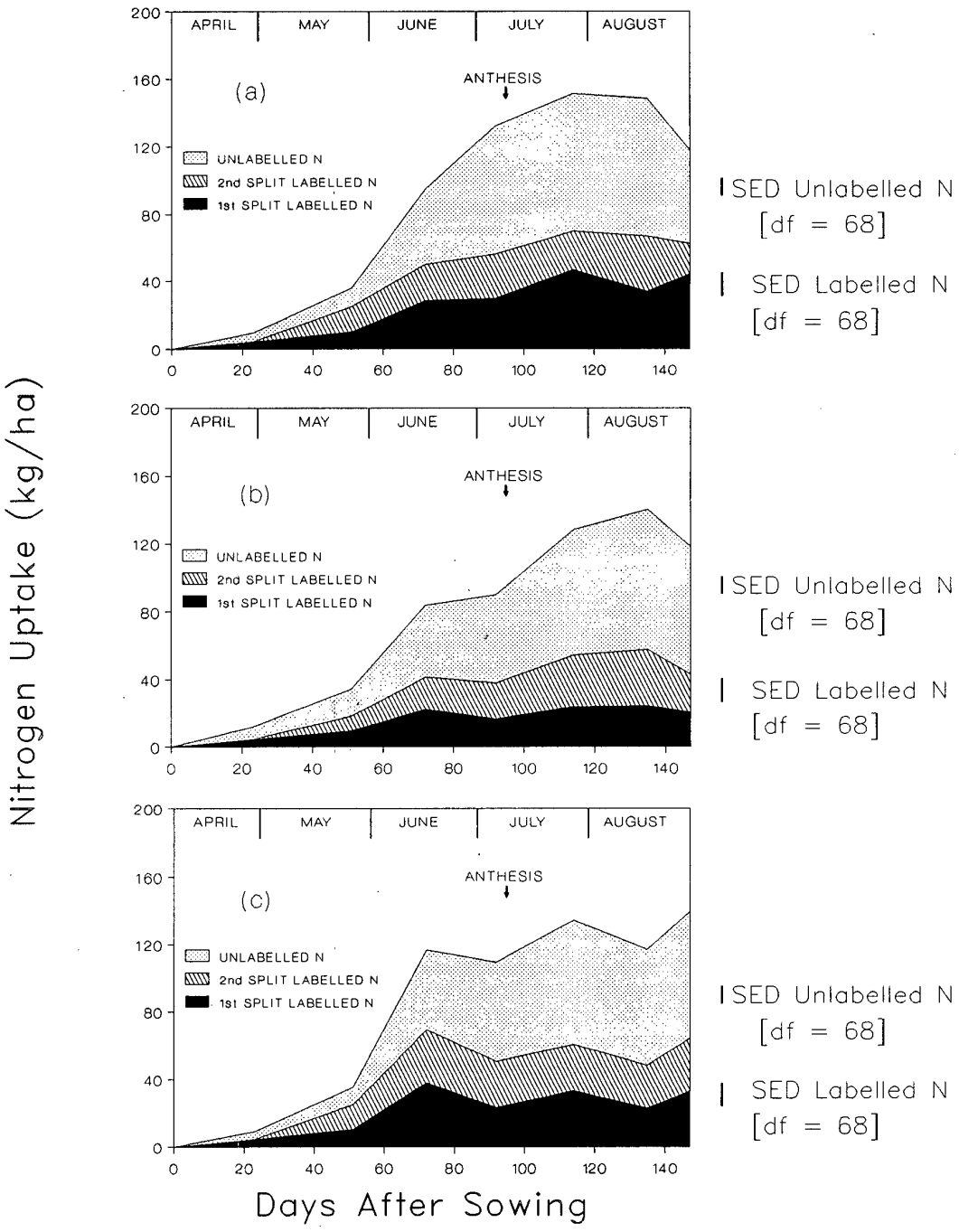


Figure 17. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen application of 60 kg/ha at sowing and 60 kg/ha at emergence in the form of (a) calcium nitrate, (b) ammonium sulphate and (c) ammonium nitrate, Bush 1988

continued to rise until well after anthesis. Maximum uptake was 62 kg N/ha, lower than the other fertiliser forms, but there was still a loss of 26 kg N/ha by harvest.

3.1.4: Middlestot 1988

The uptake of seed-bed applied labelled nitrogen in the ammonium nitrate form was less rapid than at Bush 1988, but continued to rise for most of the growing season (Figure 18). Uptake of labelled nitrogen applied as ammonium sulphate followed a similar pattern, but there was a significant loss from a maximum uptake of 66 kg N/ha after 128 days growth to 48 kg N/ha at harvest 29 days later. The overall uptake of unlabelled nitrogen was much lower than at Bush 1988, and also the pattern of uptake differed in that uptake at Middlestot reached a maximum shortly after anthesis and remained constant until harvest. The minimal nitrogen losses after anthesis were probably due to the very much lower nitrogen concentrations in the plant tissue. As shown earlier the grain nitrogen contents were very much lower than at Bush in 1988, but yields were similar. This fact, in conjunction with a much lower uptake of unlabelled nitrogen, meant that there were adequate sinks in the developing grains to accommodate the translocation of nitrogen from other plant tissues. This agreed with Schjorring et al (1989), who found the lowest losses in years of high grain yields and harvest indexes. Uptake of labelled nitrogen from first and second split applications was similar within a few weeks of the second application whether applied at emergence or tillering. In the calcium nitrate form labelled nitrogen uptake was more rapid especially in the tillering treatment. The uptake of unlabelled nitrogen continued to rise until shortly before harvest in all treatments followed by a slight decline in most treatments. When 120 kg N/ha fertiliser was applied all at emergence the uptake of labelled nitrogen peaked earlier in the calcium nitrate and ammonium nitrate treatments compared with the ammonium sulphate treatment. The rate of uptake in each of the three fertiliser treatments was not as great as the equivalent treatment at Bush 1988. This was probably due to the much drier soil conditions at Middlestot.

3.1.5: Bush 1989

At this site, there was significantly greater uptake of labelled nitrogen applied in the calcium nitrate form. With 120 kg N/ha applied at sowing there

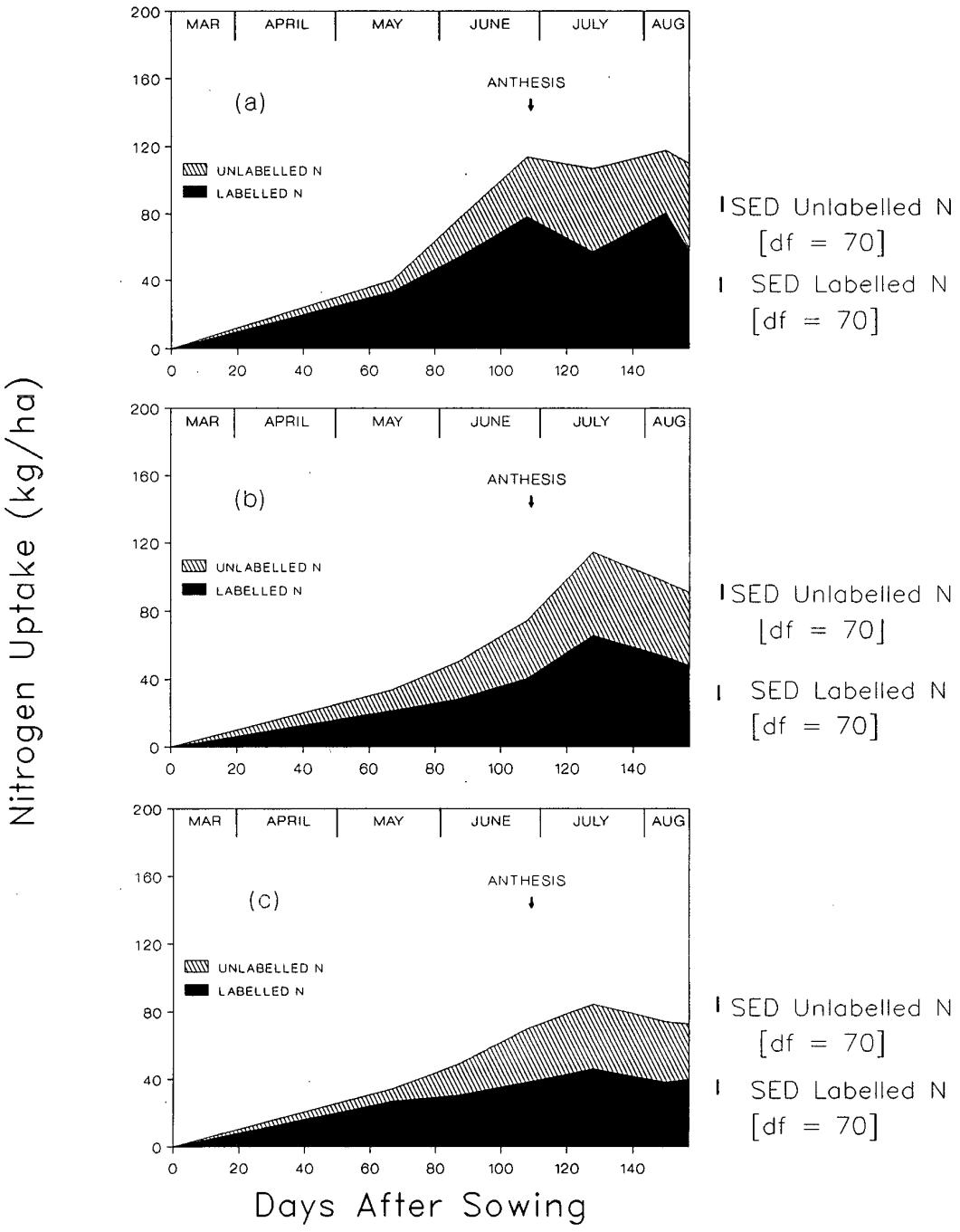


Figure 18. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen applications of 120 kg/ha at sowing in the form of (a) calcium nitrate, (b) ammonium sulphate and (c) ammonium nitrate, Middlestot 1988

was rapid uptake between 48 and 68 days growth during which period uptake rose from 13 kg N/ha to 63 kg N/ha (Figure 19). Thereafter uptake rose more steadily, reaching 98 kg N/ha by harvest. Uptake of labelled nitrogen was less rapid in the other two fertiliser forms, reaching approximately 41 kg N/ha after 68 days. Uptake continued to rise gradually, reaching a maximum level three weeks after anthesis and remaining constant until harvest. Schjorring et al (1989) showed that lower overall uptake of labelled nitrogen, and maximum uptake delayed until after anthesis, was a result of a higher soil nitrogen turnover rate.

Uptake of unlabelled nitrogen was similar for all treatments over the first 108 days growth reaching a maximum of about 70 kg N/ha, but then losses occurred in the two nitrate fertiliser treatments. The loss was derived mainly from the unlabelled nitrogen content of the plant. This suggested that the uptake of labelled nitrogen continued until harvest. In 1989 the soil moisture content fell quickly during the growing season. This would have reduced the losses of labelled nitrogen via leaching and denitrification. Vinten et al (1991) showed a loss of only 6 kg N/ha under spring barley grown locally in the same season. This means that labelled nitrogen would still be available for uptake later in the growing season. The earlier reduction of uptake in the ammonium sulphate treatment may have been an indication of greater pool substitution of NH_4-N exhausting the labelled nitrogen pool earlier.

3.1.5.1: Effect of splitting When fertiliser applications were split there was a significantly more rapid uptake of labelled nitrogen in the calcium nitrate treatments indicating greater mobility of nitrogen as NO_3-N. In the ammonium sulphate treatments from 47 to 89 days after sowing, during stem elongation, the uptake of unlabelled nitrogen was greater than labelled nitrogen split applications at 90 kg N/ha rates. In the 120 kg N/ha treatment split between sowing and emergence (Figure 20) there was a total nitrogen uptake of 81 kg N/ha in the calcium nitrate treatment by the end of the period of stem elongation. Of this 81 kg, 69 kg was derived equally from each of the labelled fertiliser applications, and only 12 kg from unlabelled nitrogen. In contrast, uptake of labelled nitrogen was much lower at 39 kg N/ha and 47 kg N/ha in the ammonium sulphate and ammonium nitrate treatments respectively. The uptake of unlabelled nitrogen was approximately 39 kg N/ha. The main reason for these differences was the rate of uptake of labelled nitrogen from the second split application. During stem elongation there is a large demand for nitrogen

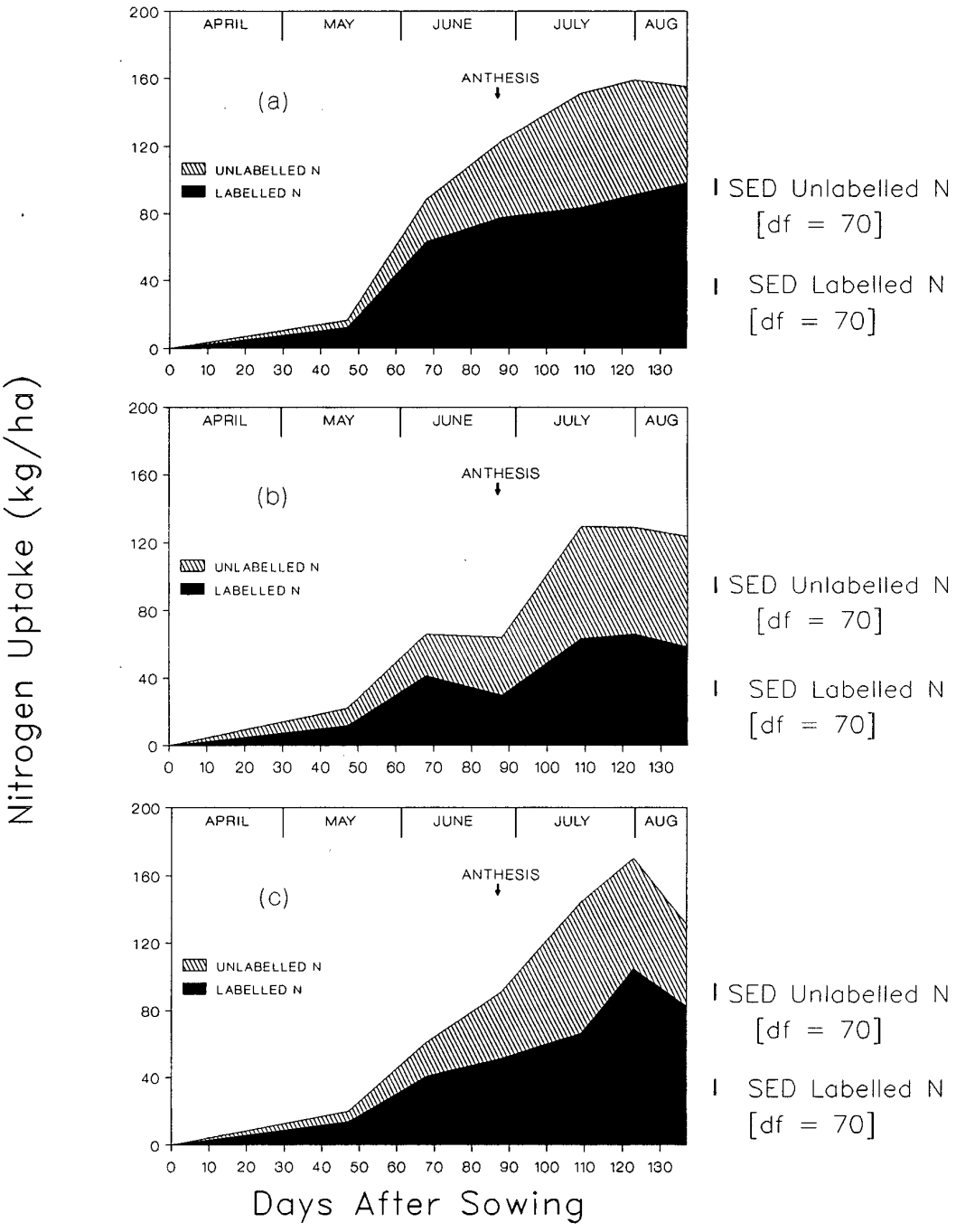


Figure 19. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen applications of 120 kg/ha at sowing in the form of (a) calcium nitrate, (b) ammonium sulphate and (c) ammonium nitrate, Bush 1989

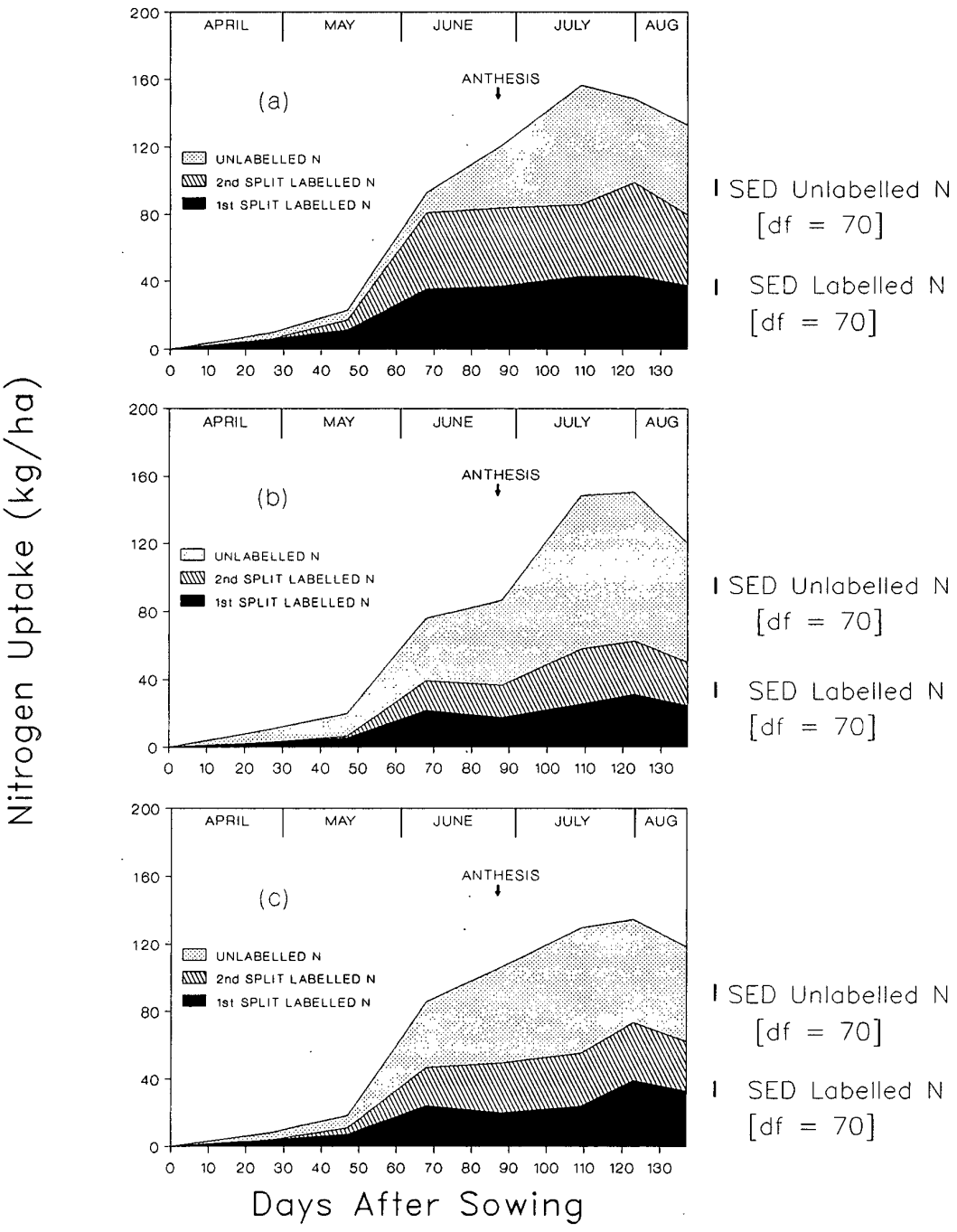


Figure 20. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen application of 60 kg/ha at sowing and 60 kg/ha at emergence in the form of (a) calcium nitrate, (b) ammonium sulphate and (c) ammonium nitrate, Bush 1989

by the rapidly growing plant. The much greater uptake of labelled nitrogen in the calcium nitrate treatment indicated the greater mobility of NO_3-N in the soil. To compensate for the reduced uptake of labelled nitrogen in the ammonium treatments there was a greater uptake of native unlabelled soil nitrogen which was more accessible. The fact that labelled nitrogen uptake continued to rise until shortly before harvest in the ammonium sulphate and ammonium nitrate treatments tended to confirm the lack of mobility of the NH_4-N slowing down the rate of uptake.

3.1.6: Upper Cairnie 1989

There was very little uptake of labelled nitrogen before the onset of stem elongation. Even when applied in the form of calcium nitrate there was only 5 kg N/ha taken up during the first 50 days of growth when 120 kg N/ha was applied at sowing (Figure 21). By anthesis labelled nitrogen uptake had risen to 62 kg N/ha in the calcium nitrate treatment, but was only 44 kg N/ha in the ammonium sulphate treatment. Between anthesis and harvest labelled nitrogen levels remained constant in the ammonium nitrate and ammonium sulphate treatments, but continued to rise by 30 kg N/ha in the calcium nitrate treatment. This is a highly efficient recovery and appeared to be due to the labelled nitrate remaining longer in the soil as described earlier for Bush 1989. The cessation of uptake after 91 days growth in the other fertiliser forms was likely due to the less mobile NH_4-N reducing uptake and also a consequence of pool-substitution shown by the higher uptake of unlabelled nitrogen in the ammonium sulphate treatment. The uptake of unlabelled nitrogen was much lower than at Bush 1989, rising until harvest to 43 kg N/ha in the calcium nitrate and ammonium nitrate treatments and 51 kg N/ha in the ammonium sulphate treatment.

Split fertiliser applications significantly reduced the uptake of labelled nitrogen applied in the ammonium sulphate treatments compared to applications at sowing only. Labelled nitrogen uptake was greater when the second application was applied at emergence rather than tillering in the calcium nitrate and ammonium nitrate treatments. By the time of the later application the soil surface had dried out considerably; less than the measured moisture content for 0-20 cm. This meant that the fertiliser moved down into the soil much more slowly. Maximum uptake, which occurred 3 weeks after anthesis, was 68 kg N/ha and 61 kg N/ha for the calcium nitrate and ammonium nitrate

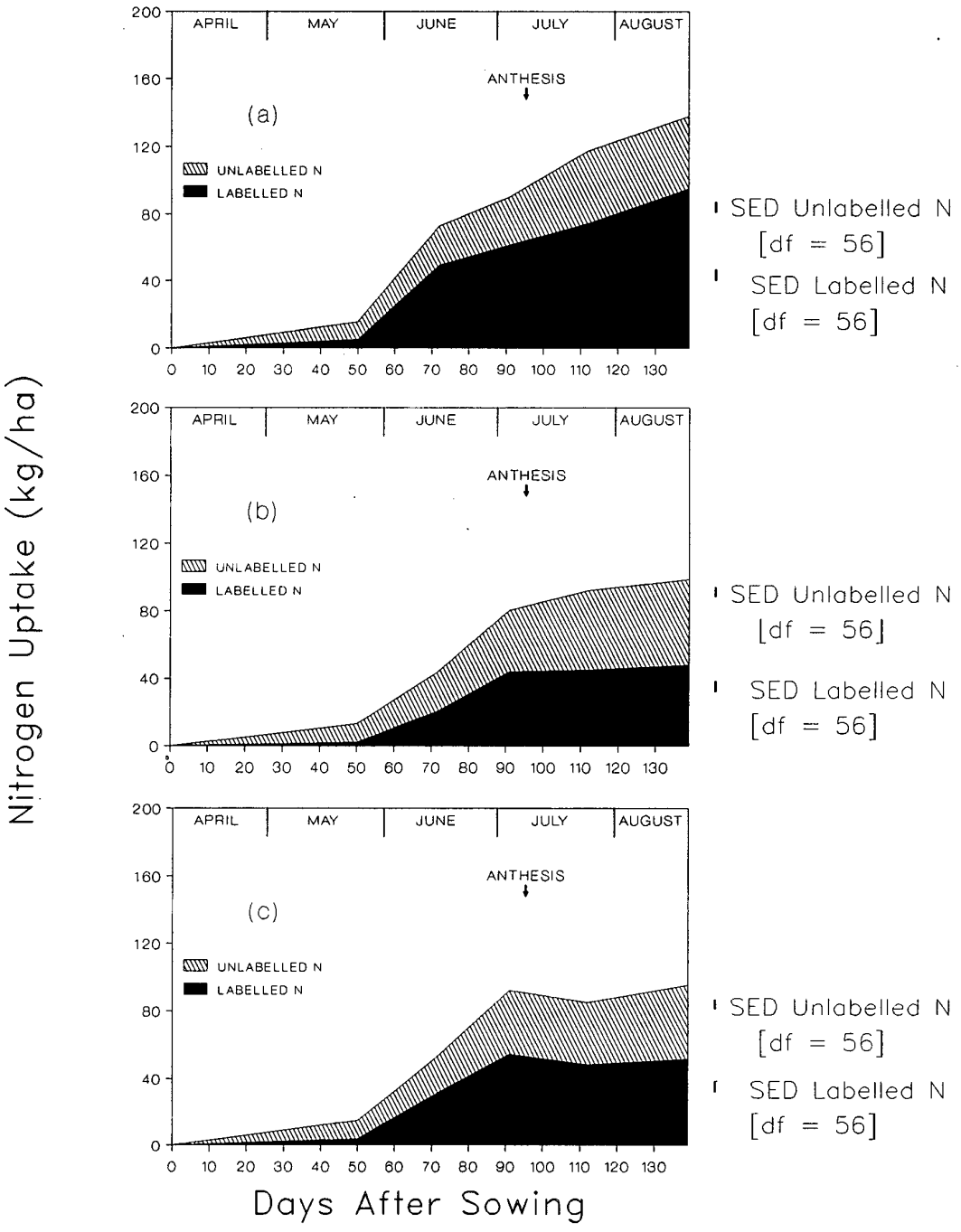


Figure 21. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen applications of 120 kg/ha at sowing in the form of (a) calcium nitrate, (b) ammonium sulphate and (c) ammonium nitrate, Upper Cairnie 1989

treatments respectively on the sowing/emergence split treatment. The uptake of unlabelled fertiliser rose steadily throughout the growing season with no significant effect of the form in which the fertiliser was applied. There was a similar uptake pattern in the sowing/tillering treatment. In conjunction with data presented earlier (Section 2), and taking into account the very dry soil conditions, it is most likely that there was not a complete mixing of the labelled and unlabelled nitrogen pools which is necessary for significant pool substitution to occur (Jenkinson et al, 1985).

3.2: 1990 season

The uptake of labelled and unlabelled nitrogen from the six sites fertilised with 120 kg N/ha at sowing is discussed. There was no evidence of any losses of labelled nitrogen between anthesis and harvest at any of the sites.

3.2.1: Manorhill

There was little increase in the uptake of labelled nitrogen in the ammonium sulphate treatment after 109 days growth. From 109 days until harvest uptake rose faster in the ammonium nitrate treatment after a lag in uptake over the previous few weeks. Uptake of unlabelled nitrogen levelled off after 109 days growth in the ammonium sulphate treatment but continued rising in the ammonium nitrate treatment.

3.2.2: Quixwood

The uptake of labelled nitrogen was low in the early stages of growth with only 8 kg N/ha taken up by tillering. Uptake was more rapid between 44 and 73 days growth, during stem elongation, reaching 35 kg N/ha by anthesis, and continuing to rise gradually until harvest for both fertiliser treatments. There was a greater uptake of unlabelled nitrogen compared to labelled nitrogen in the early stages of growth, with uptake rising rapidly after anthesis to 90 kg N/ha. The site at Quixwood was at a high altitude, which reduced the early growth rate and consequently caused the low nitrogen uptake early in the growing season. The high uptake of unlabelled nitrogen was due to the mineralisation of organic matter in the soil, as illustrated by the increase in mineral nitrogen in the zero fertiliser plots (Section 5).

3.2.3: Bush

At Crofts and Farmers Holding, there was more rapid uptake of labelled nitrogen in the ammonium nitrate treatments. At Farmers Holding a maximum uptake of 51 kg N/ha was achieved in the ammonium nitrate treatment before anthesis then remaining constant until harvest. At Crofts the uptake of labelled nitrogen applied in the same form was greater with uptake levelling off at 64 kg N/ha about two weeks after anthesis. Uptake from the ammonium sulphate-labelled fertiliser rose throughout the season with a final value greater than the ammonium nitrate treatment. After 82 days growth near the end of stem elongation at Crofts, the uptake of unlabelled nitrogen from the ammonium sulphate treatment was higher than the ammonium nitrate treatment, and also greater than labelled nitrogen uptake. However, by harvest there was no significant difference between labelled and unlabelled nitrogen uptake due to continued uptake of labelled nitrogen after anthesis. This indicated the occurrence of pool substitution with the late uptake of labelled nitrogen attributed to the re-mineralisation of previously immobilised $^{15}NH_4$-N.

3.2.4: Treaton

There was a rapid uptake of labelled nitrogen between 50 and 83 days growth, during stem elongation, of 45 kg N/ha and 50 kg N/ha for the ammonium sulphate and ammonium nitrate treatments respectively by the end of this period. There was then a loss of around 6 kg N/ha over the next 28 days in both treatments before uptake rose again before harvest to 56 kg N/ha and 60 kg N/ha respectively. Unlabelled nitrogen rose steadily over the first 111 days in both treatments with no significant increase after that.

3.2.5: Kettle

There was very little uptake of nitrogen prior to stem elongation (Figure 22b). Between then and anthesis uptake increased rapidly in both treatments by over 50 kg N/ha in 21 days. However, as at Manorhill (Figure 22a) and Treaton there was a period of stable or falling labelled nitrogen content over the next 21 days, followed by a rise in uptake once again through to harvest. During this final period of grain filling uptake was greater in the ammonium nitrate treatment. This may have been a reflection of greater losses occurring at the time of anthesis which were reduced later in the season. Other research has

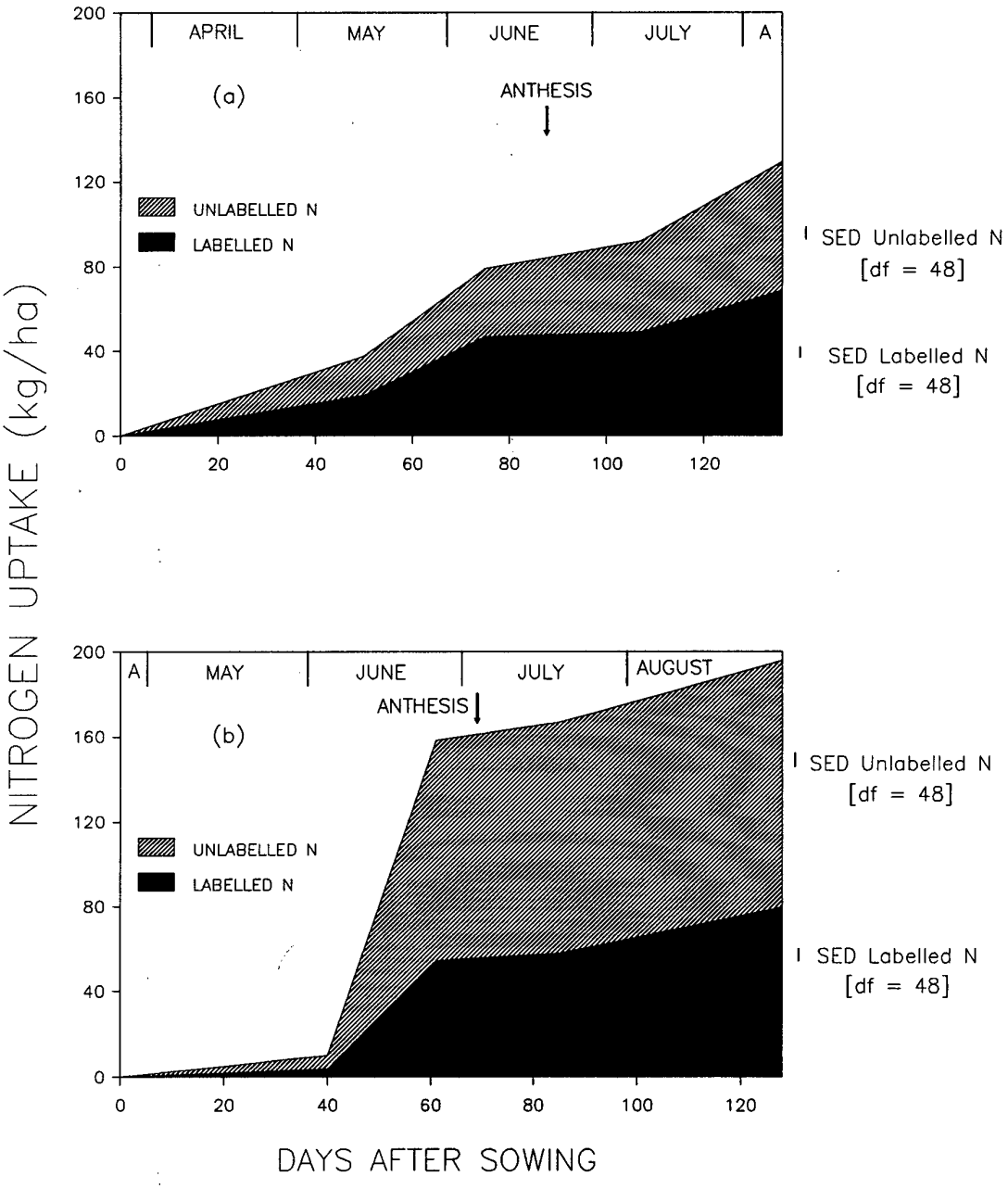


Figure 22. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after ammonium nitrate fertiliser applications of 120 kg N/ha at sowing (a) Manorhill 1990 and (b) Kettle 1990

shown that the most rapid losses occur around anthesis (Mary et al, 1988; Schjorring et al, 1989).

The uptake of unlabelled nitrogen was much greater than labelled nitrogen throughout the whole season with 85 kg N/ha and 97 kg N/ha taken up during stem elongation by the ammonium sulphate and ammonium nitrate treatments respectively. Over the following 21 days the difference in the uptake of unlabelled nitrogen between the two treatments increased, with a slight fall to 85 kg N/ha in the ammonium sulphate treatment and a rise to 109 kg N/ha in the ammonium nitrate treatment. Clay and Clapp (1990) showed that the addition of fertiliser NH_4-N to a soil inhibited the mineralisation of crop residues. This may have been the reason for the lower uptake of unlabelled nitrogen in the ammonium sulphate treatment during the middle part of the growing season. Late in the season the amount of fertiliser nitrogen remaining in the soil was small, reducing any inhibitory effect and accounting for the late rise in uptake of unlabelled nitrogen in the ammonium sulphate treatment.

The overall uptake of unlabelled nitrogen at Kettle was very high, despite the fact that the concentration of soil organic matter was low (2.8%). This was in contrast to Manorhill where uptake of unlabelled nitrogen was much lower. Despite this the uptake of labelled fertiliser nitrogen was similar at both sites (Figure 22). At Kettle, residual nitrogen at the beginning of the growing season was 25 kg N/ha, and while this may have contributed to the uptake of unlabelled nitrogen in the plant it was small compared to the overall uptake of unlabelled nitrogen. The source of the unlabelled nitrogen would appear therefore to have been predominantly derived from the residues of the previous year's crop (brussels sprouts). However, Ladd and Amato (1986) using ^{15}N-labelled legume residues, found that these were only partly available to the following crop, with the remainder incorporated into the soil organic matter and released over a period of years. Azan et al (1989) found that crop residues were mineralised more quickly in soils low in organic matter. This may explain the large uptake of unlabelled nitrogen at Kettle with its light soil texture and low organic matter content.

4: General Discussion of Grain Nitrogen Content and Nitrogen Uptake, 1987-1990

The form in which the fertiliser nitrogen was applied had little effect on the nitrogen content in the grain. Where there was an effect, as occurred at Lintlaw and Upper Cairnie the higher grain nitrogen contents in the calcium nitrate treatments were caused by a greater uptake of fertiliser nitrogen compared to the other fertiliser treatments. At low fertiliser rates the calcium nitrate treatments gave higher grain yields than the ammonium sulphate treatments. With increasing fertiliser rates yields reached a maximum at between 90-120 kg N/ha in the calcium nitrate treatments, whereas in the ammonium sulphate treatments yields generally rose steadily with increased fertiliser rates. Sites with dry soil conditions, such as at Middlestot and Upper Cairnie gave higher overall yields in the calcium nitrate treatments compared to the other treatments. These effects appeared to be determined by the efficiency of recovery of applied fertiliser nitrogen. Calcium nitrate fertiliser was more efficiently recovered in the plant when applied at low rates or in split applications, as this reduced the possibility of losses via leaching or denitrification. The less mobile NH_4-N in the ammonium sulphate treatments reduced recoveries at lower rates as a result of less movement in the soil toward plant roots, and also because of a proportionately greater effect of pool substitution on ^{15}N-labelled fertiliser at low rates (Jenkinson et al, 1985). This effect could have been enhanced by the delayed uptake of fertiliser nitrogen during germination and early growth immediately after sowing, and also because of the preference of soil micro-organisms for NH_4-N as a substrate.

Split applications only increased yields over seedbed applied fertiliser in the calcium nitrate treatments applied to the early sown crop at Lintlaw. Heavy rain shortly after sowing reduced the uptake of calcium nitrate all applied at sowing probably due to increased leaching. Grain nitrogen concentrations were generally not significantly affected by split applications. In 1989 split applications at the lower rate of 90 kg N/ha gave lower grain nitrogen contents when compared with 120 kg N/ha all applied at sowing, but did not significantly reduce yields. This year, however, soil conditions were very dry and this led to very high grain nitrogen contents. This appeared to be caused by a reduction in the grain filling period due to moisture stress in the plant and this reduced the amount of photosynthate translocated to the grain. In 1990 there was no significant difference in grain yields and grain nitrogen concentrations between

the ammonium sulphate and ammonium nitrate treatments studied at 120 kg N/ha.

The uptake of labelled nitrogen occurred mainly during the early part of the growing season. After an initial period of low uptake, there was generally a dramatic rise in uptake as the plant entered the period of stem elongation, most notably in the calcium nitrate and ammonium nitrate treatments, and reached a maximum around anthesis. Losses of labelled nitrogen between anthesis and harvest were recorded at some sites. These were most significant in the calcium nitrate and ammonium nitrate treatments at sites where there was a large and rapid uptake of labelled nitrogen, such as occurred at Bush 1988, where losses of up to 25 kg N/ha were recorded. The concentration of nitrogen in these plant tissues would have been high, and this seemed to determine the extent of nitrogen losses. Reports of losses of fertiliser nitrogen from plant tissues have been reported and it has been suggested that these losses could have occurred as a result of root exudation (Recous et al, 1988b) or ammonia volatilisation from senescing plant tissues later in the growing season (Schjorring et al, 1989). When applied in the form of ammonium sulphate the uptake of labelled nitrogen was slower, continuing later into growing season than the other fertiliser forms. This may have been due to the less mobile NH_4-N restricting root uptake early in the growing season, but also remaining longer in the soil. Another possible reason for the late uptake of labelled nitrogen could have been the re-mineralisation of previously immobilised $^{15}NH_4$-N later in the growing season.

Similar patterns of uptake of labelled nitrogen were recorded under very dry conditions at Middlestot and Upper Cairnie in the calcium nitrate and ammonium nitrate treatments. Uptake of labelled nitrogen continued late into the growing season at these two sites, up to harvest at Upper Cairnie, due to the reduced mobility of NO_3-N in the soil under these conditions. There were no losses of labelled nitrogen from the plants at these sites which could have been attributed to the lower accumulation of nitrogen in the plant tissues around the time of anthesis compared to results from the other sites.

The uptake of unlabelled nitrogen was not as rapid as labelled nitrogen especially through the rapid uptake phase during stem elongation. Over this period the uptake of unlabelled nitrogen was higher in the ammonium sulphate treatments compared with the other fertiliser forms. This was probably due to a

combination of pool substitution of NH_4-N, and also the uptake of unlabelled NO_3-N when the plant was unable to satisfy its high demand for nitrogen from the less mobile applied $^{15}NH_4$-N. Uptake of unlabelled nitrogen continued after labelled nitrogen uptake had ceased, continuing to rise until harvest under the dry soil conditions at Middlestot and Upper Cairnie while remaining constant from shortly after anthesis at the other sites. This constant uptake occurred despite the significant losses of labelled nitrogen which suggested that there would also have been some losses of unlabelled nitrogen given no discrimination between ^{15}N and ^{14}N. This meant that there would also have been continued uptake of labelled nitrogen until harvest at these sites indicating continued mineralisation of soil organic matter, as by this time mineral nitrogen levels in the soil were low at most sites.

However, these treatments studying the effect of fertiliser form and timing on grain nitrogen concentrations and yields were found to be relatively small when compared to the effects of site and season. The most important determining factor at each site was the uptake of unlabelled nitrogen in the plant. Uptake of unlabelled nitrogen was significantly more variable between sites than the uptake of labelled nitrogen. Variation in the uptake of unlabelled soil nitrogen between sites ranged up to 100% even between sites of similar cropping histories grown in the same season. Most of these sites would have been categorised as N-Index zero soils, based on previous cropping (MAFF, 1985) and would have meant similar fertiliser recommendations. Therefore it appeared that the most important factor to be determined, to assist in the production of a good crop of malting barley, was an assessment of the likely uptake of soil nitrogen in the crop. Results of assessments made using simple laboratory techniques are presented in Section 6.

5: Mineral Nitrogen in the Soil, 1987-1990

In the following section the effect of site and treatment differences on the quantity of mineral nitrogen in the upper soil profile during the growing season is discussed. Representative diagrams are presented in the main text, with the remaining diagrams to be found in the appendix.

5.1: 1987-1989 seasons

5.1.1: Bush 1987

At this site, the amount of mineral nitrogen in the soil declined steadily over the first 82 days growth after the addition of 120 kg N/ha ammonium nitrate in the seedbed (Figure 23a). Thereafter there was no significant change in the amount of mineral nitrogen in the soil. Over this period there was a reduction of 108 kg/ha mineral nitrogen which was of the same order as total nitrogen uptake in the plant tissues (Section 3.1). The lack of any significant decline in mineral nitrogen after this, despite the continued uptake of unlabelled nitrogen in the plants, suggested net mineralisation continued up until harvest.

5.1.2: Lintlaw 1987

Here, the rate of decline of mineral nitrogen in the soil, over the first 54 days growth, was similar for both 120 kg N/ha and 150 kg N/ha treatments (Figure 23b). By this time there was an even distribution of mineral nitrogen in the top 40 cm of the soil in the 120 kg N/ha treatment (Figure 24b). This mineral nitrogen contained only 24 kg/ha NH_4-N indicating a greater rate of nitrification, and was significantly lower in proportion than the NH_4-N present in the soil at Bush. This was probably a consequence of the lighter soil texture at Lintlaw (Table 1) allowing more solute movement, and possibly better aeration increasing nitrification activity. The greater quantity of NH_4-N applied in the 150 kg/ha treatment may have prevented sufficient nitrification and downward movement in the soil to provide an even mix throughout the top 40 cm over the first 54 days. There then followed a more rapid decline over the following 14 days, which was greater in the 150 kg N/ha treatment. By 100 daysgrowth the decline in soil mineral nitrogen ceased with no further change up to harvest. During this later growth period there was continued uptake of unlabelled nitrogen in the plant. This suggested that mineralisation proceeded through until harvest.

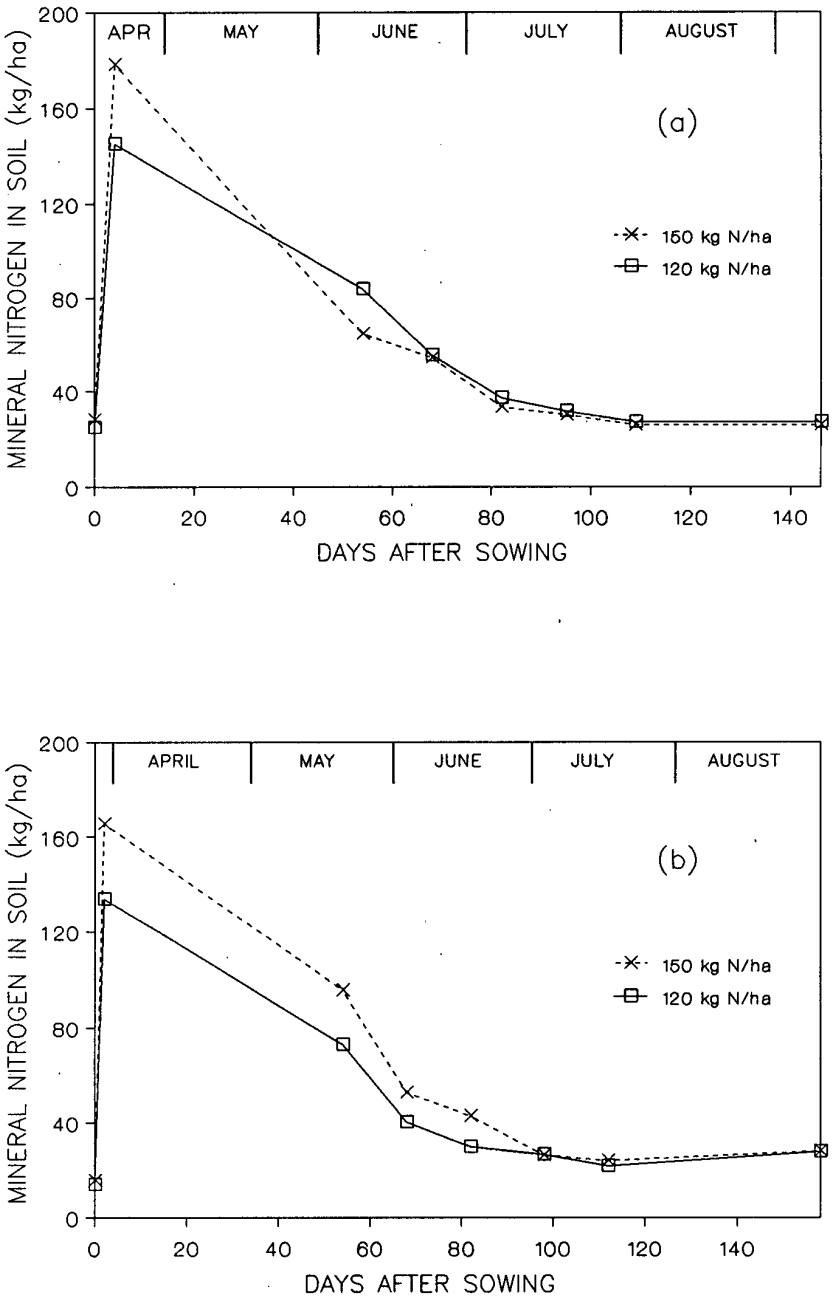


Figure 23. Changes in mineral nitrogen in the soil (0-40 cm) over the growing season, under spring barley applied with ammonium nitrate fertiliser at sowing, (a) Bush and (b) Lintlaw, 1987

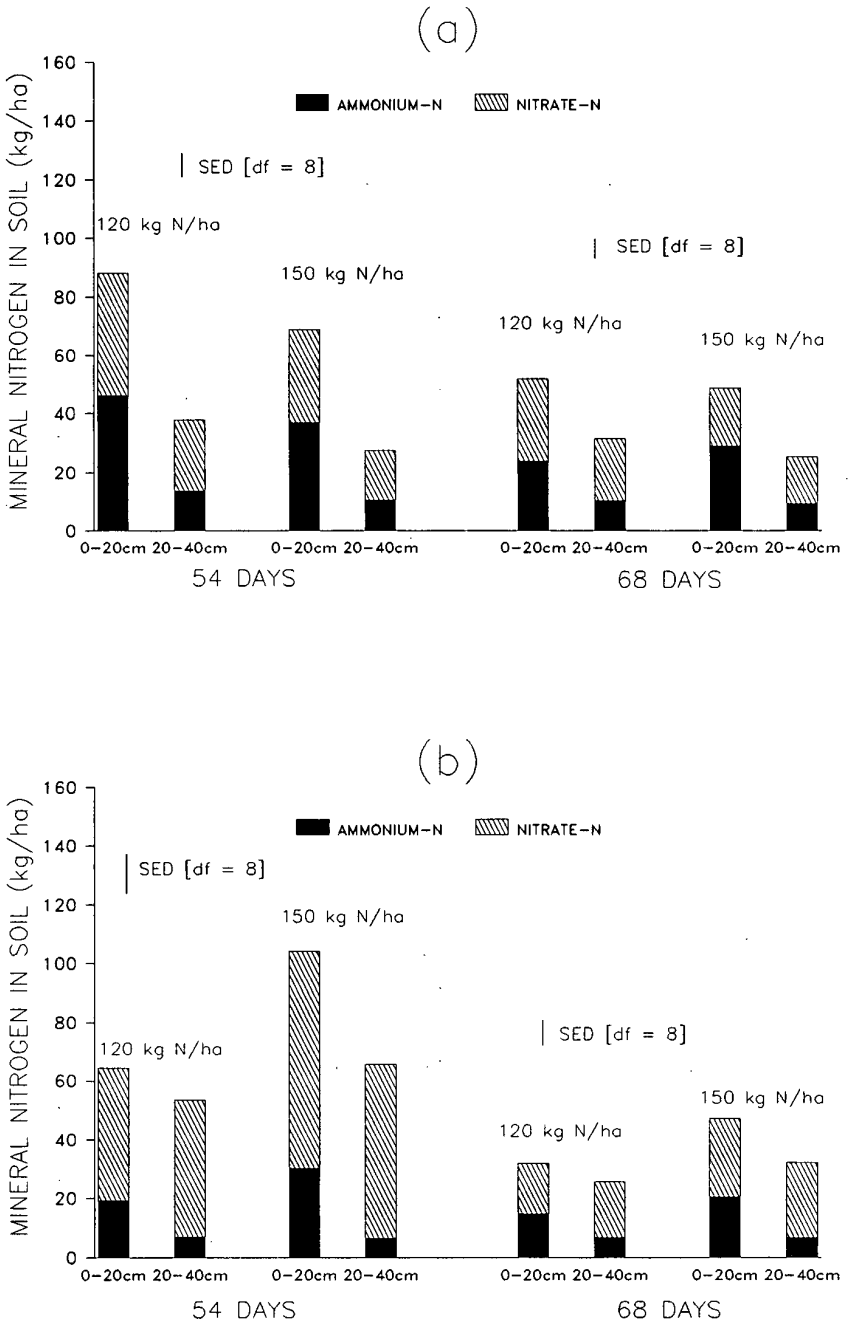


Figure 24. Quantities of nitrate- and ammonium-N at different depths in the soil at first two sampling dates, under spring barley fertilised with ammonium nitrate at sowing, (a) Bush and (b) Lintlaw, 1987

5.1.3: Bush 1988

At this site, there was a rapid fall in soil mineral nitrogen in all treatments between 51 days and 72 days after sowing (Figure 25a). There was no significant difference between the form of fertiliser applied. This coincided with increased rates of plant uptake (Section 3.1). At 51 days after the application of 120 kg N/ha ammonium sulphate all at sowing, there were 49 kg/ha NH_4-N remaining in the soil making up 49% of total mineral nitrogen present. This indicated that there was still a considerable proportion of the ammonium sulphate fertiliser which had been neither nitrified nor immobilised. Over the following 21 days, the amount of mineral nitrogen in the soil fell to very low levels in all treatments despite the lower plant uptake in the ammonium sulphate treatment. This suggested that there had been immobilisation of labelled fertiliser nitrogen during this period. Also the continued uptake of labelled nitrogen until shortly before harvest in the ammonium sulphate treatment indicated the re-mineralisation of previously immobilised $^{15}NH_4$-N. This effect was apparent in the ammonium sulphate treatment due probably to the preference of soil micro-organisms for NH_4-N as a substrate as described earlier.

5.1.4: Middlestot 1988

At this site, there was no significant difference in the soil mineral nitrogen content between the different fertiliser forms after 67 days growth, except in the 90 kg N/ha treatment where there was a significantly higher quantity of mineral nitrogen in the ammonium sulphate treatment (Figure 25b). In the 120 kg N/ha treatments there was significantly more nitrogen in the top 0-20 cm of the soil than 20-40 cm in the two ammonium containing fertiliser treatments (Figure 26). This indicated that the applied NH_4-N was less mobile than the NO_3-N applied in the calcium nitrate treatment, andtherefore was not so well distributed throughout the soil profile, reducing its availability to roots other than those growing close to the soil surface. After a further 21 days growth, during which time the plant demand for nitrogen increased (Section 3.1), there were still 62 kg/ha of mineral nitrogen in the ammonium sulphate treatment, which was significantly greater than the 23 kg N/ha and 32 kg N/ha in the calcium nitrate and ammonium nitrate treatments respectively. 42 kg/ha of the mineral nitrogen in the ammonium sulphate treatment were in the NH_4-N form (Figure 26), indicating that the reduced mobility of the NH_4-N in the

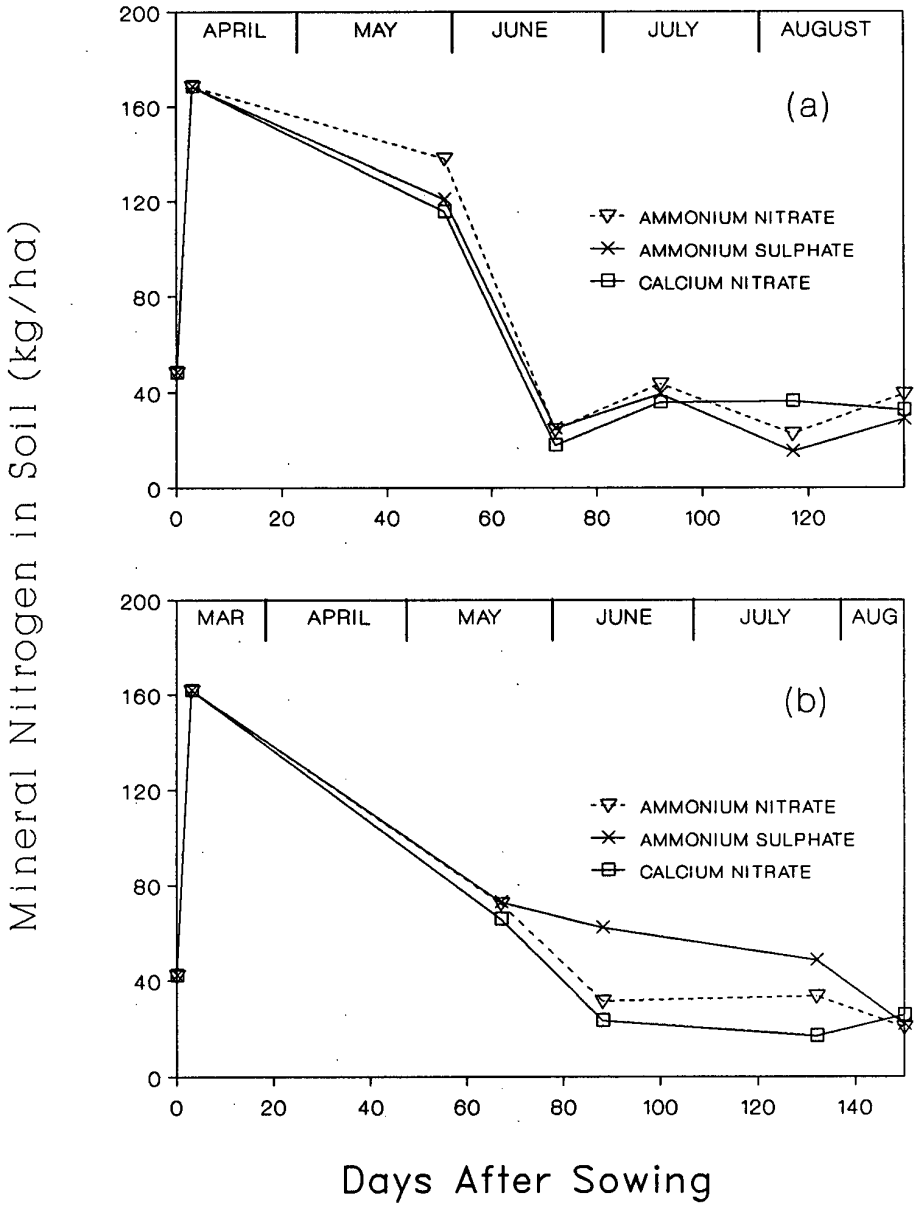


Figure 25. Changes in mineral nitrogen in the soil (0-40 cm) over the growing season, under spring barley, with 120 kg/ha fertiliser nitrogen applied at sowing (a) Bush 1988 and (b) Middlestot 1988

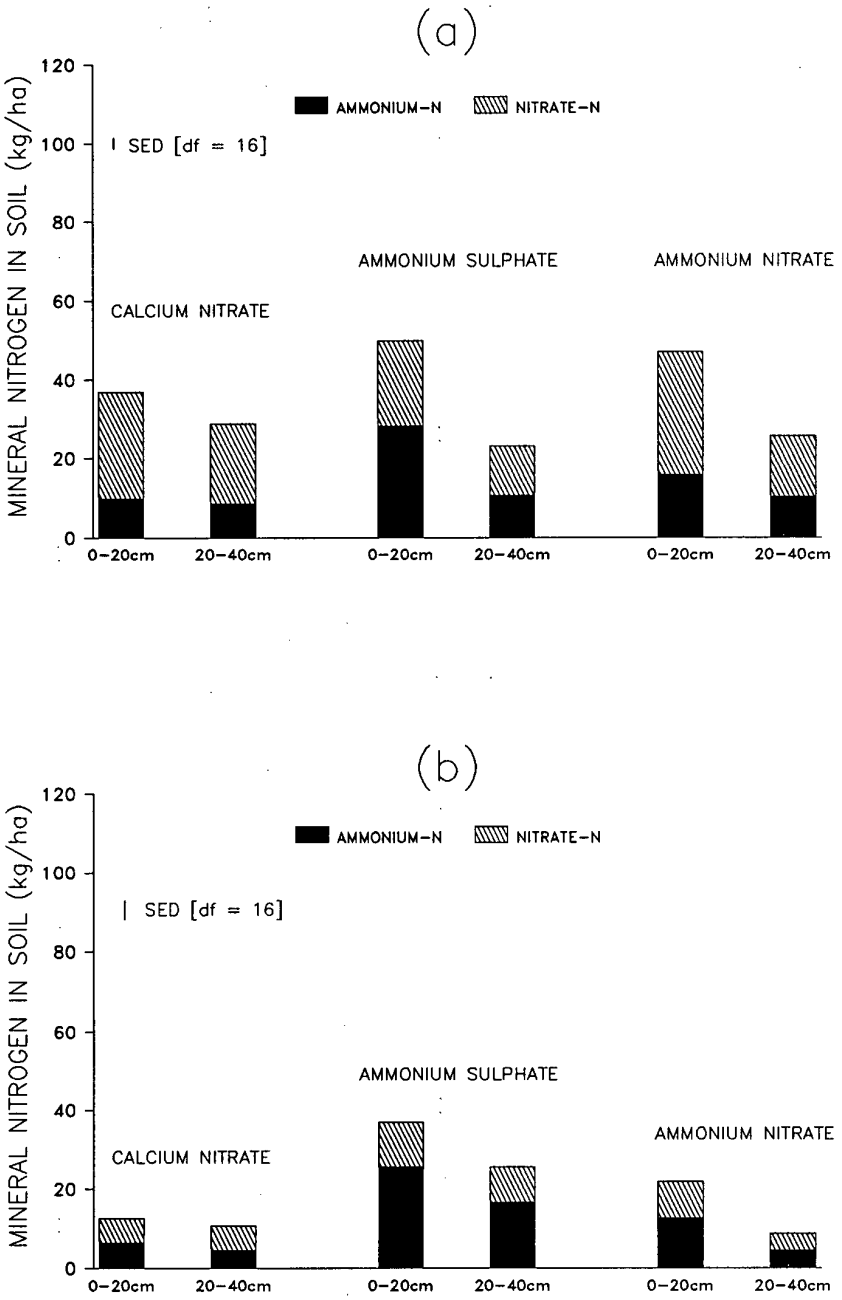


Figure 26. Quantities of nitrate- and ammonium-N at different depths in the soil at first two sampling dates, under spring barley fertilised with 120 kg/ha N fertiliser at sowing, (a) after 67 days (b) after 88 days, Middlestot 1988

soil was restricting uptake. The lower soil moisture content at Middlestot (Table 11) meant that the reduced mobility of the NH_4-N was a more significant factor than at Bush. However, by harvest there was no significant difference in the residual nitrogen in the soil between the different fertiliser forms, due to the late uptake of labelled nitrogen in the ammonium sulphate treatment.

5.1.5: Bush 1989

Here, there was no significant decrease in mineral nitrogen in the calcium nitrate and ammonium sulphate treatments all applied at sowing over the first 45 days (Figure 27a). There was, however, a drop of 38 kg N/ha after 120 kg N/ha ammonium sulphate had been applied at sowing. This loss was significantly greater than the plant uptake over the same period indicating that some immobilisation of NH_4-N may have occurred. Over the next 21 days there was a rapid decline in mineral nitrogen in all treatments which coincided with increased plant uptake during stem elongation (Section 3.1). However, the rate of uptake could not account for the disappearance of all of the mineral nitrogen in the soil in any of the treatments. Therefore it appeared that there were some losses, which were more likely to be as a result of immobilisation by soil micro-organisms rather than leaching, due to the rapidly drying soil conditions (Table 12) and the imperfectly draining soil texture (Table 1). In both the ammonium sulphate and ammonium nitrate treatments there was significantly less movement of mineral nitrogen down the soil profile over the first 45 days growth compared with the calcium nitrate treatment, and this was still apparent after 66 days (Figure 28). At this time, after 66 days, there were still over 43 kg/ha of mineral nitrogen in the soil in all treatments. This could explain the continued uptake of labelled nitrogen late in the growing season as described on Section 3.1.

5.1.6: Upper Cairnie 1989

At this site, there was a steady decline in soil mineral nitrogen from sowing until shortly before harvest in all treatments, which did not appear to be influenced by increased rates of plant uptake after 48 days growth (Figure 27b). There were greater losses of mineral nitrogen in the ammonium sulphate treatments over the first 48 days compared with the calcium nitrate and ammonium nitrate treatments; up to 20 kg N/ha greater in the 120 kg N/ha treatments. This difference could not be accounted for by plant uptake and

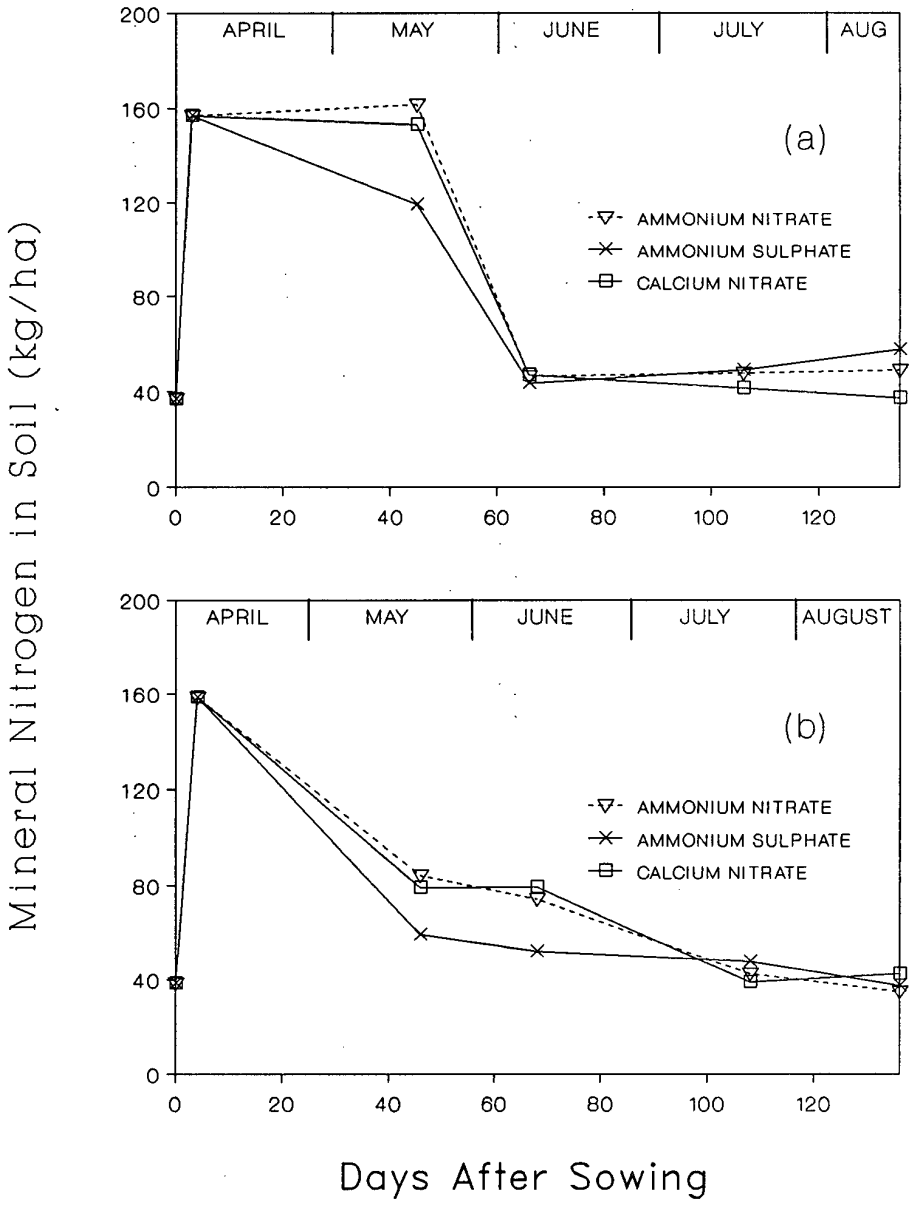


Figure 27. Changes in mineral nitrogen in the soil (0-40 cm) over the growing season, under spring barley, with 120 kg/ha fertiliser nitrogen applied at sowing (a) Bush 1989 and (b) Upper Cairnie 1989

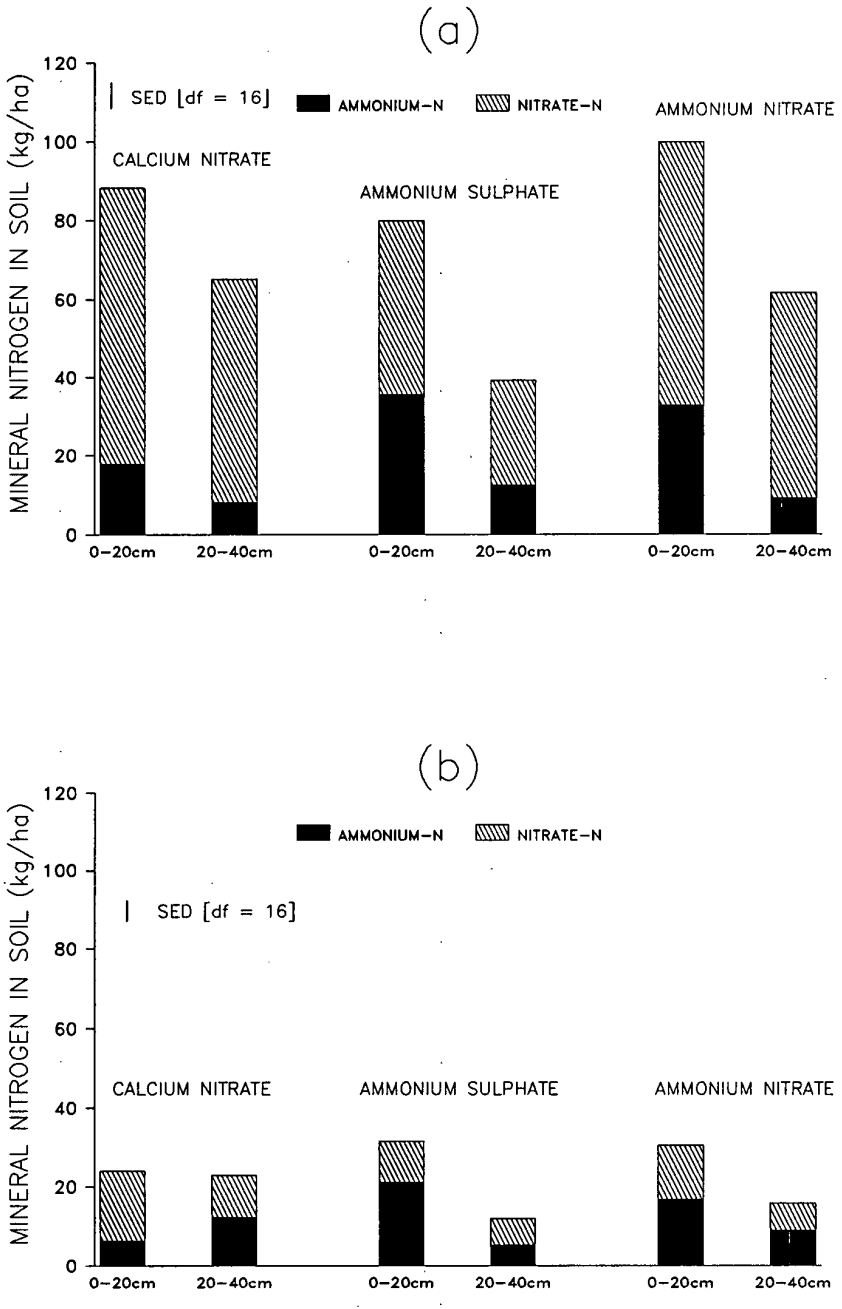


Figure 28. Quantities of nitrate- and ammonium-N at different depths in the soil at first two sampling dates, under spring barley fertilised with 120 kg/ha N fertiliser at sowing, (a) after 45 days (b) after 66 days, Bush 1989

Table 11: Soil moisture content over the growing season at two sites, 1988

Bush			Middlestot		
Date	0-20 (cm)	20-40 (cm)	Date	0-20 (cm)	20-40 (cm)
5/4	21.6	25.3	11/3	15.8	19.8
25/5	22.7	23.7	17/5	15.6	15.9
11/6	13.8	15.8	7/6	15.1	16.0
19/6	22.9	15.6	21/7	16.8	15.8
4/7	24.9	24.6	9/8	21.5	20.9
20/8	24.6	25.4			
SED 0.95 [df=5]			SED 1.07 [df=4]		

Table 12: Soil moisture content over the growing season at two sites, 1989

Bush			Upper Cairnie		
Date	0-20 (cm)	20-40 (cm)	Date	0-20 (cm)	20-40 (cm)
13/4	26.6	27.9	14/4	22.7	24.6
4/5	22.5	24.8	5/5	18.5	21.4
31/5	15.4	16.3	30/5	15.4	16.8
13/7	11.0	11.7	12/7	7.1	8.4
16/8	9.8	9.9	22/8	8.3	9.0
SED 1.1 [df=4]			SED 0.85 [df=4]		

therefore possibly indicated greater immobilisation of NH_4-N by soil microbes. At this time there were only 28 kg/ha NH_4-N remaining in the soil out of 120 kg N/ha ammonium sulphate applied at sowing with 31 kg/ha present as NO_3-N. Total labelled and unlabelled nitrogen uptake in the plant at this time was only 13 kg/ha, so therefore there was a disappearance of approximately 45 kg N/ha from the soil mineral nitrogen pool. In the calcium nitrate and ammonium nitrate treatments the unaccounted mineral nitrogen was less with more mineral nitrogen retained in the soil. The amount of mineral nitrogen in the soil remained high with 80 kg/ha present, even after 68 days growth, in the calcium

nitrate and ammonium nitrate treatments. It appeared that the rapidly drying soil conditions (Table 12) and heavier soil texture at Upper Cairnie (Table 1) reduced the possibility of leaching, and also reduced the movement of soil nutrients towards plant roots. This could explain the steady uptake of labelled nitrogen with calcium nitrate up to harvest.

5.2: 1990 season

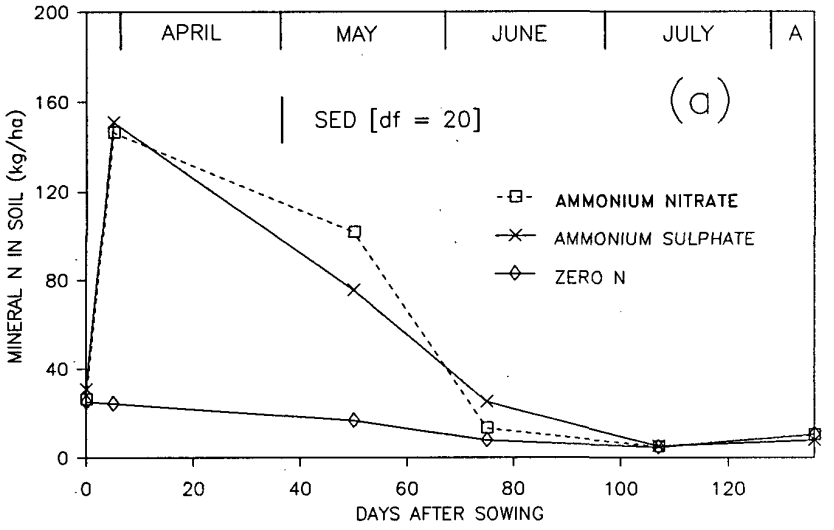
The quantities of mineral nitrogen in the soil at the six sites studied in 1990 are discussed.

5.2.1: Manorhill 1990

Here, the quantity of mineral nitrogen in the ammonium sulphate treatment fell steadily over the first 50 days growth, from 151 kg N/ha to 75 kg N/ha (Figure 29a). In contrast the decline in the ammonium nitrate treatment was smaller, falling to 102 kg N/ha after 50 days. This was despite a similar rate of uptake in the plant (Section 3.2) suggesting that there may have been greater immobilisation of NH_4-N in the ammonium sulphate treatment. Over the following 25 days the quantity of mineral nitrogen in the soil fell to 25 kg N/ha in the ammonium sulphate treatment and 13 kg N/ha in the ammonium nitrate treatment. The greater quantity of mineral nitrogen in the ammonium sulphate treatment appeared to be due to a greater amount of NH_4-N retained in the soil (Figure 30) during a period of increased plant uptake. This could have been the result of reduced NH_4-N mobility in the dry soil conditions (Table 13).

5.2.2: Quixwood 1990

At this site, there was a significant rate of net mineralisation in the zero fertiliser treatment over the first 44 days as illustrated by the increase in mineral nitrogen. Over this initial growth period uptake of labelled nitrogen in the fertilised plots was low, but despite this there was a large decline in soil mineral nitrogen in the fertilised plots. This decline, therefore, appeared to be due to the immobilisation of labelled fertiliser nitrogen. These two factors, and the high soil organic matter levels (Table 8), indicated significant mineralisation/immobilisation turnover of nitrogen in the soil. Also, the form in which the mineral nitrogen was present in the soil after 44 days (Figure 30) showed that the mineralised nitrogen in the zero plots was nitrified very rapidly. At this time there were only 33 kg/ha and 21 kg/ha of NH_4-N in the mineral



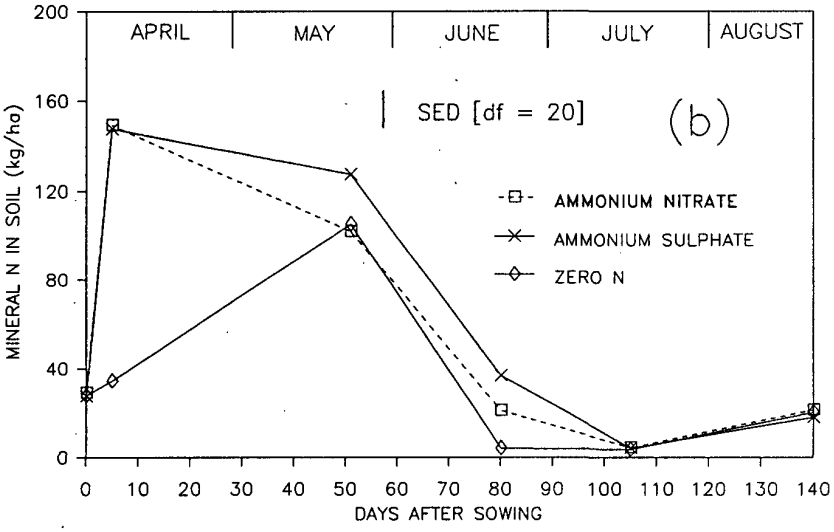


Figure 29. Changes in mineral nitrogen in the soil (0-30 cm) over the growing season, under spring barley, with 120 kg/ha fertiliser nitrogen applied at sowing (a) Manorhill 1990 (b) Bush (Fm.Holding) 1990

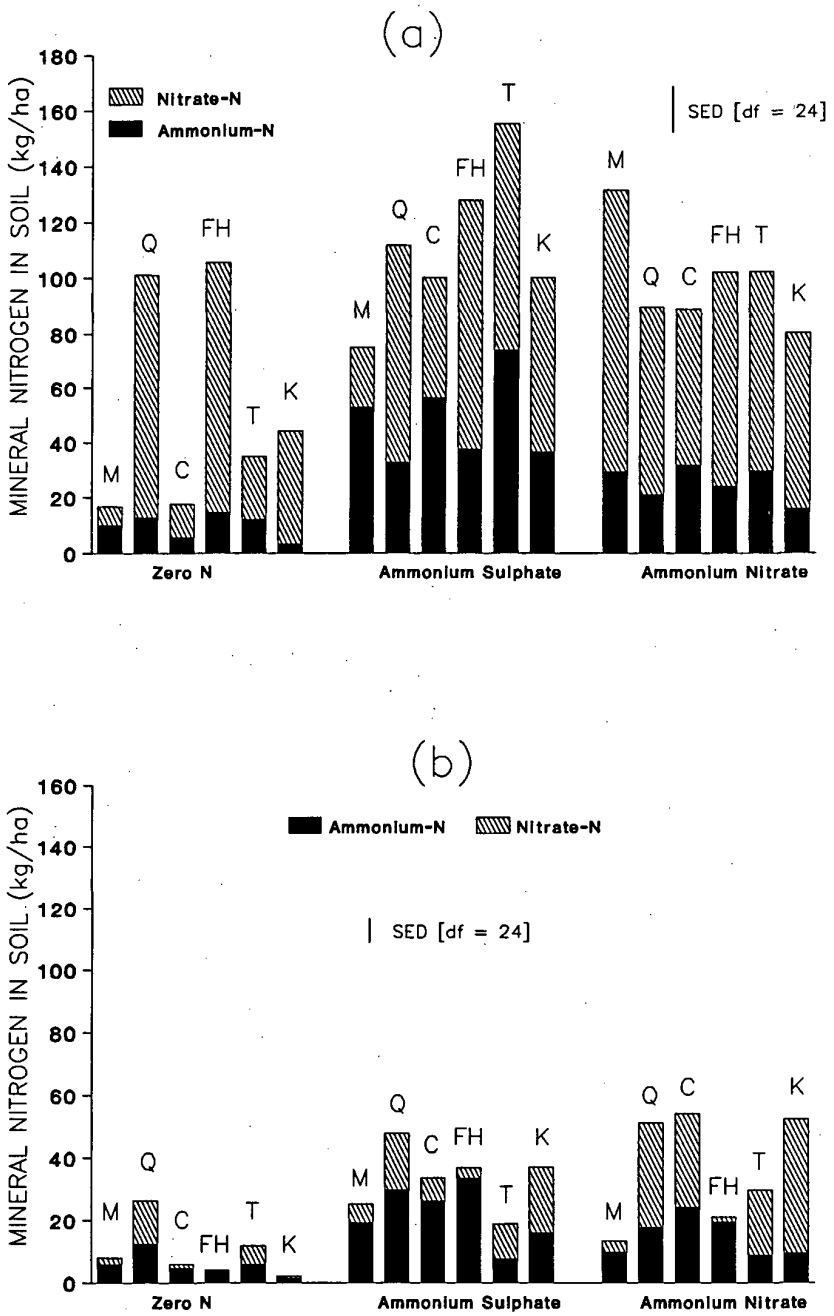


Figure 30. Quantities of nitrate- and ammonium-N in the soil at six sites in 1990 at first two sampling dates, under spring barley either unfertilised or given 120 kg N/ha at sowing, (a) 1st sampling and (b) 2nd sampling M- Manorhill; Q- Quixwood; C- Bush (Crofts) FH- Bush (Fm.Holding); T- Treaton; K- Kettle

nitrogen pools of the ammonium sulphate and ammonium nitrate treatments respectively. Taking into account the low uptake of labelled nitrogen in the plant, and significant uptake of unlabelled nitrogen, it was probable that there was significant pool substitution occurring. This would have been made possible by the high rate of mineralisation/immobilisation turnover in the soil and the moist soil conditions (Table 13) allowing a better mixing together of the labelled fertiliser and native unlabelled soil nitrogen pools. The continued uptake of unlabelled nitrogen until harvest without any depletion of soil mineral nitrogen levels late in the growing season indicated that net mineralisation continued up to harvest.

5.2.3: Bush (Crofts) 1990

Here, there was no significant difference between the two fertiliser treatments in the decline of soil mineral nitrogen over the first 54 days. At this time there were 56 kg/ha NH_4-N present in the ammonium sulphate treatment (Figure 30a). Over the following 28 days total mineral nitrogen in the ammonium sulphate treatment fell from 100 kg N/ha to 34 kg N/ha, all of which could not be accounted for by plant uptake whether labelled or unlabelled. It appeared likely that some of the NH_4-N had been immobilised rather than being nitrified and then leached down the soil profile, especially as there was still a significant quantity of NO_3-N present in the ammonium nitrate treatment (Figure 30b). The late plant uptake of both labelled and unlabelled nitrogen in the ammonium sulphate treatment without any significant depletion of soil mineral nitrogen over the same period suggested that mineralisation continued up to harvest and included the re-mineralisation of previously immobilised $^{15}NH_4$-N.

5.2.4: Bush (Farmers' Holding) 1990

At this site, there was a large increase in soil mineral nitrogen in the zero nitrogen plot over the first 51 days (Figure 29b). Over the same period there was no significant decline of mineral nitrogen in the ammonium sulphate treatment, but there was a drop of 47 kg N/ha in the ammonium nitrate treatment. Plant uptake of labelled nitrogen was greater in the ammonium nitrate treatment (Section 3.2) which could explain the greater decline of soil mineral nitrogen in that treatment. However, the large accumulation of mineral nitrogen in the zero plot, and the significant uptake of unlabelled nitrogen in the plant suggested that there was considerable microbial activity which could have affected the composition of the mineral nitrogen in the soil. By this time,

Table 13: Soil moisture content over the growing season at six sites, 1990.

Manorhill	Date	25/3	14/5	8/6	10/7	8/8	SED
	Moisture (%)	18.8	17.0	13.6	17.0	9.8	(0.7)
Quixwood	Date	31/3	14/5	12/6	12/7	29/8	SED
	Moisture (%)	27.4	26.2	26.7	25.2	21.5	(0.9)
Bush (Crofts)	Date	30/3	23/5	21/6	16/7	27/8	SED
	Moisture (%)	24.7	21.6	17.9	24.5	19.5	(0.7)
Bush (Fm.Holding)	Date	2/4	23/5	21/6	16/7	20/8	SED
	Moisture (%)	24.3	26.2	17.0	23.3	24.5	(0.7)
Treaton	Date	28/3	17/5	19/6	17/7	22/8	SED
	Moisture (%)	27.4	25.8	21.5	23.6	26.0	(0.5)
Kettle	Date	25/4	4/6	25/6	19/7	31/8	SED
	Moisture (%)	18.2	15.2	17.5	11.7	13.4	(1.2)

(%) Moisture by weight (g/100g d.wt.)

51 days after sowing, there were only 38 kg/ha NH_4-N remaining in the soil in the ammonium sulphate treatment with the other 90 kg/ha as NO_3-N (Figure 30a). Over the following 29 days growth there was a large fall in soil mineral nitrogen in all treatments which appeared to be mainly derived from the NO_3-N present with no significant change in the amount of NH_4-N (Figure 30b). These losses were significantly greater than plant uptake of both labelled and unlabelled nitrogen. The late uptake of labelled nitrogen in the ammonium sulphate treatment appeared to be due to the higher levels of NH_4-N retained in the soil after 80 days growth. The loss of the NO_3-N could have been due to leaching down the profile or immobilisation. Over the period between 51 days and 80 days growth the soil was drying out rapidly (Table 12), and also given the soil texture which was imperfectly draining (Table 8) it seemed unlikely that

there would be significant solute movement down the soil profile. Recous et al (1988b) found that immobilisation in winter wheat increased up to the time of anthesis. Given the high microbial activity demonstrated by the rapid mineralisation in the zero plots, it is possible that NO_3-N was rapidly immobilised during this period and that the NH_4-N avoided this due to its reduced mobility in the drier soil conditions.

5.2.5: Treaton 1990

Here, over the first 50 days growth there was a fall in the mineral nitrogen content in the ammonium nitrate treatment of 50 kg N/ha, whereas in the ammonium sulphate treatment there was no significant change. At this time there were 74 kg/ha and 30 kg/ha NH_4-N remaining in the ammonium sulphate and ammonium nitrate treatments respectively (Figure 30a). Therefore, taking into account the low plant uptake of labelled nitrogen approximately 50% of the applied NH_4-N had either been nitrified or immobilised. There were 81 kg/ha and 73 kg/ha NO_3-N in the soil in the respective treatments. Over the next 33 days the amount of mineral nitrogen in the soil fell to 18 kg N/ha and 30 kg N/ha in the ammonium sulphate and ammonium nitrate treatments respectively. Similarly to Farmers Holding, the increased rate of plant uptake could not fully account for the decline in mineral nitrogen levels. Unlike Farmers Holding, however, the soil remained quite moist throughout this period (Table 13) and the soil was light in texture and freely draining (Table 8). Therefore it was likely that there was some movement of nitrogen down the soil profile. This may explain the greater decline in the ammonium nitrate treatment over the first 50 days, despite the similar rate of plant uptake.

Even though a significant proportion of the NH_4-N in the ammonium sulphate treatment had been nitrified, there would have been a sufficient delay for most of this nitrogen still to be in the upper soil profile. The high levels of organic matter in the soil (Table 8) indicated that there was likely to be a significant rate of mineralisation/immobilisation turnover. Taking into account the late uptake of labelled nitrogen despite minimal levels of mineral nitrogen after 110 days growth, it appeared likely that there was significant immobilisation of labelled nitrogen between 50 and 83 days growth, some of which was re-mineralised later in the growing season. The greater decline of mineral nitrogen between 50 and 83 days in the ammonium sulphate treatment could possibly be attributed to the greater availability of NH_4-N at that time,

both in terms of quantity and accessibility in the more moist soil compared with Farmers Holding.

5.2.6: Kettle 1990

Here, over the first 40 days there was a decline of approximately 50 kg N/ha in both fertiliser treatments. Over this period there was less than 10 kg/ha total nitrogen uptake in the plant (Section 3.2). The zero nitrogen treatment showed a rise of 20 kg N/ha over the same period indicating some net mineralisation. This nitrogen was virtually all present as NO_3-N (Figure 30a). Also, in the fertilised treatments most of the mineral nitrogen was in the NO_3-N form at this time. Therefore it appeared that most of the nitrogen lost from the soil mineral nitrogen pool up to this time had been as NH_4-N. Over the next 21 days there was a very large uptake of nitrogen in the plant tissues which was partly due to the late sowing of the crop resulting in more rapid growth in the warmer conditions. The decline in soil mineral nitrogen indicated that there was very considerable net mineralisation. Despite a decline of only 40 kg N/ha in the zero nitrogen treatment, uptake in the plant over the same period was 86 kg N/ha. Similar amounts of unlabelled nitrogen were taken up in the fertilised treatments. It appeared that the rate of mineralisation was great enough to prevent mineral nitrogen levels in the fertilised plots falling below 40 kg/ha. At this time there was very little NH_4-N present in the soil (Figure 30b). Therefore, it appeared that the mineralised nitrogen was rapidly nitrified before being taken up in the plant. This again indicated the high rates of microbial activity in the soil. The late uptake of labelled and unlabelled nitrogen indicated continued mineralisation up to harvest, some of which appeared to be the re-mineralisation of previously immobilised labelled fertiliser nitrogen.

5.3: Discussion

During the early stages of growth there were differences between sites with regard to soil mineral nitrogen levels. At most of the sites there was little change in mineral nitrogen levels over the first 50-60 days growth. However, at Middlestot and Upper Cairnie there were significant declines in soil mineral nitrogen over this period. At these two sites soil moisture contents were falling rapidly.

Neeteson et al (1986), working on potatoes, suggested that rapid immobilisation of fertiliser nitrogen shortly after application was due to the uptake of nitrogen ions by micro-organisms, but that this uptake was into the vacuoles for the purpose of osmoregulation when under moisture stress, rather than being incorporated into the biomass structure itself. In their trials there was no moisture stress as the soils were near to field capacity, but they concluded that upon the dissolution of fertiliser granules the soil solution in the immediate vicinity would have high osmotic concentrations. It was also shown that most of this immobilised nitrogen reappeared over the next 5 weeks as the micro-organisms decomposed. By this time there would not have been such localised, highly concentrated solute pools and therefore no great further demand for nitrogen ions to act as an osmoticum. Similar results were reported under spring barley (Nielsen and Jensen, 1986) where up to 80% of applied ammonium nitrate could not be detected in the soil nor in plant tissue within 12 days of application, but over the next 50 days growth at least 20-30% of this nitrogen reappeared.

Under the dry soil conditions encountered at Middlestot and Upper Cairnie there would have been significant moisture stress after 50-60 days growth and therefore the reduced mineral nitrogen at these sites could be attributed to a greater accumulation of nitrogen in the micro-organisms.

There was a similar decrease in mineral nitrogen at Quixwood under more moist conditions. However, taking into account the high soil organic matter content and large net mineralisation in the zero nitrogen treatment, it is probable that there was significant mineralisation/immobilisation turnover which resulted in net immobilisation upon the addition of large quantities of mineral nitrogen.

At most sites there then followed a period of rapid decline which coincided with rapid plant uptake. However, at several of the sites plant uptake could not account for all of the mineral nitrogen decline. Recous et al (1988b) reported increased rates of immobilisation up to anthesis in winter wheat. It was suggested that this increase was correlated to available carbon, which would have been exuded from plant roots into the rhizosphere during plant development. Wheatley et al (1990) showed that after a 10 week pot experiment growing unfertilised barley plants, that increased carbon in the rhizosphere

exuded from developing plant roots resulted in a doubling of the accumulated nitrogen in the microbial biomass.

This may have contributed to the rapid decline in mineral nitrogen that was recorded. There may also have been some leaching down the soil profile, and while there was some evidence of increasing mineral nitrogen in the 20-40 cm soil layer, the rapid decline in mineral nitrogen was occurring at a time of decreasing soil moisture contents and therefore leaching losses at this time were probably quite small.

There was no such rapid decline in the ammonium sulphate treatment at Middlestot, nor in any of the fertiliser treatments at Upper Cairnie. It appeared that the reduced mobility of the NH_4-N at Middlestot resulted in greater retention in the soil. At Upper Cairnie the soil was drying out more rapidly and this appeared to greatly reduce the mobility of NO_3-N also. Bergstrom (1986) reported that under moist conditions the uptake of calcium nitrate fertiliser by spring barley was rapid, after a stable period of one month after sowing during early crop development. It was also noted that there was reduced uptake and greater retention of mineral nitrogen in the soil under drier soil conditions in the spring.

At all sites, other than Middlestot and Upper Cairnie, the quantity of mineral nitrogen in the soil levelled off at values equal to or lower than pre-fertilisation levels from around 80-100 days after sowing. This tended to coincide with the peak uptake of labelled nitrogen in the crop. Mineral nitrogen values in the soil remained constant from then until harvest despite the continued uptake of unlabelled nitrogen in the crop. This indicated that there was net mineralisation continuing up to harvest, and that this therefore could be an important factor in determining the total nitrogen uptake in the crop.

6: The Prediction of Potentially Available Soil Nitrogen Using Two Simple Chemical Extraction Techniques

6.1: Introduction

The ability to predict the likely quantity of mineral nitrogen which will be mineralised from the soil organic matter and be available for plant uptake is of great importance in agriculture. With such information there can be better management of fertiliser N applications with resulting benefits in terms of economics, the environment and product quality of crops such as malting barley.

Many biological and chemical predictive methods have been proposed, of which there have been extensive reviews (Bremner, 1965; Keeney, 1982b; Stanford, 1982). Good correlations have generally been found with the use of biological incubation methods when compared to plant uptake in pot experiments, but less satisfactory correlations have been found with field data (Keeney, 1982a). However, because of the complexity and time-consuming nature of biological incubations it is recognised that a simple chemical soil test would be the preferred option for regular laboratory use.

Recently chemical methods have been developed using KCl as a hydrolysing agent to estimate the likely release of soil nitrogen from a range of soils (Oien and Selmer-Olsen, 1980; Whitehead, 1981; Gianello and Bremner, 1986a). The accuracy of these methods has been tested against results from biological incubation tests (Selmer-Olsen et al, 1981; Gianello and Bremner, 1986b), or with the uptake of nitrogen in pot experiments with oat plants (Oien and Selmer-Olsen, 1980), or with rye-grass (Whitehead, 1981).

The aims of this experiment were to compare the results obtained with two variants of the KCl hydrolysis method, and other soil factors such as organic matter content and mineral nitrogen content in the profile at sowing, with the uptake of soil N in spring barley as determined with the use of ^{15}N fertiliser.

6.2: Results and discussion

Tables 1 and 2 (Methods Section 1.1:) give details of the physical and chemical properties of the soils used in this investigation, from 10 sites in Eastern Scotland.

6.2.1: Chemical extraction methods

The measured potentially available soil organic nitrogen, as determined by the two KCl extraction methods, is shown in Table 14. The more concentrated extracting solution and longer boiling of the Gianello method released nearly double the amount of nitrogen compared to the Whitehead method. Also shown is the % organic matter in each soil, as this has also been recommended as a measure of potentially available soil nitrogen (Keeney, 1982b).

The results in Table 15 show the mean values for each site of the amount of soil nitrogen uptake in the above-ground tissues of the whole plant, and also in the grain only. The mean % N in the grain at a fertiliser rate of 120 kg N/ha is also shown. The uptake of soil nitrogen from the Upper Cairnie and Kettle soils was higher than expected, based on the predictions of the KCl extraction methods. These two soils differed from the others in terms of cropping history (Tables 1 and 2). This classified them as N-Index 1 soils (Scottish Agricultural Colleges, 1985), which should have a larger pool of potentially mineralisable organic nitrogen derived from the previous year's crop residues than the remainder which were classified as N-index 0. However, neither the results of the KCl extraction methods nor the measure of soil organic matter appeared to account for this enhanced nitrogen uptake. Therefore the relationships between these Quantities and the measured soil nitrogen uptake were calculated excluding the two Index 1 soils, and are shown in Figures 31-35. The correlation coefficients are presented in Table 16.

Figures 31 and 32 show the relationship between the soil nitrogen uptake in above-ground plant tissue and nitrogen extracted by the Gianello and Whitehead methods, respectively. The Gianello method showed a significant correlation, and proved to be the more accurate in its predictions. Similar results were obtained by Gianello and Bremner (1986b) who found that the best correlations between chemical methods and biological incubations were

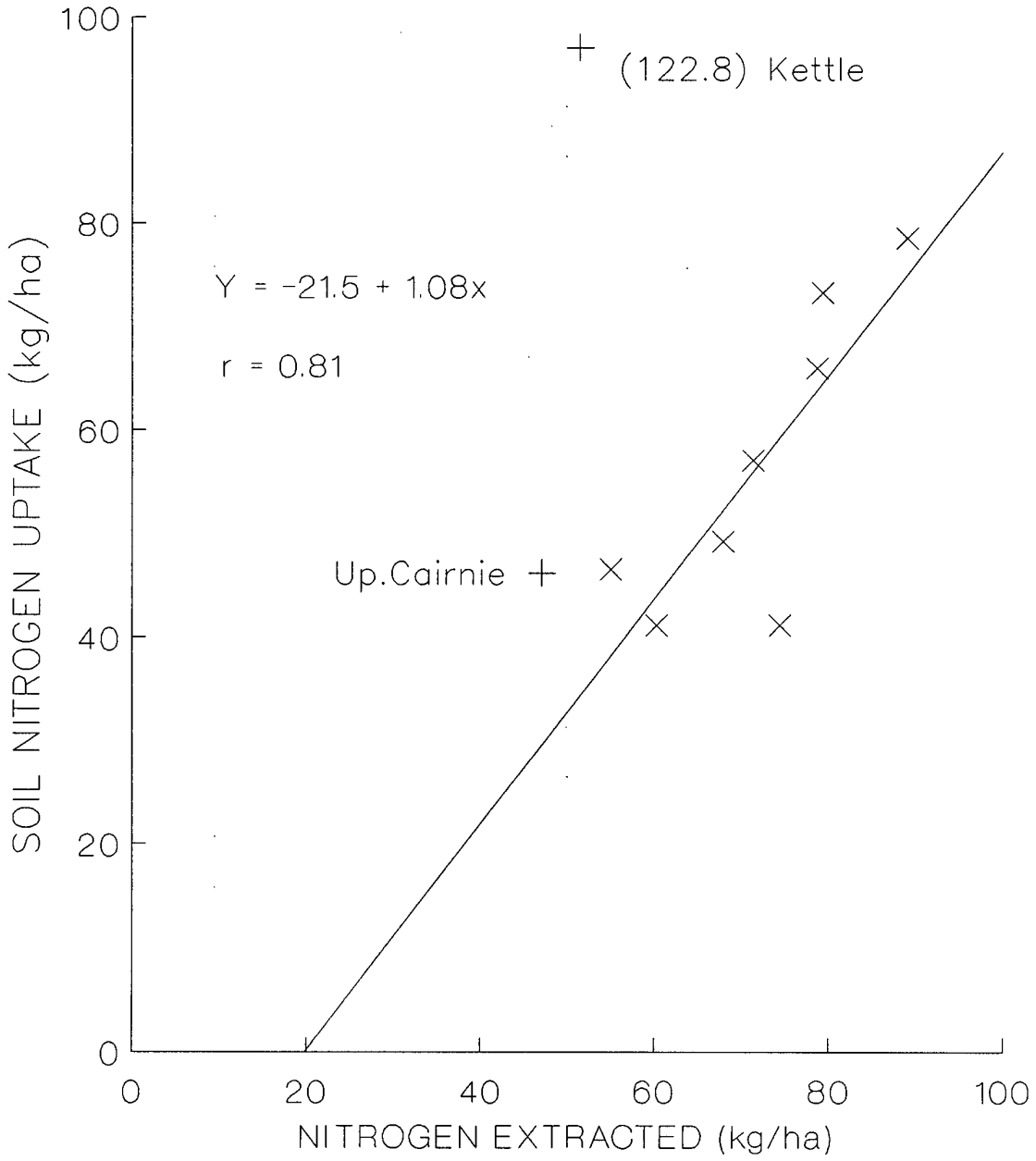


Figure 31. Relationship between nitrogen extracted by the Gianello and Bremner method and soil nitrogen uptake in above ground plant tissue. (Relationship excludes data from Upper Cairnie and Kettle).

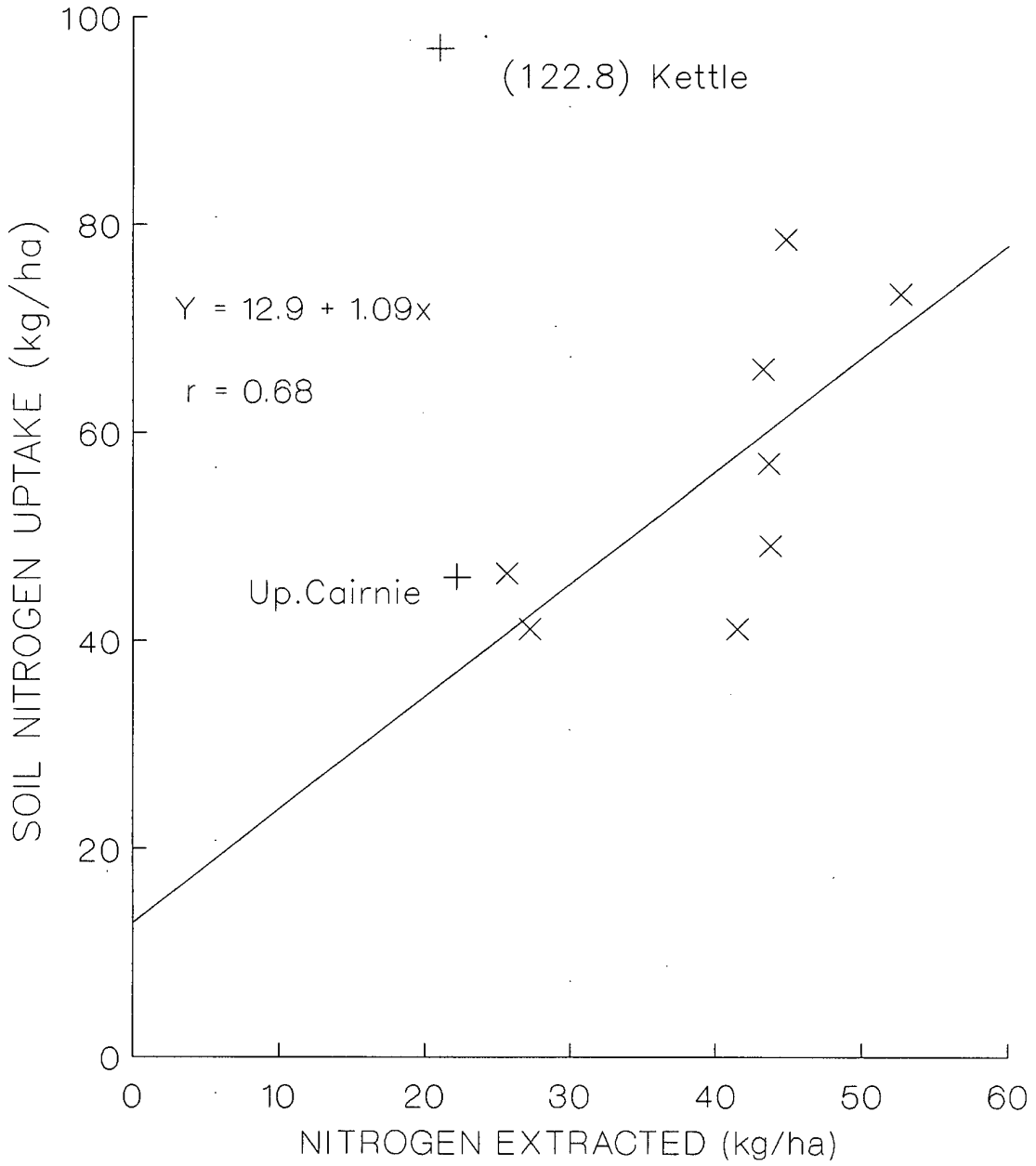


Figure 32. Relationship between nitrogen extracted by the Whitehead method and soil nitrogen uptake in above ground plant tissue. (Relationship excludes data from Upper Cairnie and Kettle).

Table 14: Estimated potentially available nitrogen released by the two chemical extraction methods and measure of soil organic matter content.

Site	Gianello & Bremner (kg/ha)	Whitehead (kg/ha)	Organic Matter[a] (%)
Bush	78.7	43.2	3.7
Middlestot	60.3	27.2	2.3
Bush	71.4	43.6	3.4
Up.Cairnie	47.1	22.2	1.8
Manorhill	55.1	25.6	2.4
Quixwood	89.0	44.8	5.1
Bush (Crofts)	79.3	52.6	4.7
Bush (Fm.Holding)	67.9	43.7	3.3
Treaton	74.4	41.5	5.7
Kettle	51.5	21.0	2.8

[a] Method of Allison (1965).

Table 15: Soil nitrogen[1] uptake by spring barley at harvest in grain, whole plant (above ground) and % grain N when 120 kg N/ha fertiliser N applied.

Site	Soil N in Grain (kg/ha)	Soil N in Plant (kg/ha)	Grain N (%)
Bush	43.2	66.0	1.66
Middlestot	30.0	41.1	1.28
Bush	48.2	57.0	1.87
Up.Cairnie	43.2	46.1	2.02
Manorhill	35.6	47.2	1.75
Quixwood	57.4	78.5	1.83
Bush (Crofts)	55.6	71.3	1.71
Bush (Fm.Holding)	40.1	49.1	1.43
Treaton	32.2	41.1	1.61
Kettle	82.6	122.8	1.91

[1] difference between total plant N and ^{15}N uptake.

obtained with methods where the extracting solutions were heated for 4 hours or longer. The relationships between the results of the KCl extractions and the amounts of soil nitrogen in the grain are presented in Figures 33 and 34. There was a significant correlation between the soil nitrogen uptake and the predicted availability of soil nitrogen by both methods. The coefficients were slightly

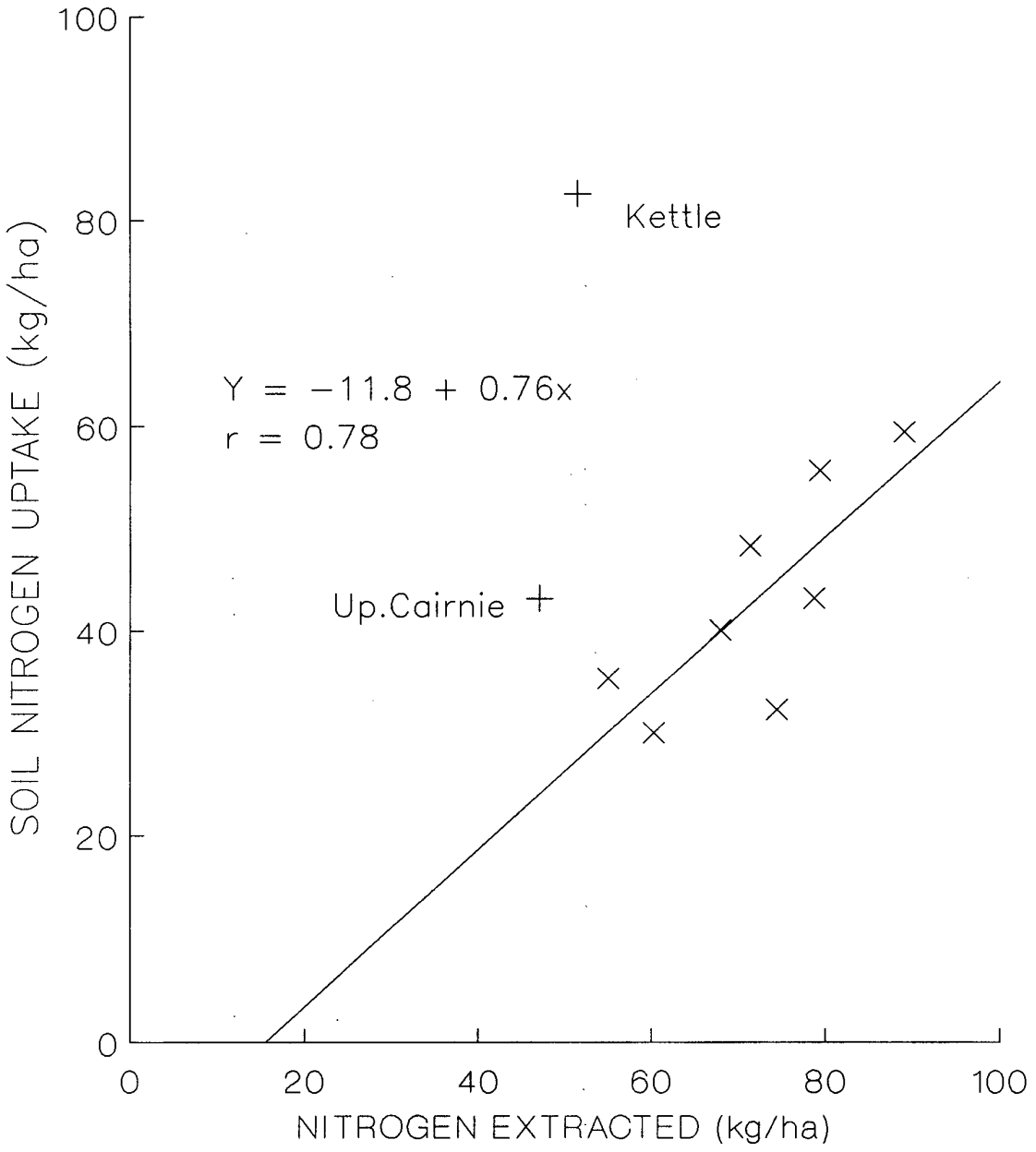


Figure 33. Relationship between nitrogen extracted by the Gianello and Bremner method and soil nitrogen uptake in the grain only. (Relationship excludes data from Upper Cairnie and Kettle).

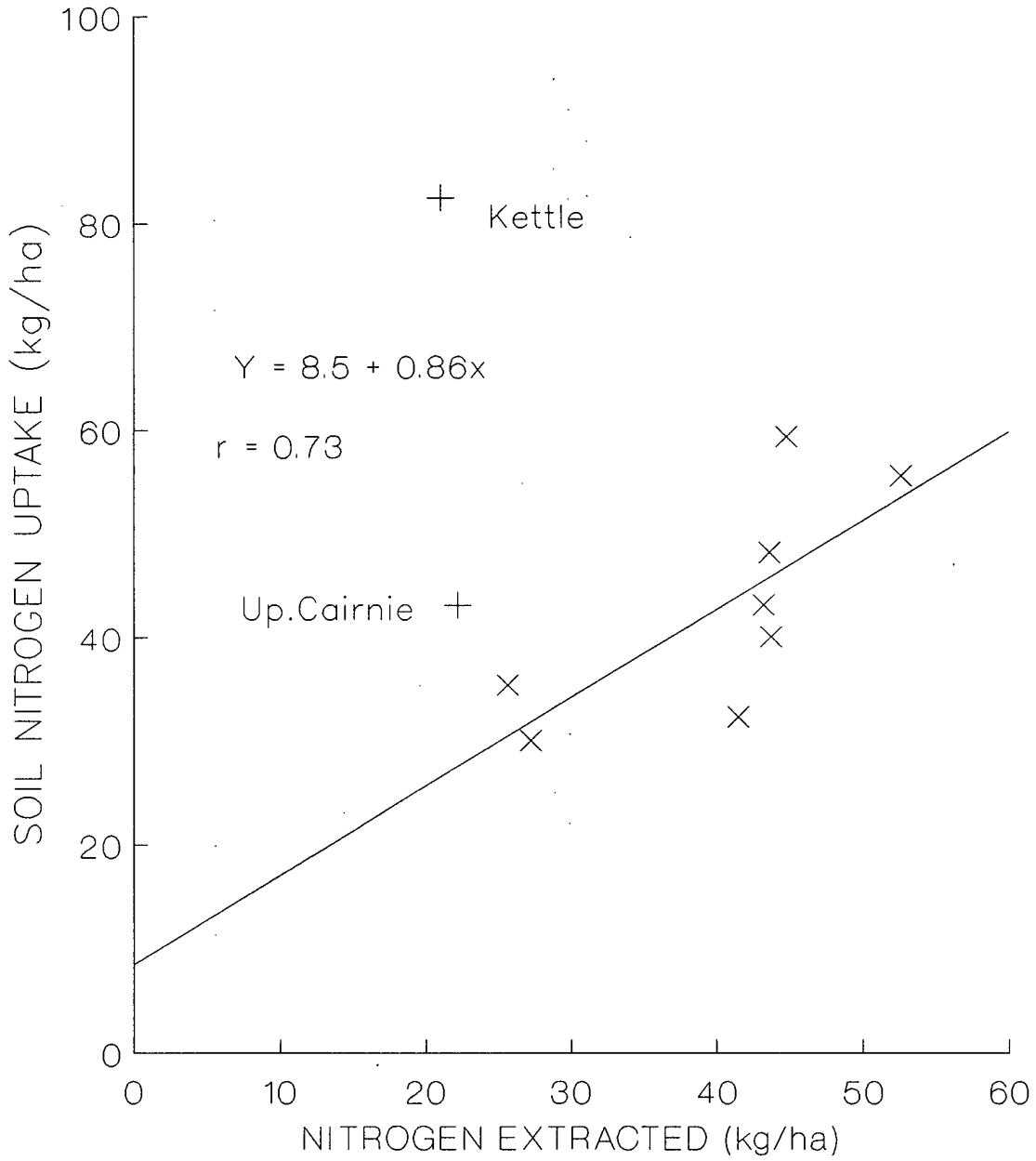


Figure 34. Relationship between nitrogen extracted by the Whitehead method and soil nitrogen uptake in the grain only. (Relationship excludes data from Upper Cairnie and Kettle).

lower than that for the Gianello variant versus N in the above-ground plant tissue, but slightly higher than the corresponding value for the Whitehead procedure.

6.2.2: Soil organic matter as a predictor of potentially available nitrogen

Figure 35 shows the relationship between soil organic matter content and the amount of soil nitrogen in the plant. Two relationships are shown in the graph; one excluding only the two high residue sites at Kettle and Upper Cairnie, and the other also excluding data from the Treaton site which had a high soil organic matter content.

A very good correlation was found when the Treaton site was excluded from the analysis, but when it was included the correlation was much poorer than with the results of the KCl extraction. In contrast, earlier research showed that, generally, soil organic matter was not as good a measure of potentially available nitrogen as some chemical extraction methods (Smith and Stanford, 1971; Gianello and Bremner, 1986b).

The explanation of our results may lie in the fact that mineralised nitrogen is not derived equally from all organic matter fractions, and that in higher organic matter soils these variations may become more important. Paul and Juma (1981) classified soil organic matter into four main pools. They found that the microbial biomass and active non-biomass pools were mineralised much more rapidly than the stabilised and old organic matter pools. Molina et al (1980) concluded that there were at least two rates of mineralisation, depending on the decomposability of the soil organic matter. Marumoto et al (1982b) found that, over a range of soil types, an average of 77% of the mineral nitrogen flush extracted after a cycle of drying and re-wetting the soil was derived from the biomass pool. This reflected the fact that the turnover of the biomass was five times faster than other fractions of soil organic matter (Amato and Ladd, 1980; Marumoto et al, 1982a). However, Paul and Juma (1981) found that during a 12-week incubation of a loam soil the biomass, active non-biomass and stabilised organic matter pools contributed equally to the total nitrogen mineralised. The faster turnovers of the biomass and active non-biomass pools were offset by the fact that they only represented approximately 5% and 8%, respectively, of the total soil nitrogen.

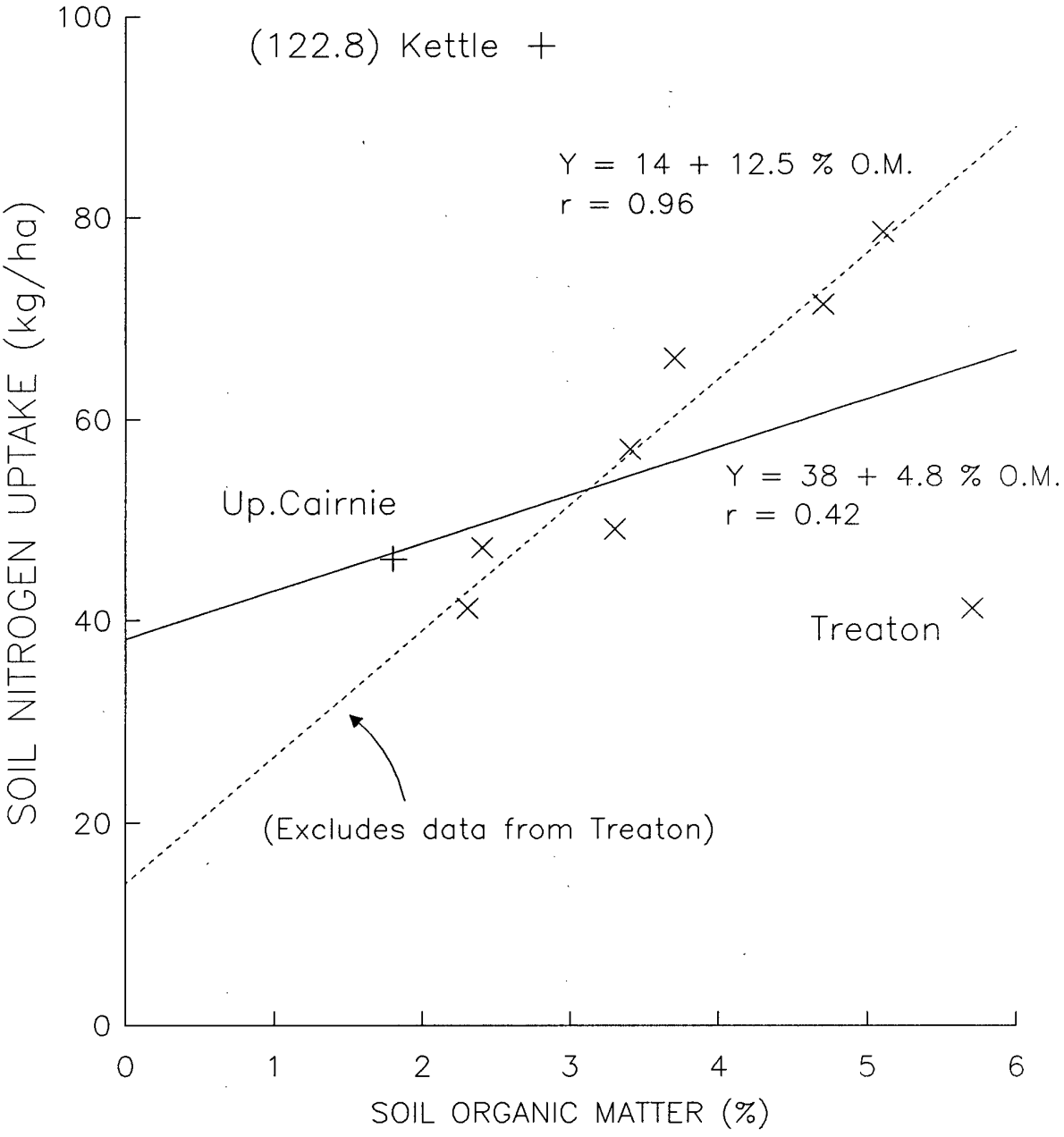


Figure 35. Relationship between soil organic matter and soil nitrogen uptake in above ground plant tissue. (Relationship excludes data from Upper Cairnie and Kettle).

Table 16: Correlation coefficients for relationships between the measurements of soil nitrogen in the plants and estimates of potentially available soil nitrogen.

	Correlation coefficient (r)			
	Measure of N in plants			
Method	Soil N (plant)	Soil N (grain)	(%) Organic Matter	Mineral N
Gianello	0.81*	0.78*	0.80*	0.93***
Whitehead	0.66	0.73*	0.70*	0.66
% Organic Matter	0.42	0.44	--	0.63
% Organic Matter (Treaton excluded)	0.96***	0.96***	--	0.84**
Mineral N	0.85**	0.75*	0.63	--

* r-values significant at the 5.0% level
** r-values significant at the 1.0% level
*** r-values significant at the 0.1% level.

Whereas these pools contribute the bulk of the mineralised nitrogen, a significant quantity can also be derived from the stabilised organic matter pool (Juma and Paul, 1984). This pool is much larger than the more active pools and therefore it may be that contributions of mineralised nitrogen from the stabilised organic matter pool are more accurately reflected by the overall size of the soil organic matter pool. When both the KCl-extracted nitrogen (which reflects the size of the biologically more active pools of the soil organic matter (Jenkinson, 1968)) and total soil organic matter were taken into account, a much better correlation was obtained with soil nitrogen uptake in the plant (Figure 36). By considering both of these factors 81% of the variation in soil nitrogen uptake in the plant was accounted for, and the Treaton site was now no longer an outlier.

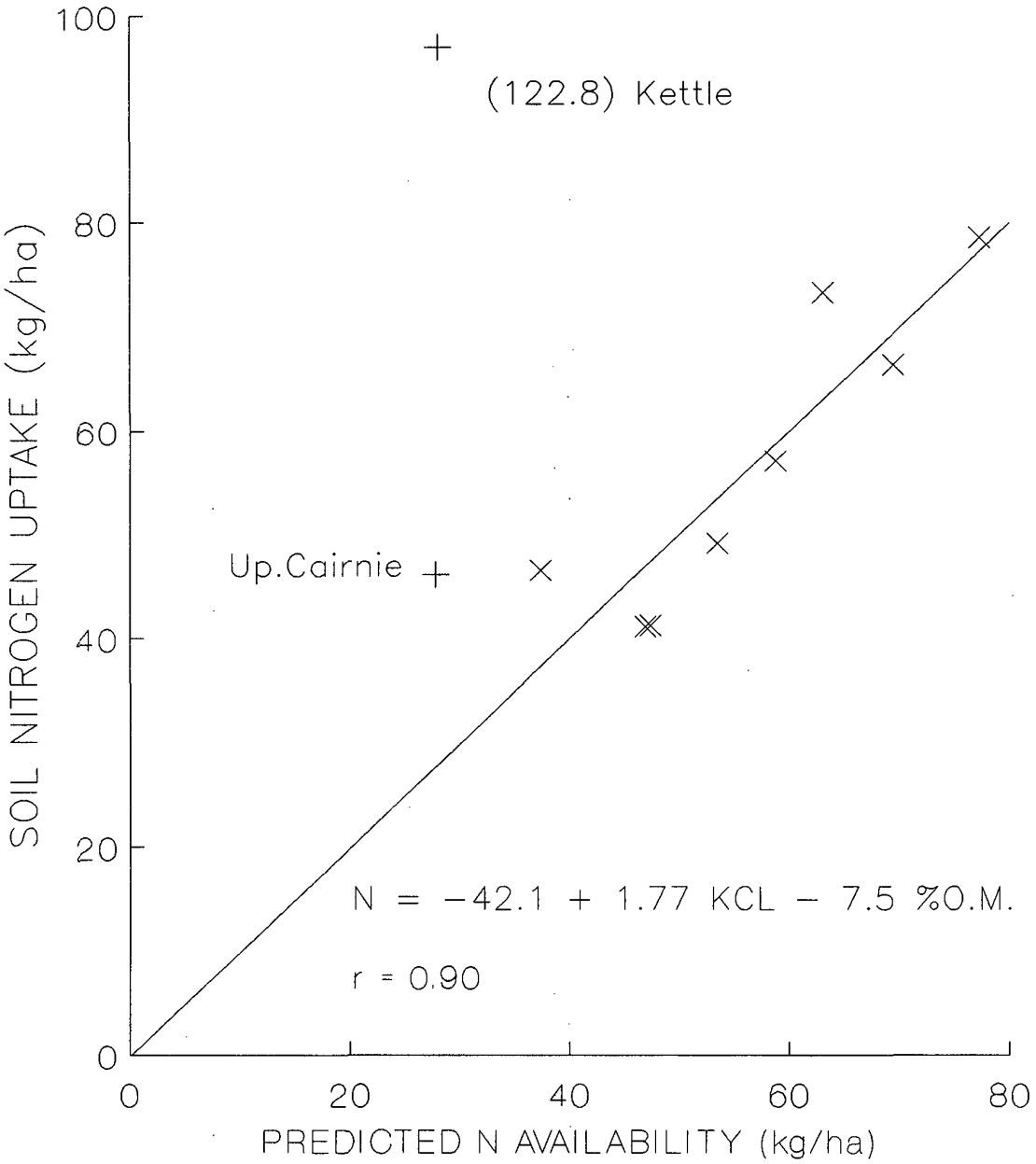


Figure 36. Relationship between prediction of soil nitrogen availability (based on both soil organic matter and nitrogen extracted by the Gianello and Bremner method) and soil nitrogen uptake in above ground plant tissue. (Relationship excludes data from Upper Cairnie and Kettle).

6.2.3: Soil pH and texture

Other soil factors such as pH and texture were also considered, but these did not significantly improve predictive correlations either individually or jointly with any other factors. This may be at least partly due to the fact that the soils studied were confined to relatively narrow ranges of both pH and texture (Tables 1 and 8).

6.2.4: Mineral nitrogen in the soil

In Western Europe, fertiliser recommendations are generally based either wholly or partly on the amount of soil mineral nitrogen present in early spring (Greenwood, 1986). In Scotland, however, with generally shallow soils and cold wet climate, quantities of mineral nitrogen in the spring are low and fertiliser recommendations are based on previous cropping (Scottish Agricultural Colleges, 1985). Figure 37 shows the relationship between soil mineral nitrogen, at the time of sowing in spring, and the soil nitrogen uptake in the plant. A very good correlation was found that was better than those with potentially mineralisable nitrogen, but not as good as that for potentially mineralisable nitrogen and organic matter combined. However, the amount of soil nitrogen taken up in the plants at harvest was more than double the amount of mineral measured in the soil at sowing. This indicated that the mineral nitrogen measured was not actually a direct measure of the amount of soil nitrogen taken up by the plants, but was rather an indicator of the soils capacity to release nitrogen both before and after sowing, and that plant uptake was related to the amount of mineralisation of organic soil nitrogen *before and during* the growing season.

At the time of sowing the soil temperature was about 6-7^{o}C. This was warm enough for the rate of mineralisation to have become significant and to have contributed to the soil mineral nitrogen pool prior to sampling. When compared with the nitrogen extracted by the Gianello method (Figure 38), an extremely high correlation was found, with 87% of the variation in soil mineral nitrogen accounted for. If soil organic matter was also considered 96% of the variation was explained. This strongly supports the suggestion above that the mineral nitrogen at the time of sampling was related to the rate of mineralisation of the soil organic matter. It appears that by the time the soil samples were taken the mineralisation that had already taken place gave a good

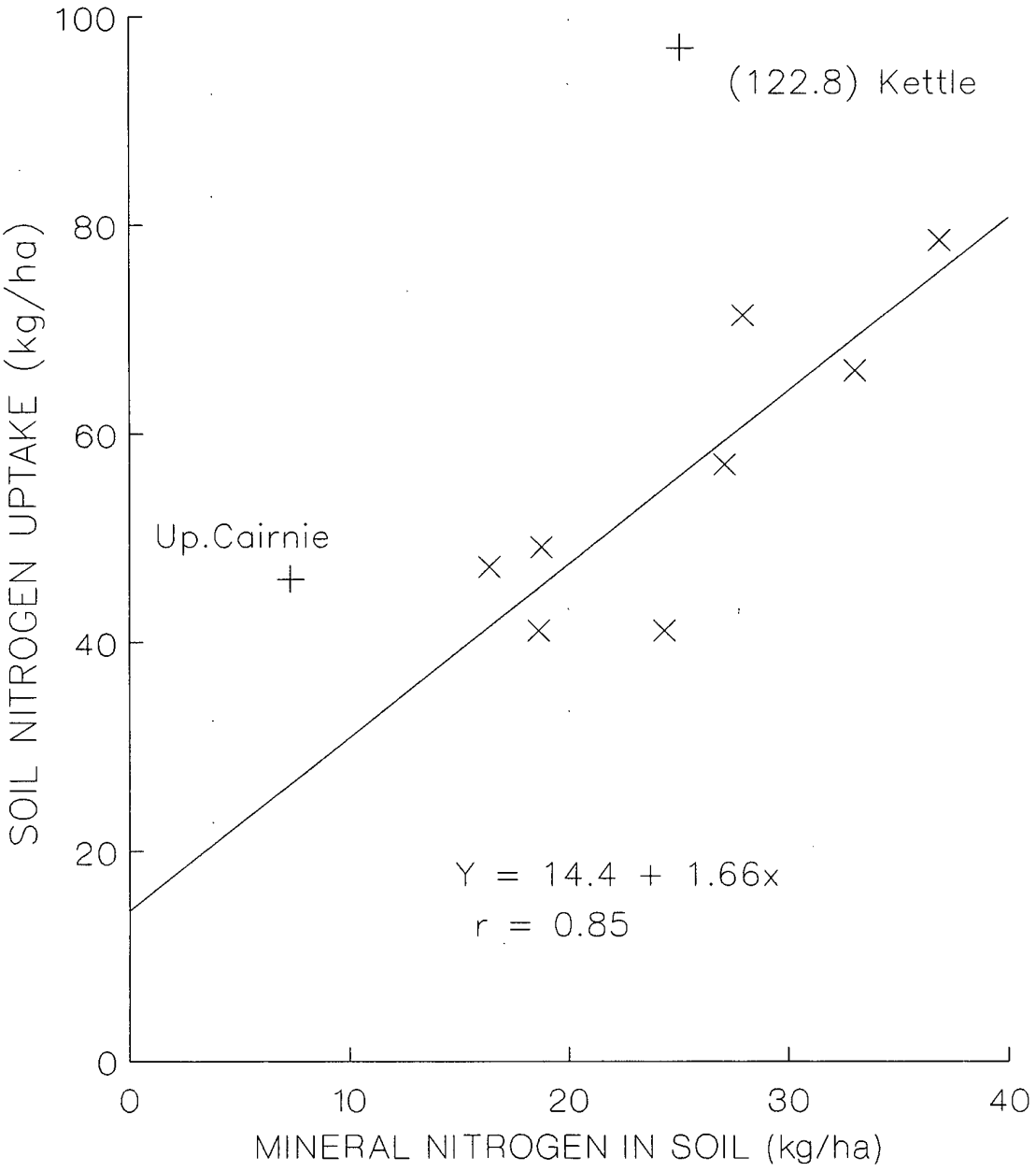


Figure 37. Relationship between mineral nitrogen in the soil prior to sowing and soil nitrogen uptake in above ground plant tissue. (Relationship excludes data from Upper Cairnie and Kettle).

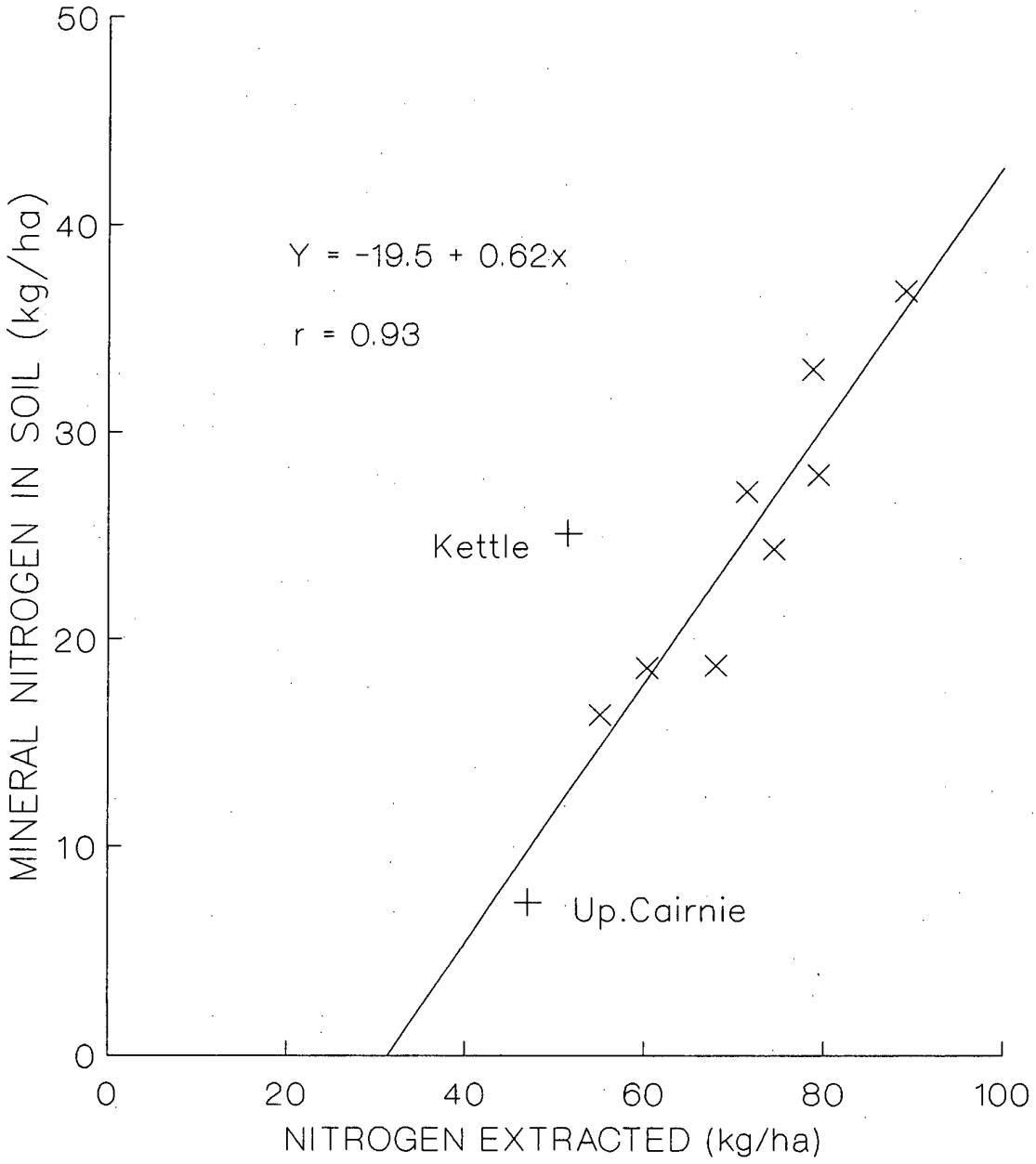


Figure 38. Relationship between nitrogen extracted by the Gianello and Bremner method and mineral nitrogen in the soil prior to sowing. (Relationship excludes data from Upper Cairnie and Kettle).

indication of the relative mineralisation of the soil organic matter over the whole growing season. However, samples taken in January 1991 at some of the same sites had much lower quantities of mineral nitrogen present (Stockdale, personal communication). Quantities of mineral nitrogen were low and there was a poor correlation with nitrogen extracted by the Gianello method. This indicated that early sampling and analysis of soil mineral nitrogen content was unlikely to be a good predictor of the uptake of soil nitrogen in the plants at harvest.

The fact that soil sampling and extraction with hot KCl could be carried out prior to sowing means that it is potentially a much more convenient method for inclusion in a soil analysis and advice service than the measuring of mineral nitrogen in the soil at the time of sowing. Also, it is much more convenient to take samples from the 0-20 cm layer for the Gianello method than it is to do a complete soil profile analysis for mineral nitrogen to 90 cm, as is the current practice in other Western European countries (Greenwood 1986).

The variation in the release of potentially mineralisable nitrogen using the Gianello method over time, prior to spring sowing, is not yet known and needs to be investigated.

6.3. Conclusions

Good correlations were found between the mineral nitrogen content of the KCl extracts and soil nitrogen uptake in the above-ground plant tissue. The longer boiling period and stronger extracting solution of the Gianello and Bremner method gave better correlations than the Whitehead method. Better correlations were obtained with the mineral nitrogen content of the soil at sowing. This latter variable was highly correlated with the amount of nitrogen released by the Gianello method, but this correlation was much poorer when applied to the very low mineral nitrogen contents found in the soil in January. This suggested that predictions of the likely uptake of soil nitrogen in the plant prior to sowing could be better achieved using the Gianello method rather than by analysing the mineral nitrogen content of the soil.

On its own, soil organic matter was a poor predictor of potentially available nitrogen, but in conjunction with the results of the chemical extraction

eemethods correlations were significantly higher than with any individual method. The relationships described only applied to N-Index zero soils, and did not hold for soils with higher amounts of plant residues from the previous crop. Further work is required to establish whether comparable but quantitatively different relationships can be established for this category of soils.

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APPENDIX

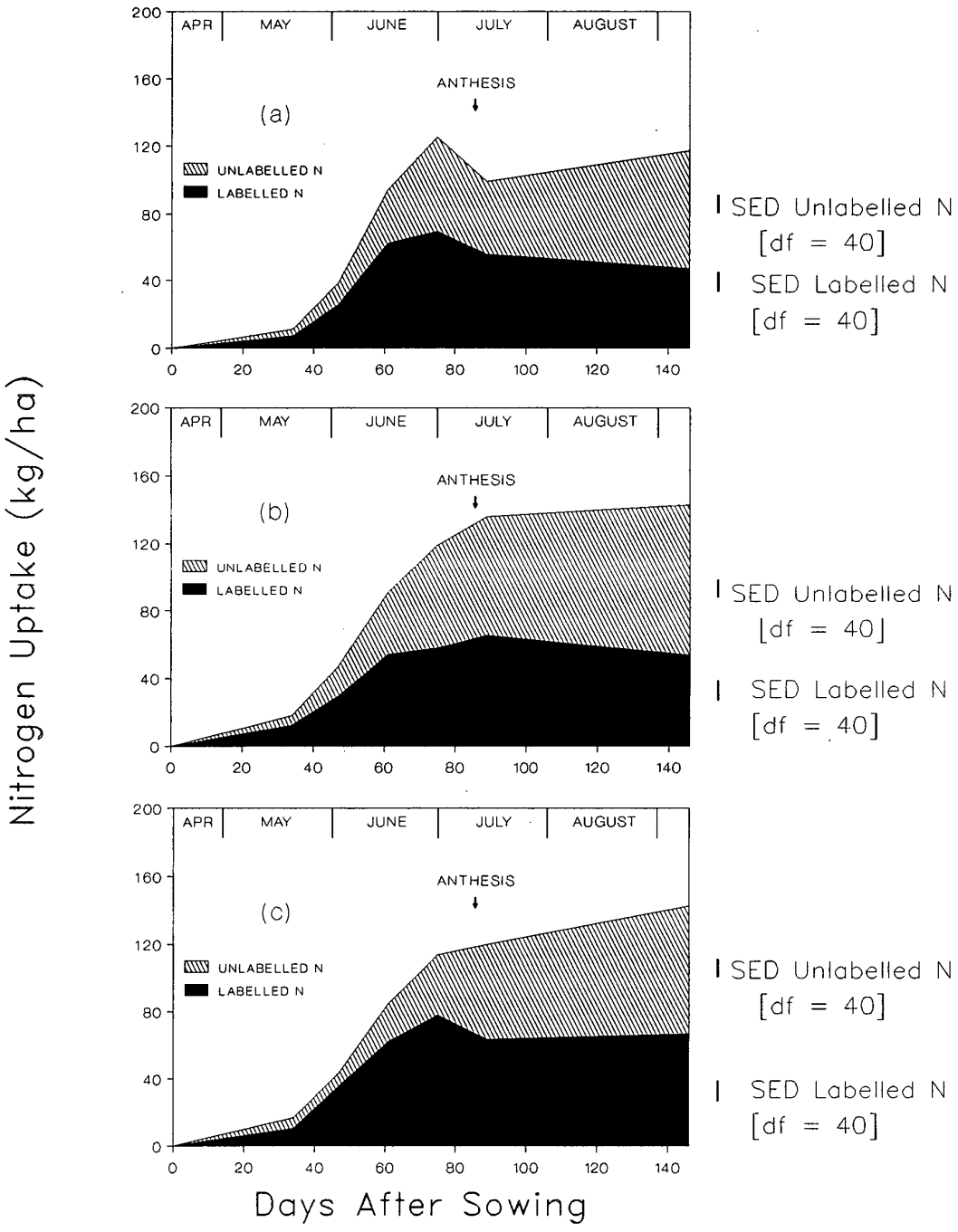


Figure A1. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen applications of 120 kg/ha at sowing in the form of (a) calcium nitrate, (b) ammonium sulphate and (c) ammonium nitrate, Bush 1987

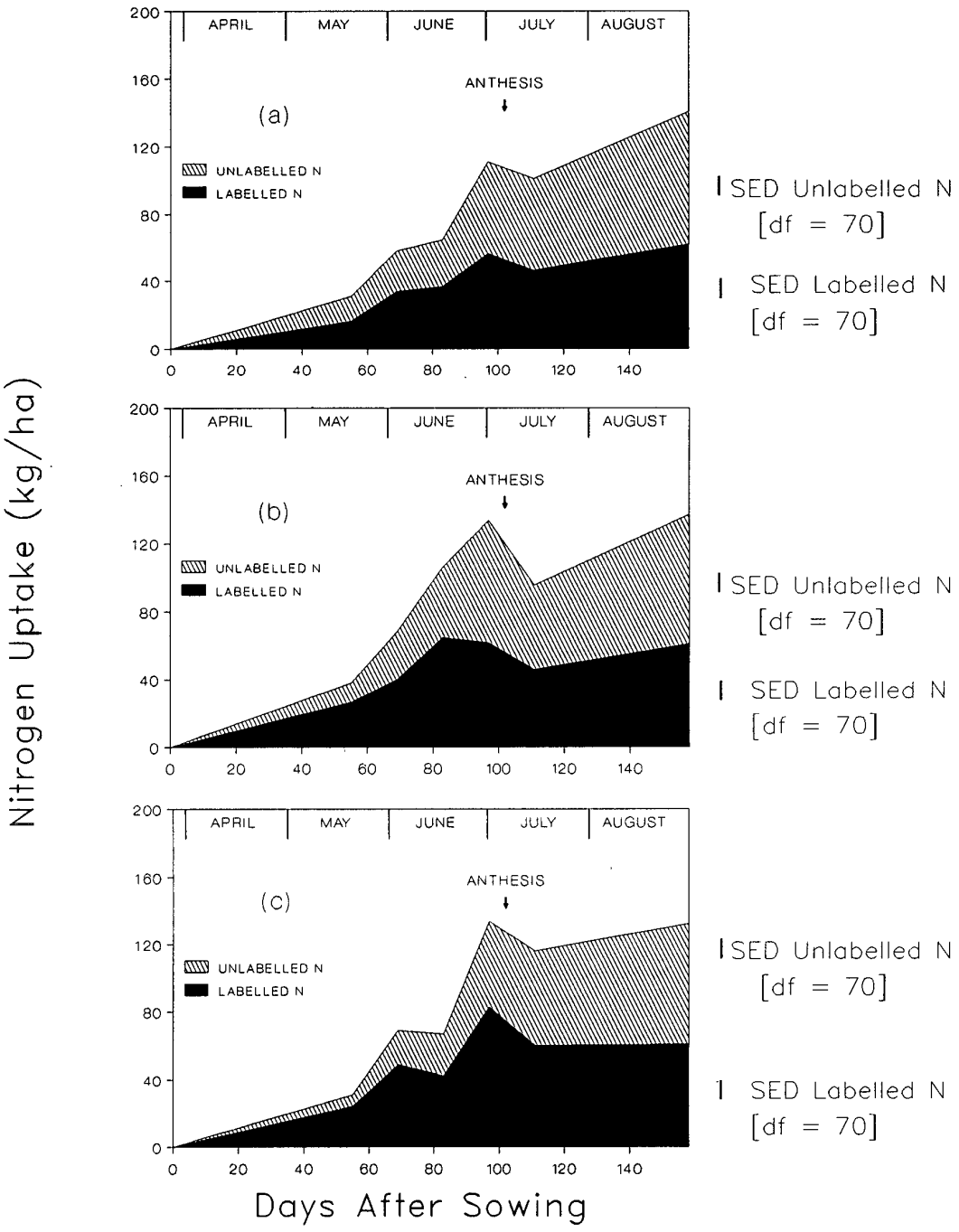


Figure A2. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen applications of 120 kg/ha at sowing in the form of (a) calcium nitrate, (b) ammonium sulphate and (c) ammonium nitrate, Lintlaw 1987

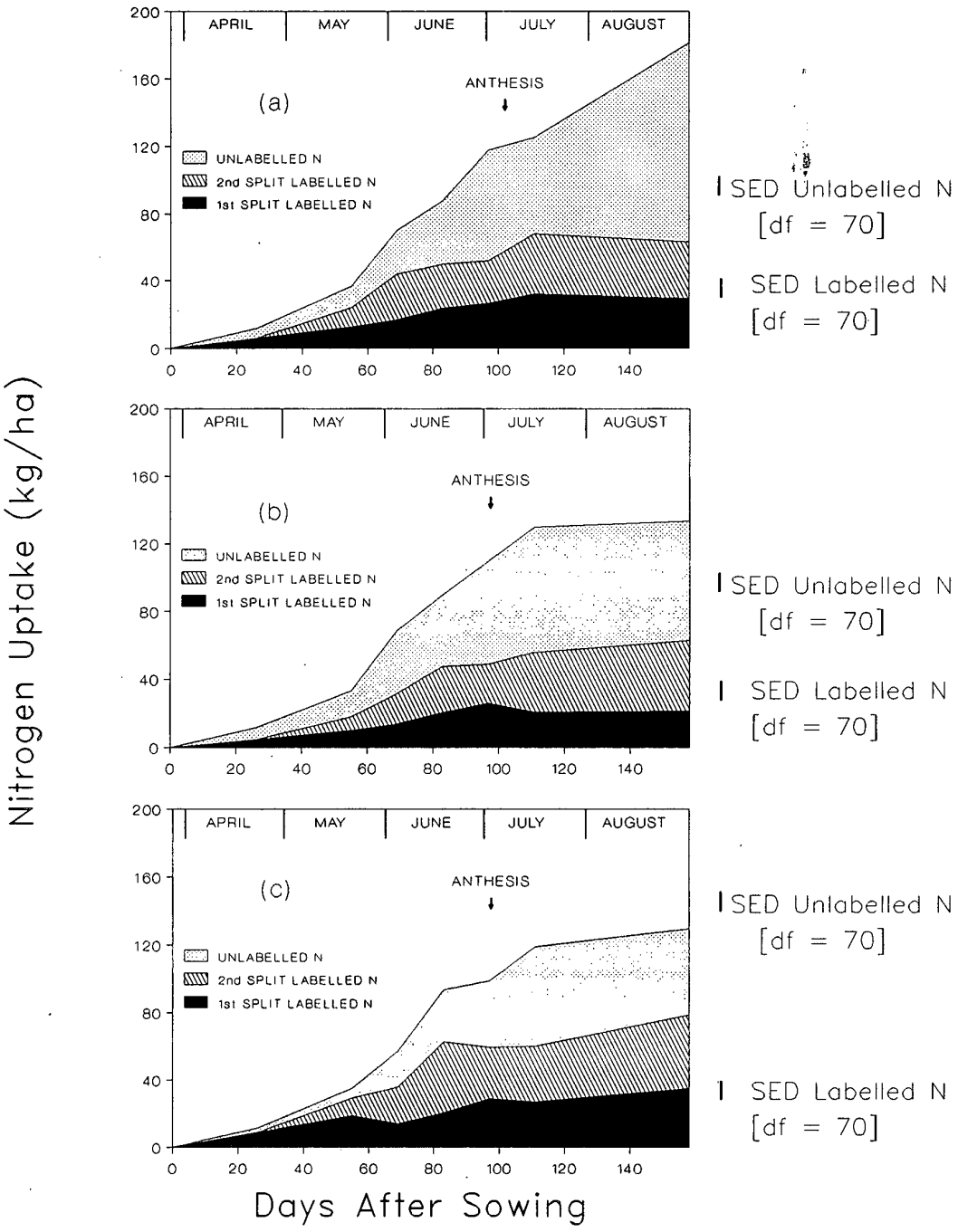


Figure A3. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen application of 60 kg/ha at sowing and 60 kg/ha at emergence in the form of (a) calcium nitrate, (b) ammonium sulphate and (c) ammonium nitrate, Lintlaw 1987

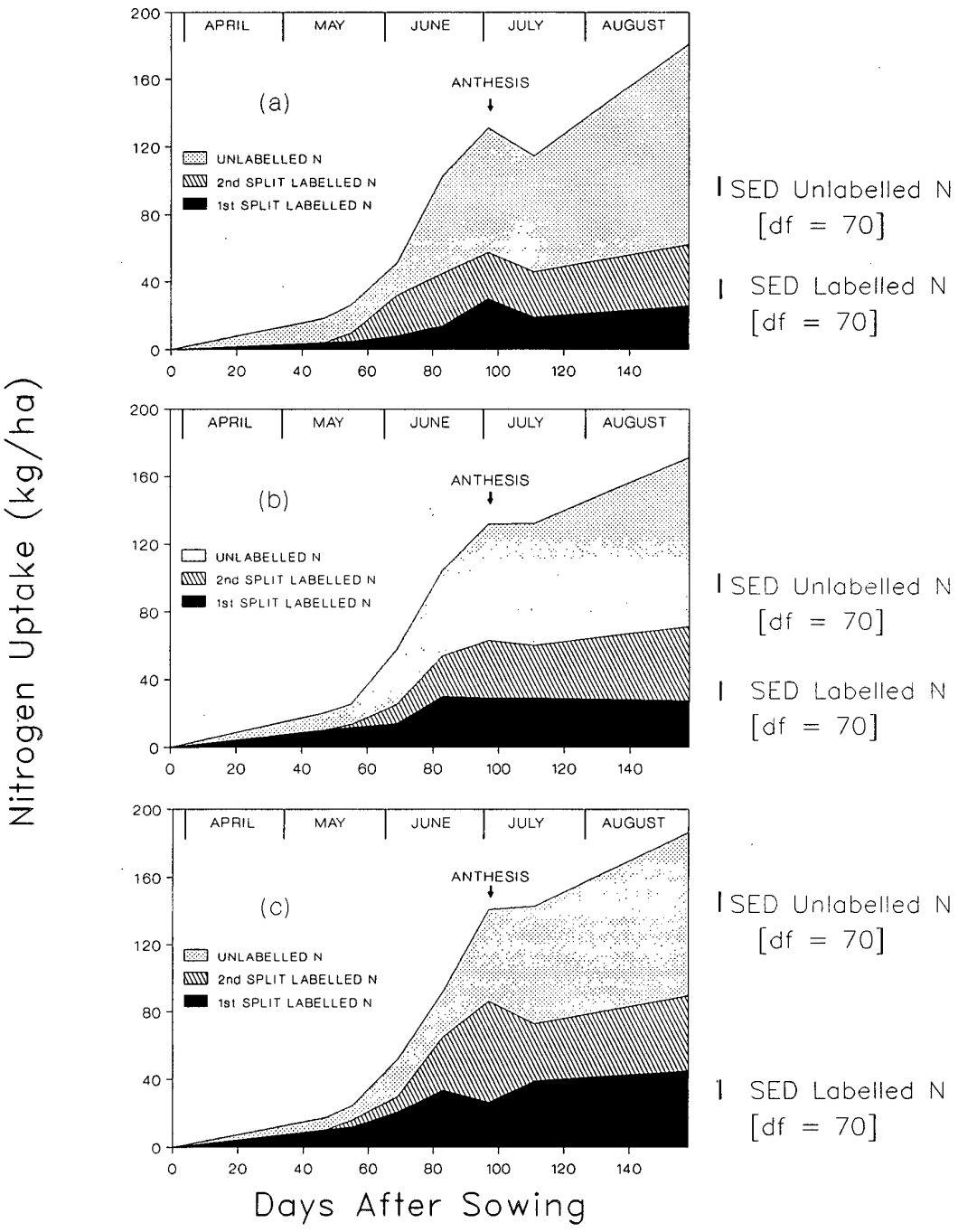


Figure A4. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertilise nitrogen application of 60 kg/ha at sowing and 60 kg/ha at tillering in the form of (a) calcium nitrate, (b) ammonium sulphate and (c) ammonium nitrate, Lintlaw 1987

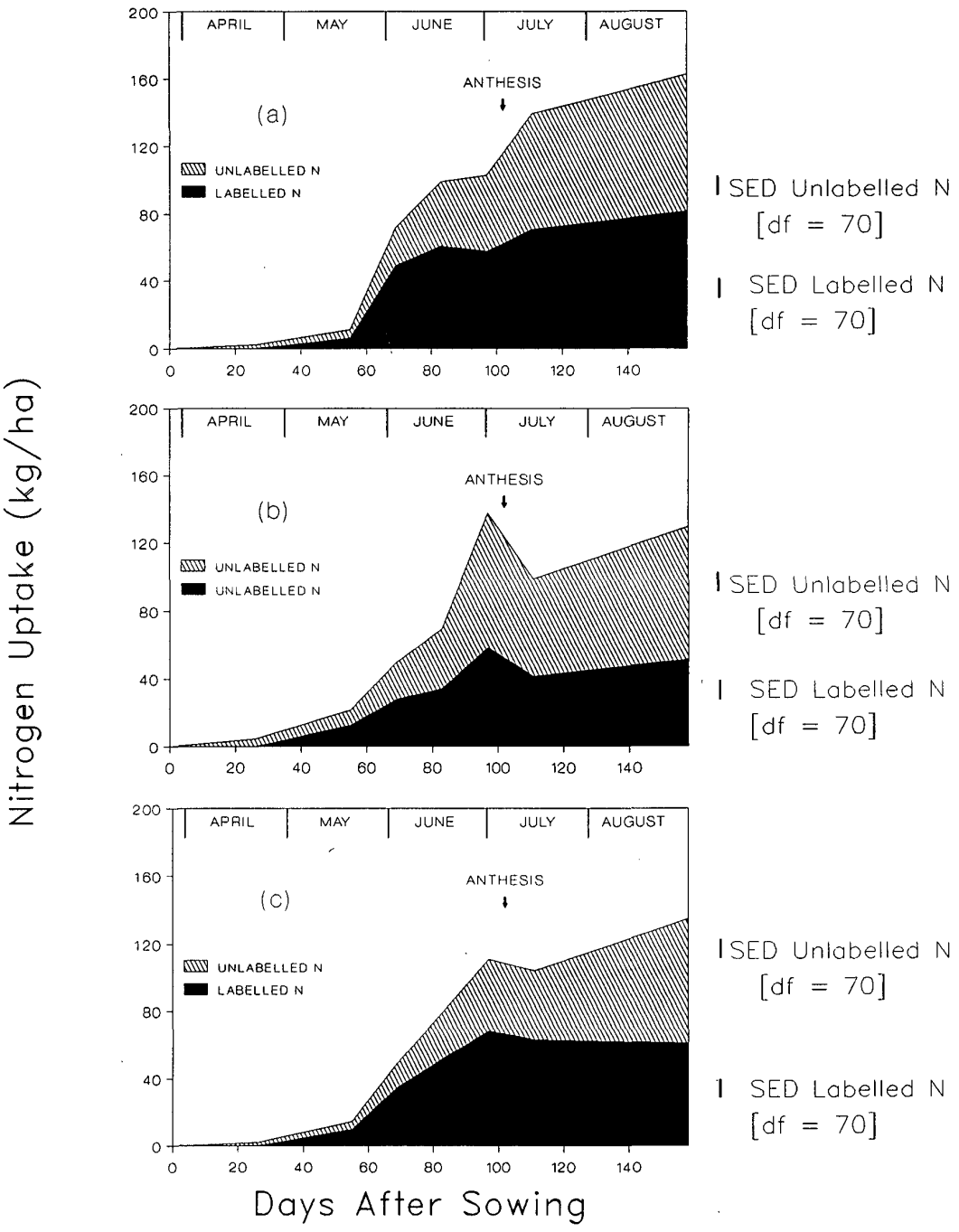


Figure A5. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen applications of 120 kg/ha at emergence in the form of (a) calcium nitrate, (b) ammonium sulphate and (c) ammonium nitrate, Lintlaw 1987

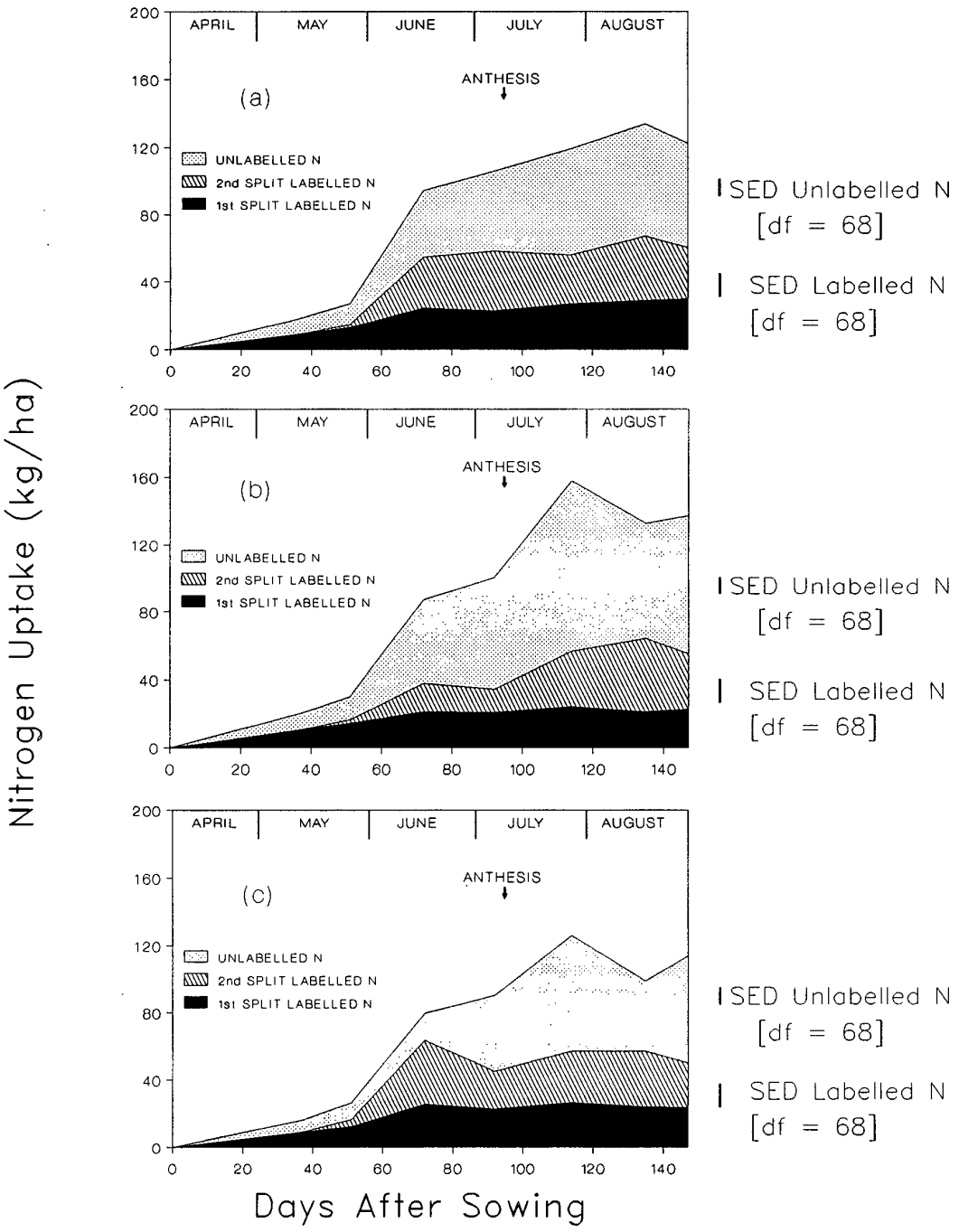


Figure A6. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen application of 60 kg/ha at sowing and 60 kg/ha at tillering in the form of (a) calcium nitrate, (b) ammonium sulphate and (c) ammonium nitrate, Bush 1988

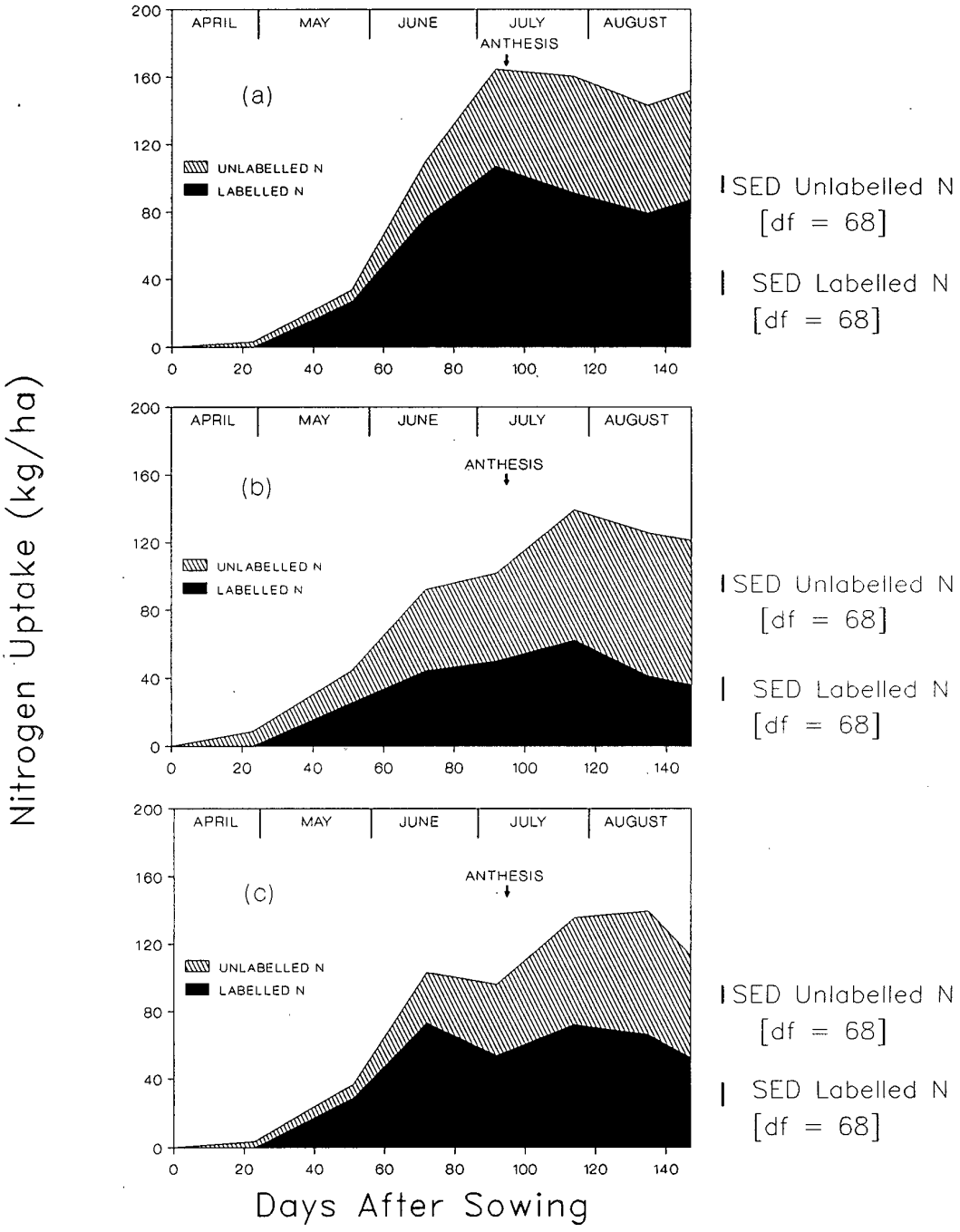


Figure A7. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen applications of 120 kg/ha at emergence in the form of (a) calcium nitrate, (b) ammonium sulphate and (c) ammonium nitrate, Bush 1988

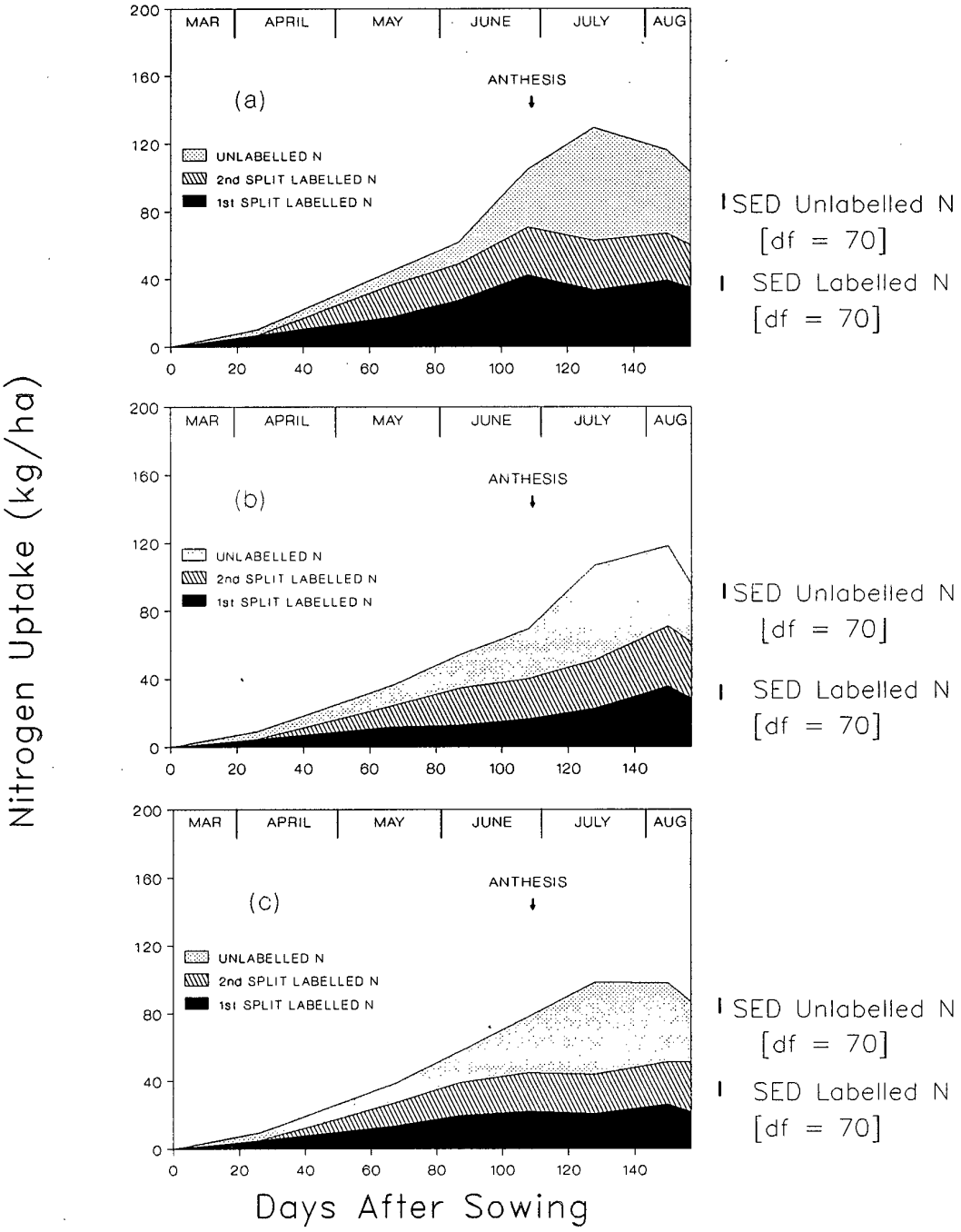


Figure A8. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen application of 60 kg/ha at sowing and 60 kg/ha at emergence in the form of (a) calcium nitrate, (b) ammonium sulphate and (c) ammonium nitrate, Middlestot 1988

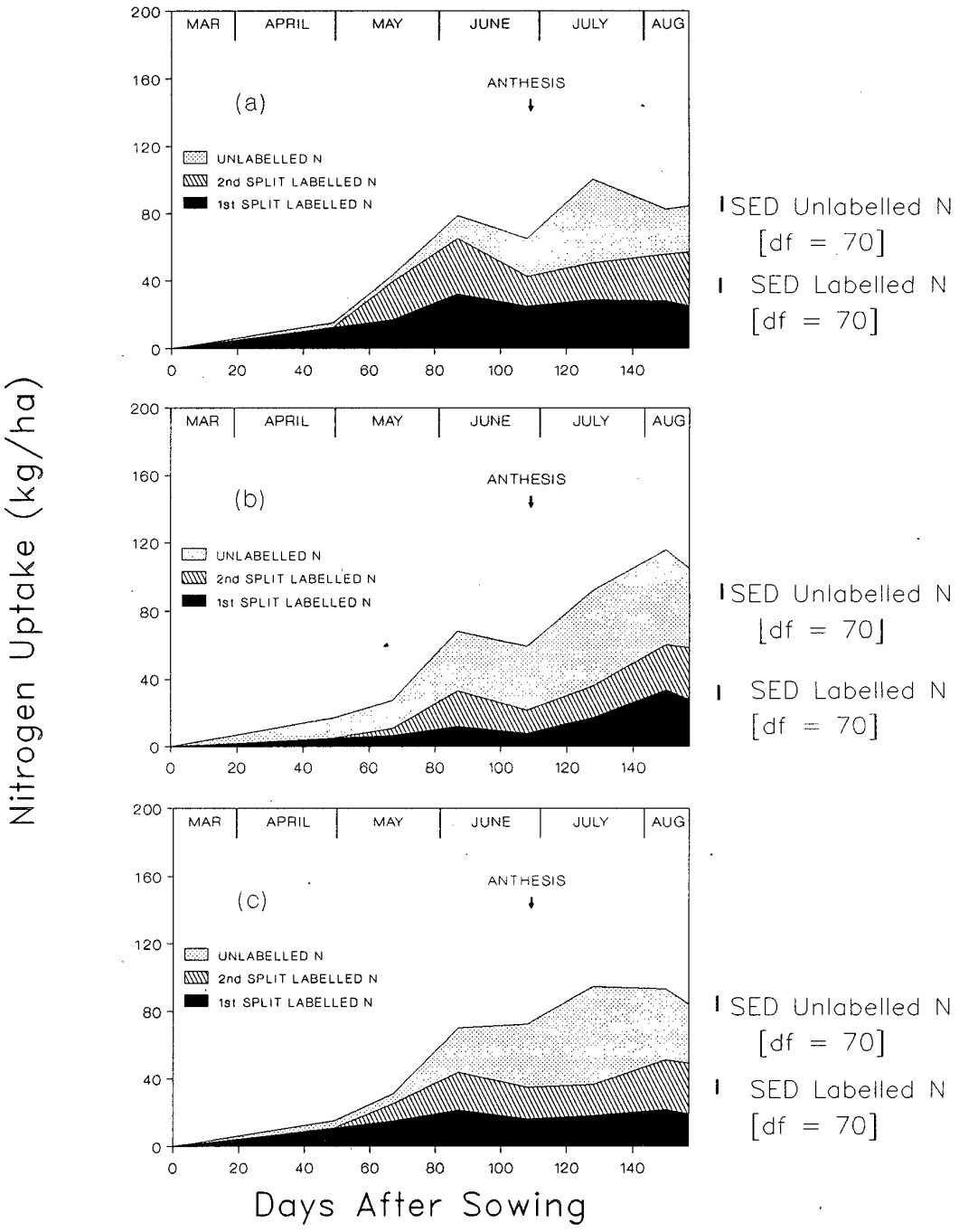


Figure A9. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen application of 60 kg/ha at sowing and 60 kg/ha at tillering in the form of (a) calcium nitrate, (b) ammonium sulphate and (c) ammonium nitrate, Middlestot 1988

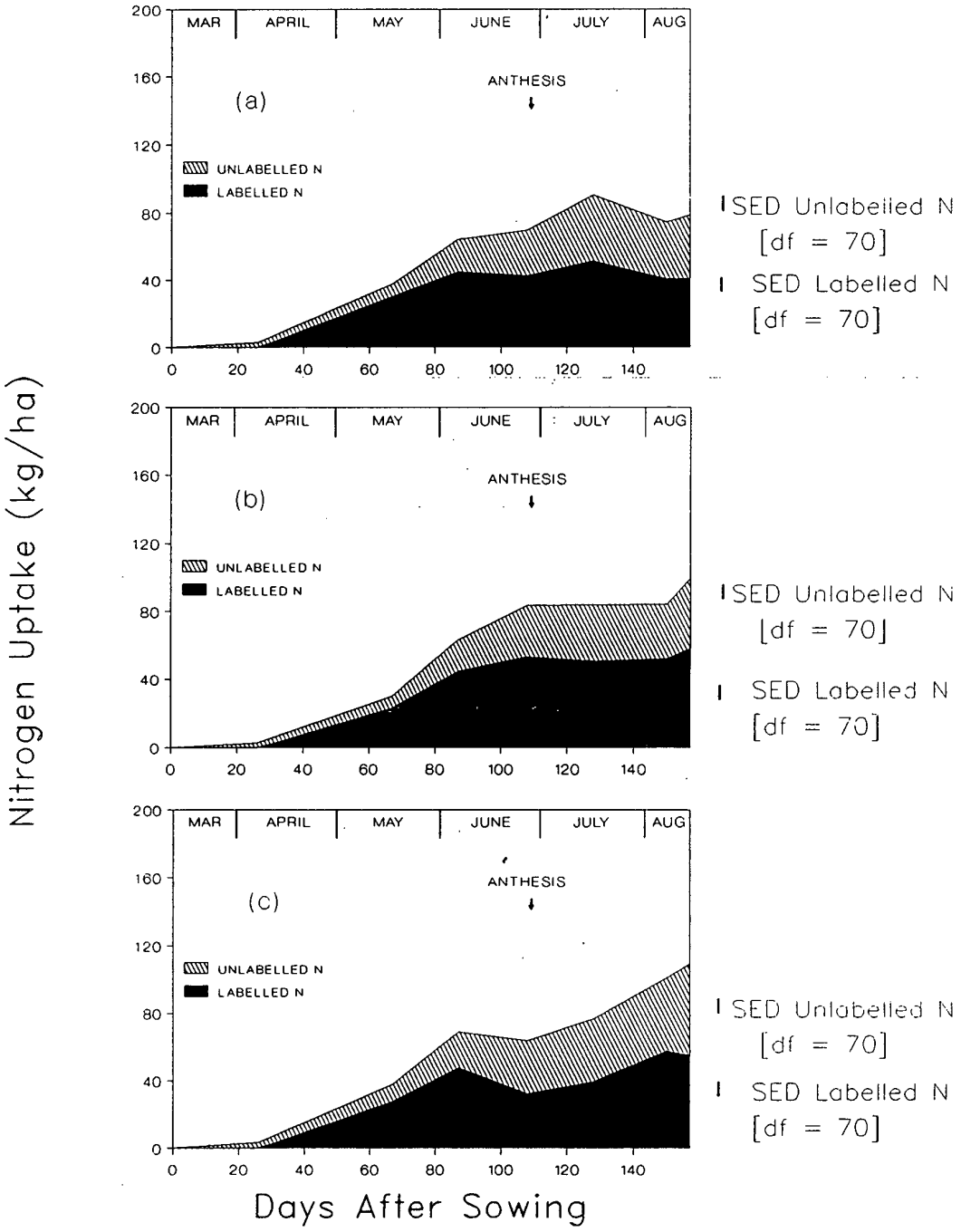


Figure A10. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen applications of 120 kg/ha at emergence in the form of (a) calcium nitrate, (b) ammonium sulphate and (c) ammonium nitrate, Middlestot 1988

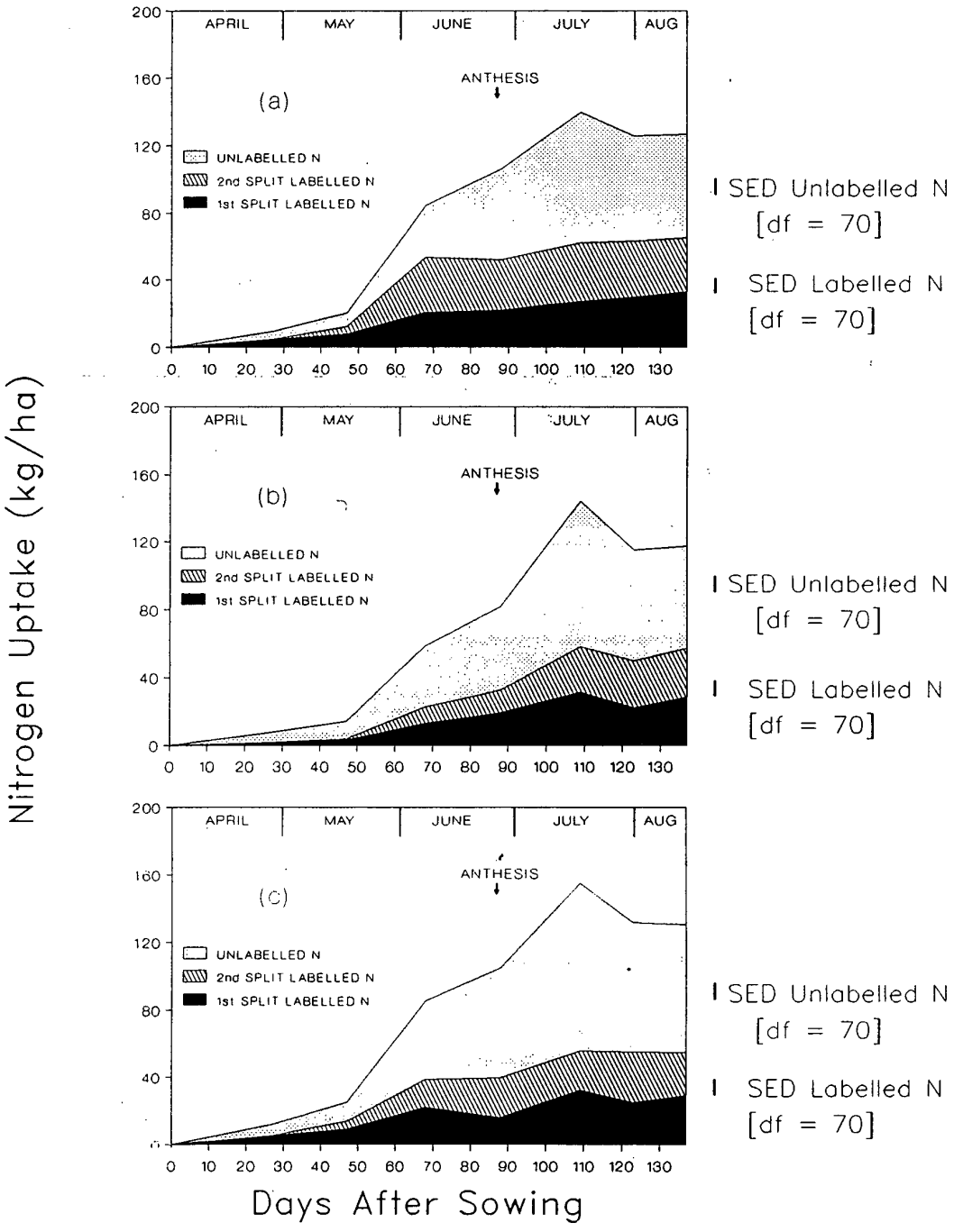


Figure A11. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen application of 45 kg/ha at sowing and 45 kg/ha at emergence in the form of (a) calcium nitrate, (b) ammonium sulphate and (c) ammonium nitrate, Bush 1989

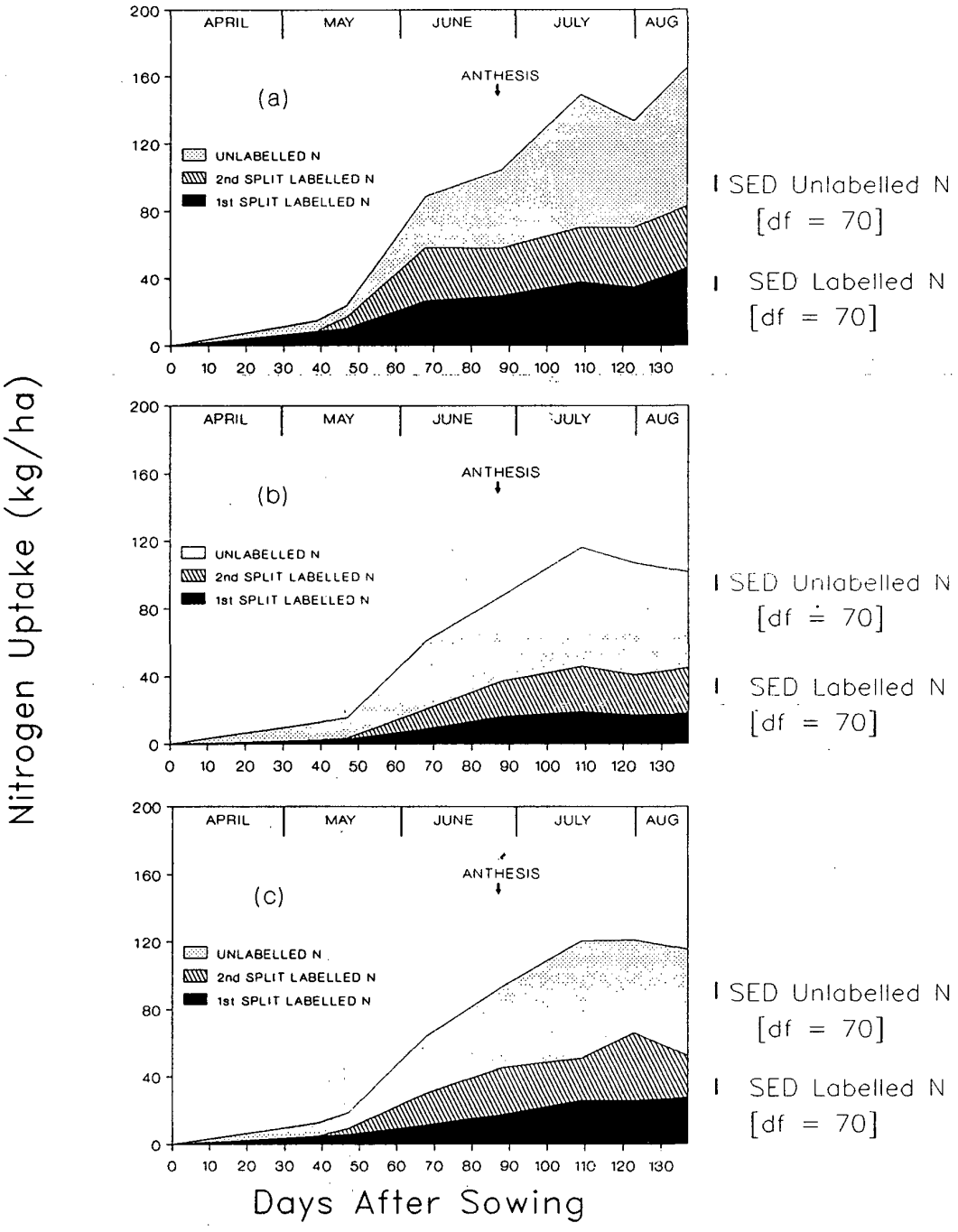


Figure A12. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen application of 45 kg/ha at sowing and 45 kg/ha at tillering in the form of (a) calcium nitrate, (b) ammonium sulphate and (c) ammonium nitrate, Bush 1989

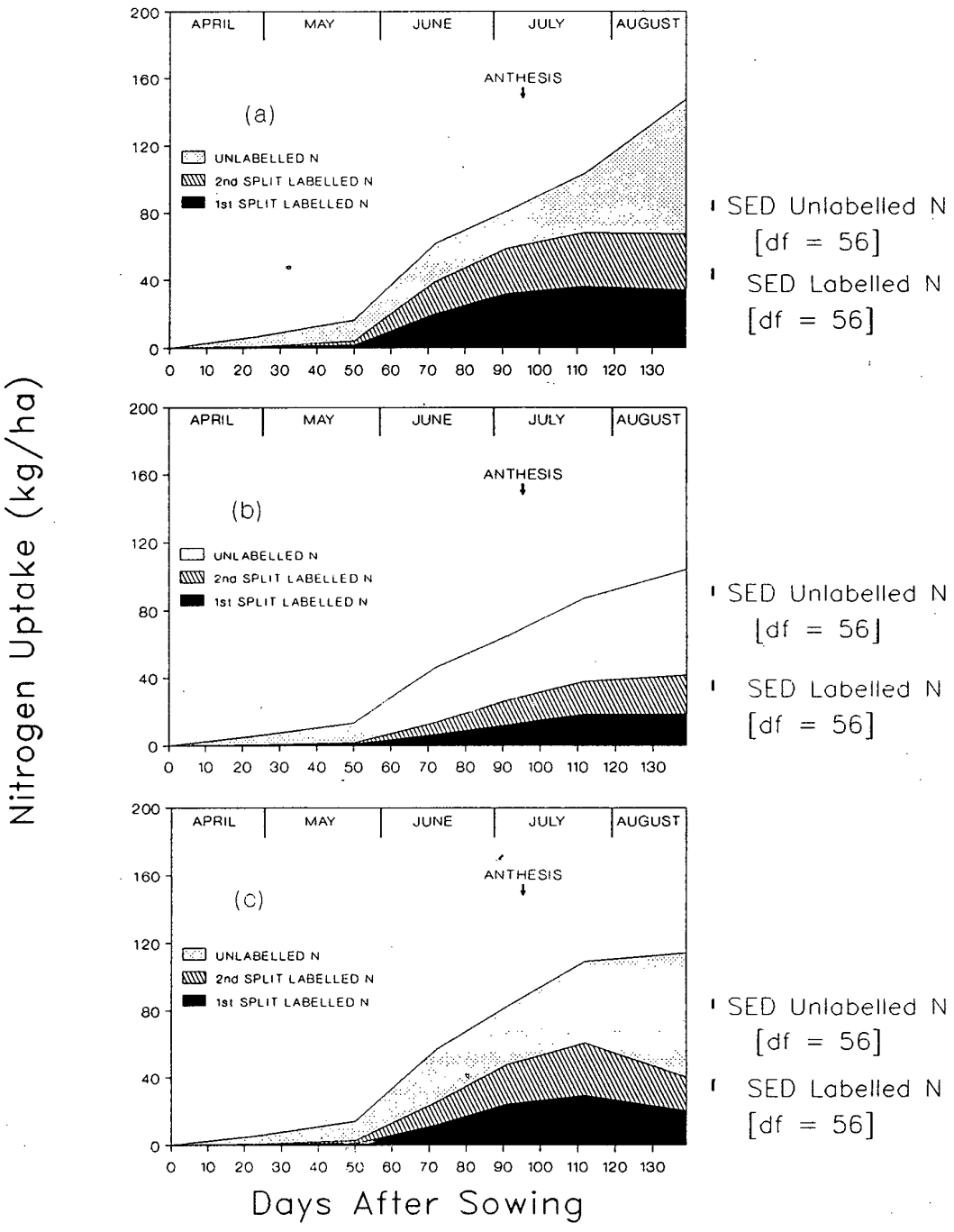


Figure A13. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen application of 45 kg/ha at sowing and 45 kg/ha at emergence in the form of (a) calcium nitrate, (b) ammonium sulphate and (c) ammonium nitrate, Upper Cairnie 1989

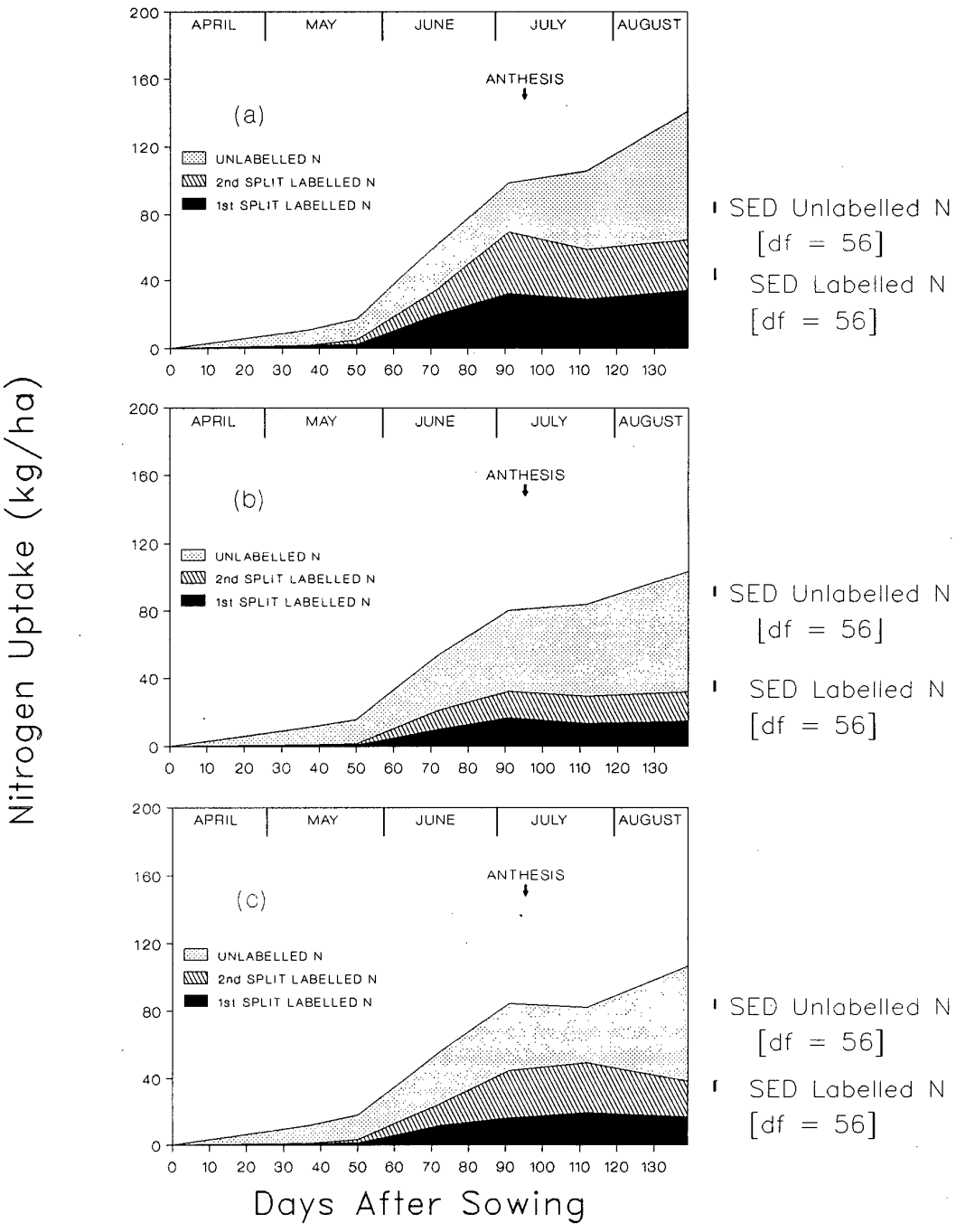


Figure A14. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen application of 45 kg/ha at sowing and 45 kg/ha at tillering in the form of (a) calcium nitrate, (b) ammonium sulphate and (c) ammonium nitrate, Upper Cairnie 1989

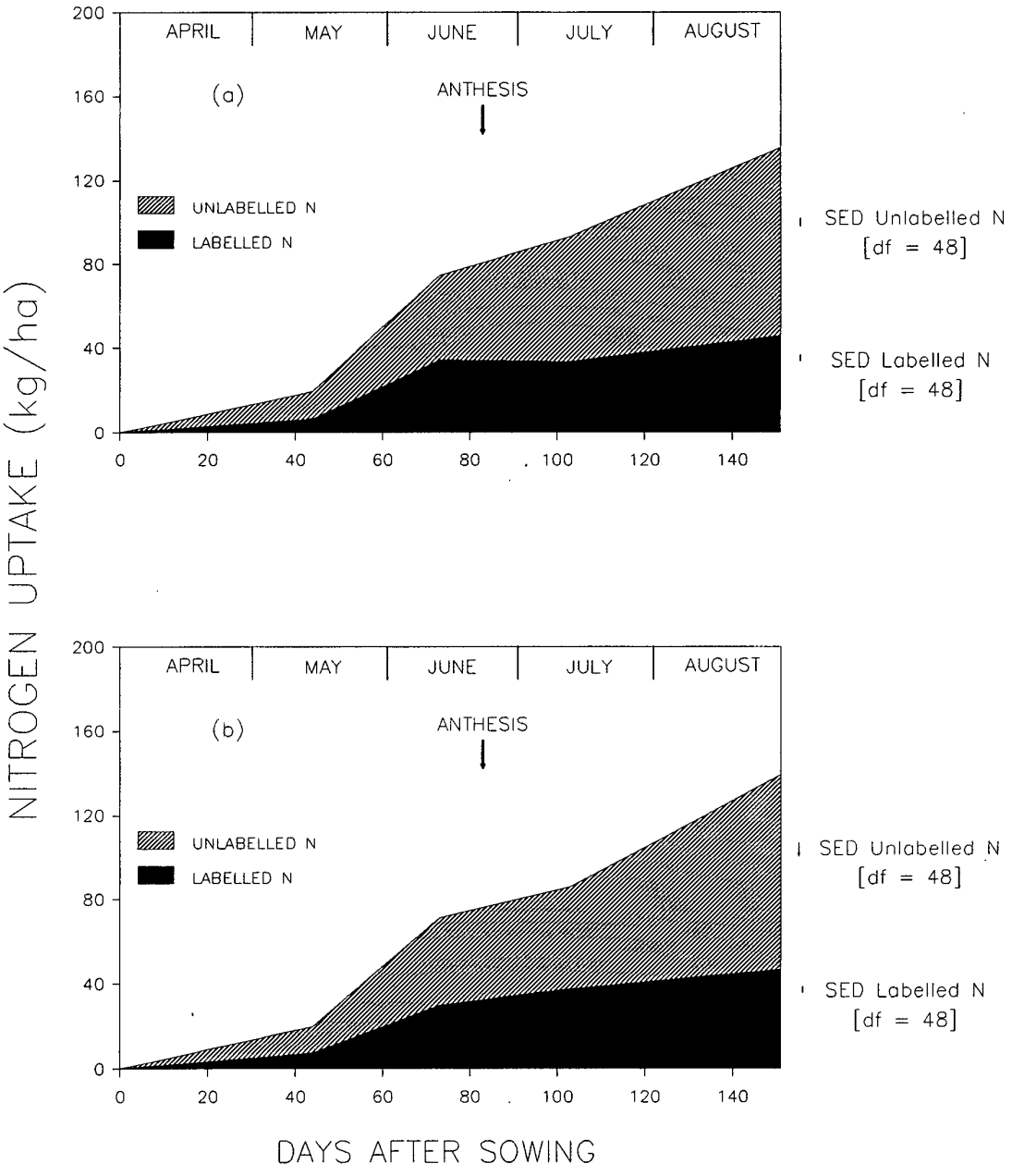


Figure A15. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen applications of 120 kg/ha at sowing in the form of (a) ammonium sulphate and (b) ammonium nitrate, Quixwood 1990

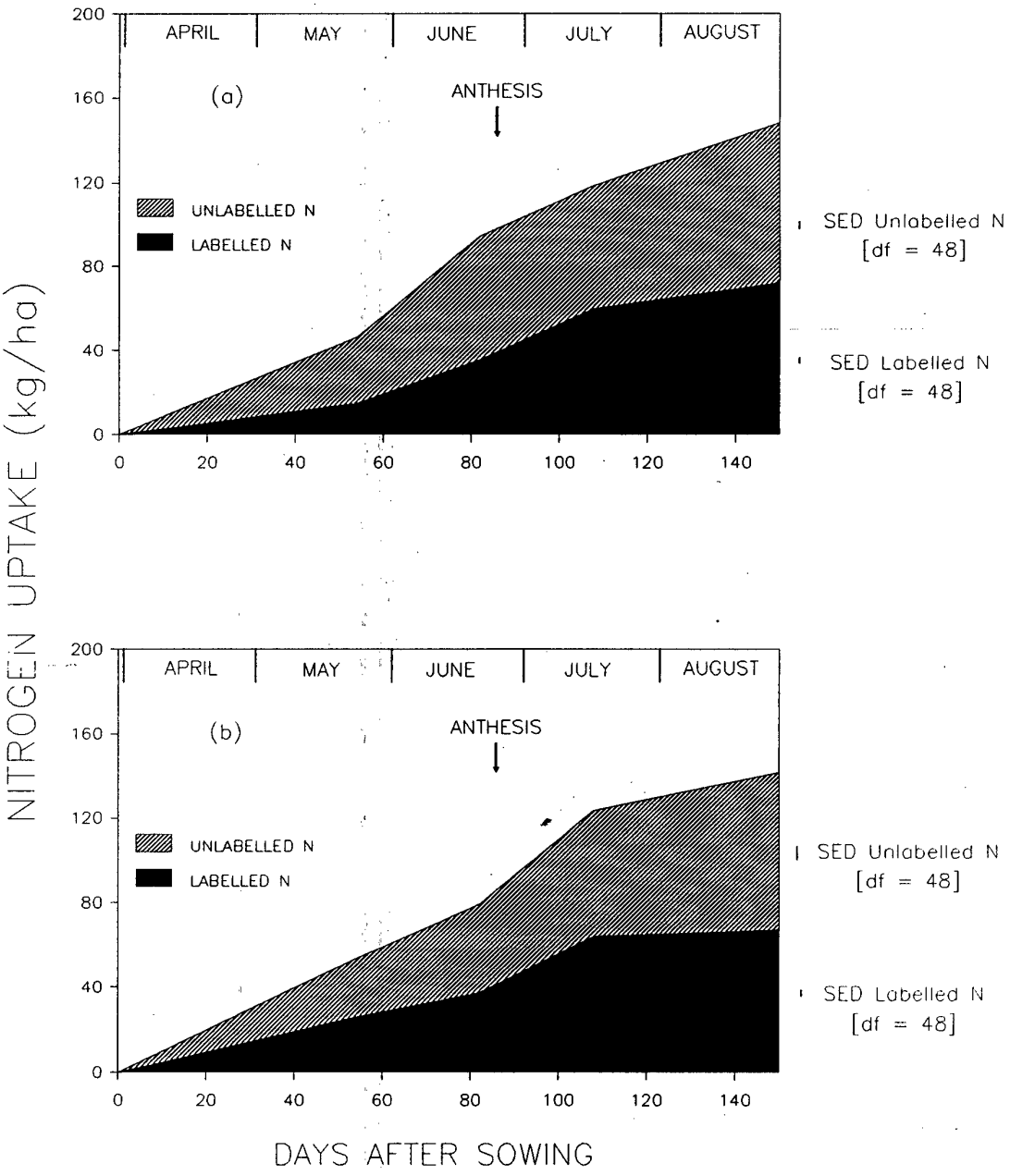


Figure A16. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen applications of 120 kg/ha at sowing in the form of (a) ammonium sulphate and (b) ammonium nitrate, Bush (Crofts) 1990

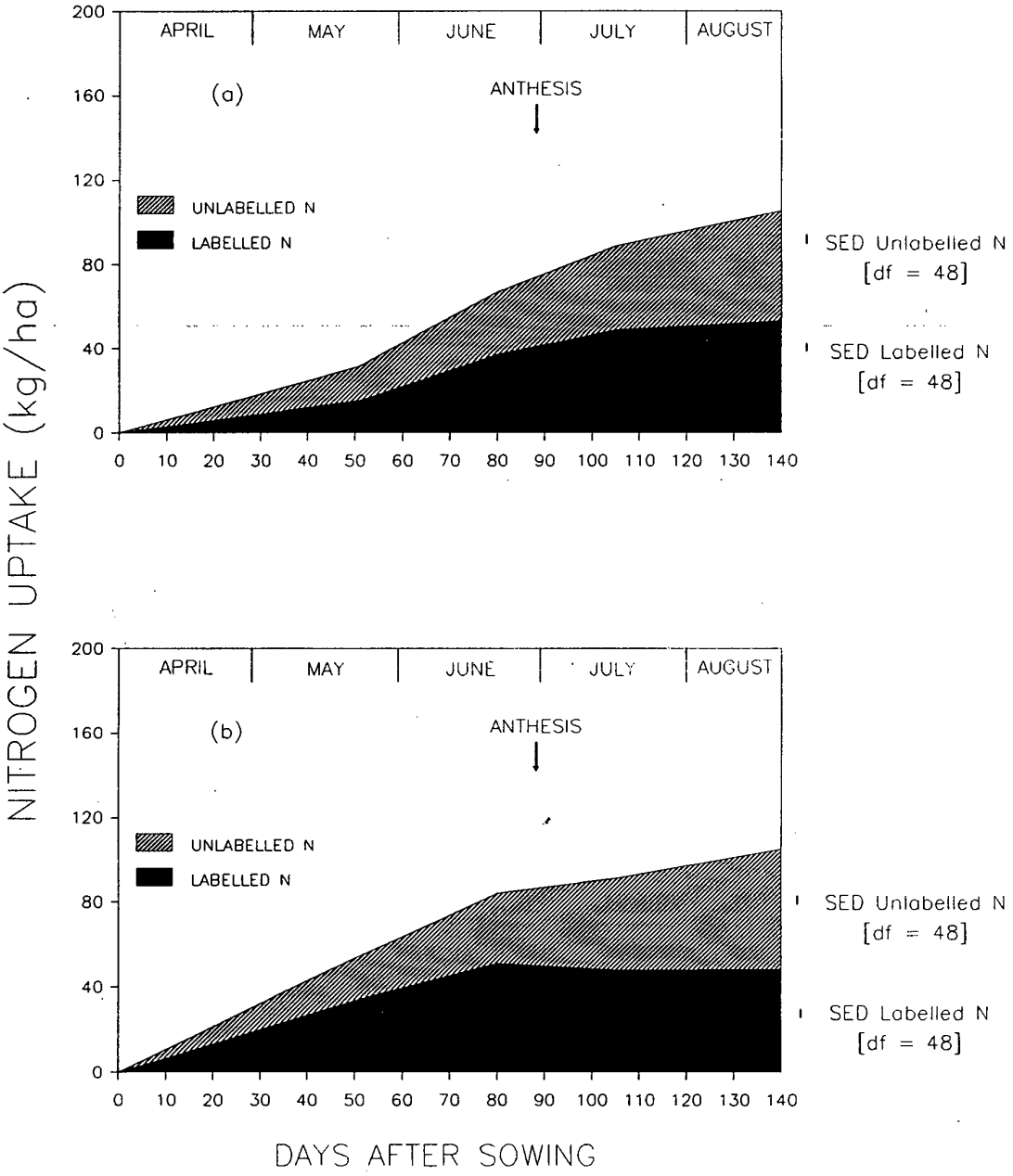


Figure A17. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen applications of 120 kg/ha at sowing in the form of (a) ammonium sulphate and (b) ammonium nitrate, Bush (Farmers Holding) 1990

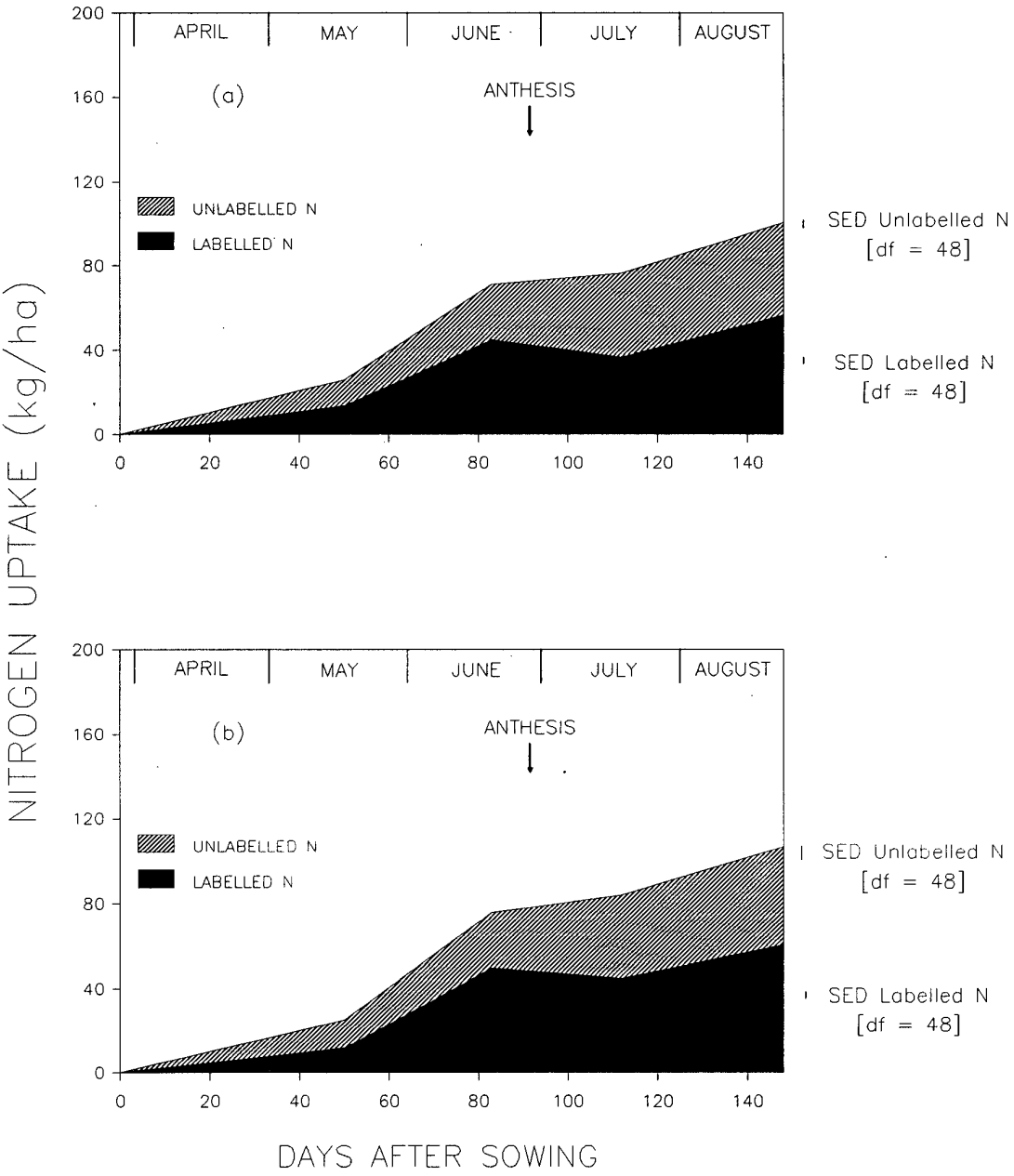


Figure A18. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after fertiliser nitrogen applications of 120 kg/ha at sowing in the form of (a) ammonium sulphate and (b) ammonium nitrate, Treaton 1990

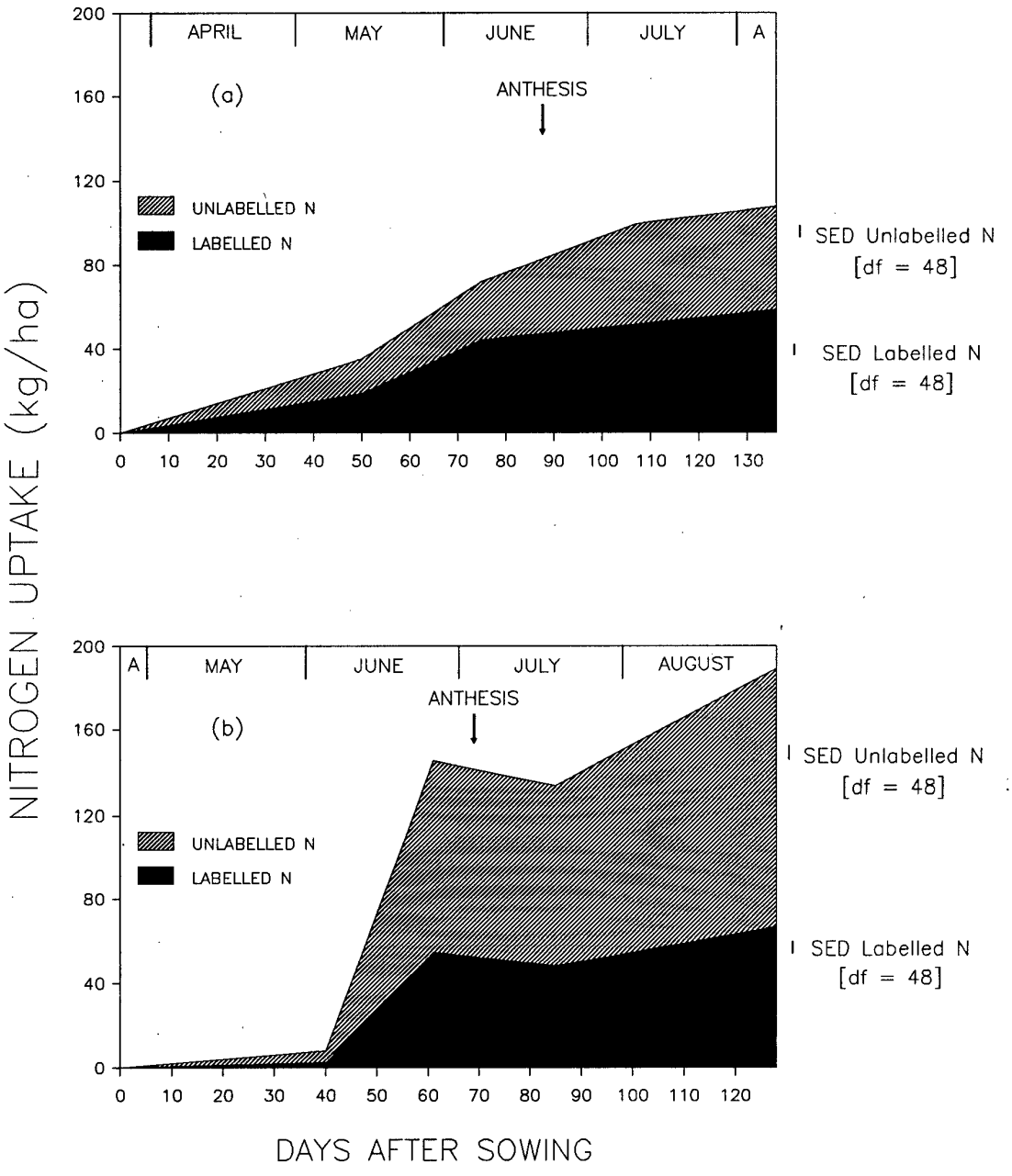


Figure A19. Uptake of labelled and unlabelled nitrogen over the growing season in spring barley after ammonium sulphate fertiliser applications of 120 kg N/ha at sowing (a) Manorhill 1990 and (b) Kettle 1990

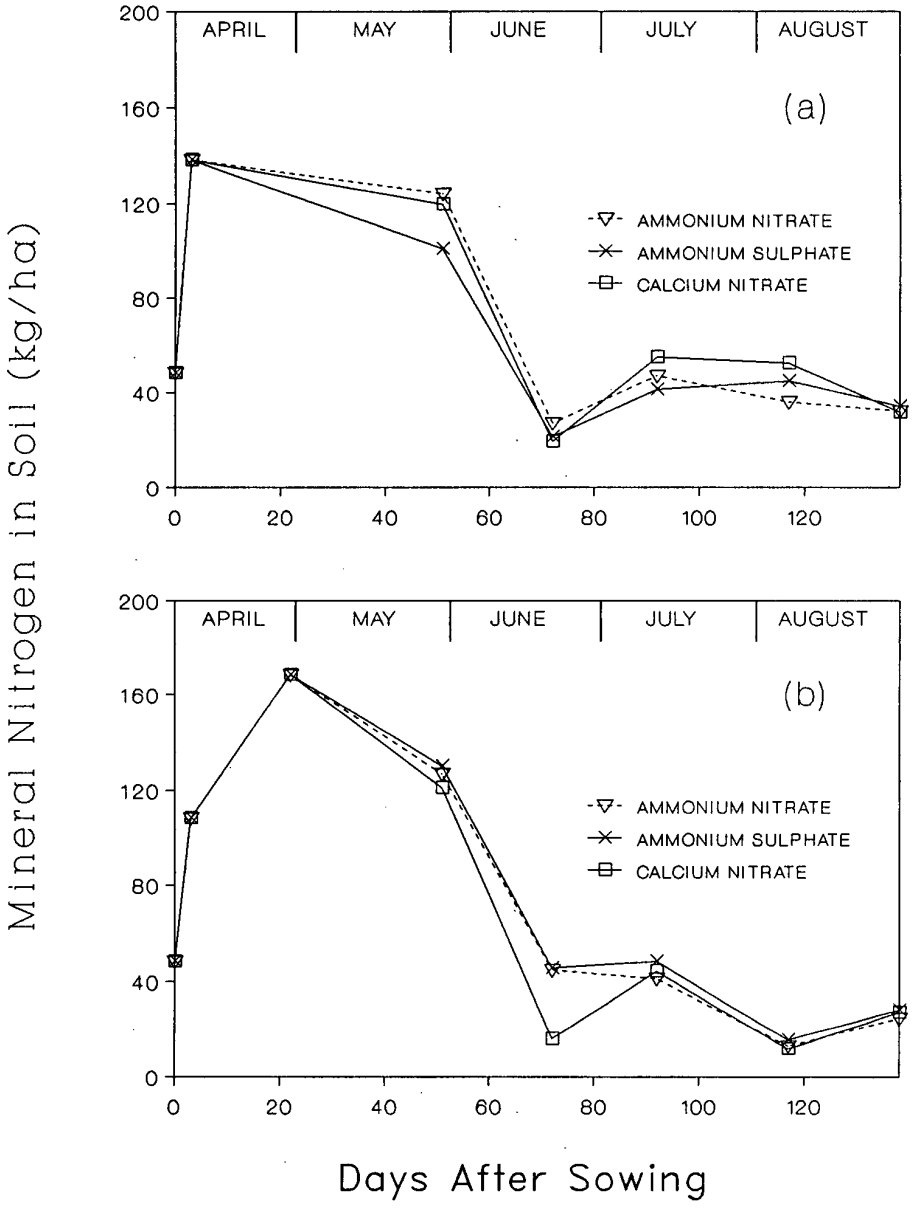


Figure A20. Changes in mineral nitrogen in the soil (0-40 cm) over the growing season, under spring barley, with fertiliser nitrogen applied (a) 90 kg/ha at sowing and (b) 60 kg/ha at sowing and 60 kg/ha at emergence, Bush 1988

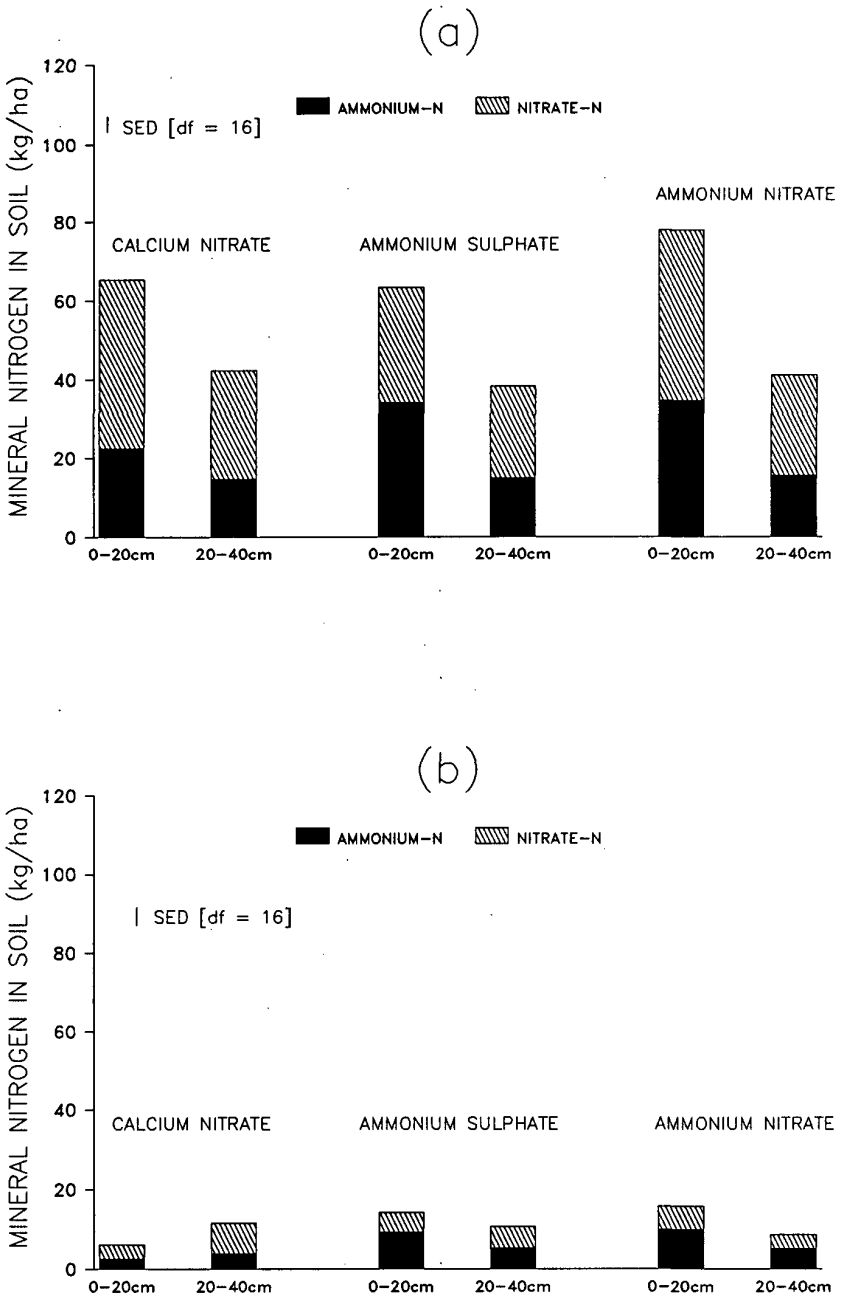


Figure A21. Quantities of nitrate- and ammonium-N at different depths in the soil at first two sampling dates, under spring barley fertilised with 120 kg/ha N fertiliser at sowing, (a) after 51 days (b) after 72 days, Bush 1988

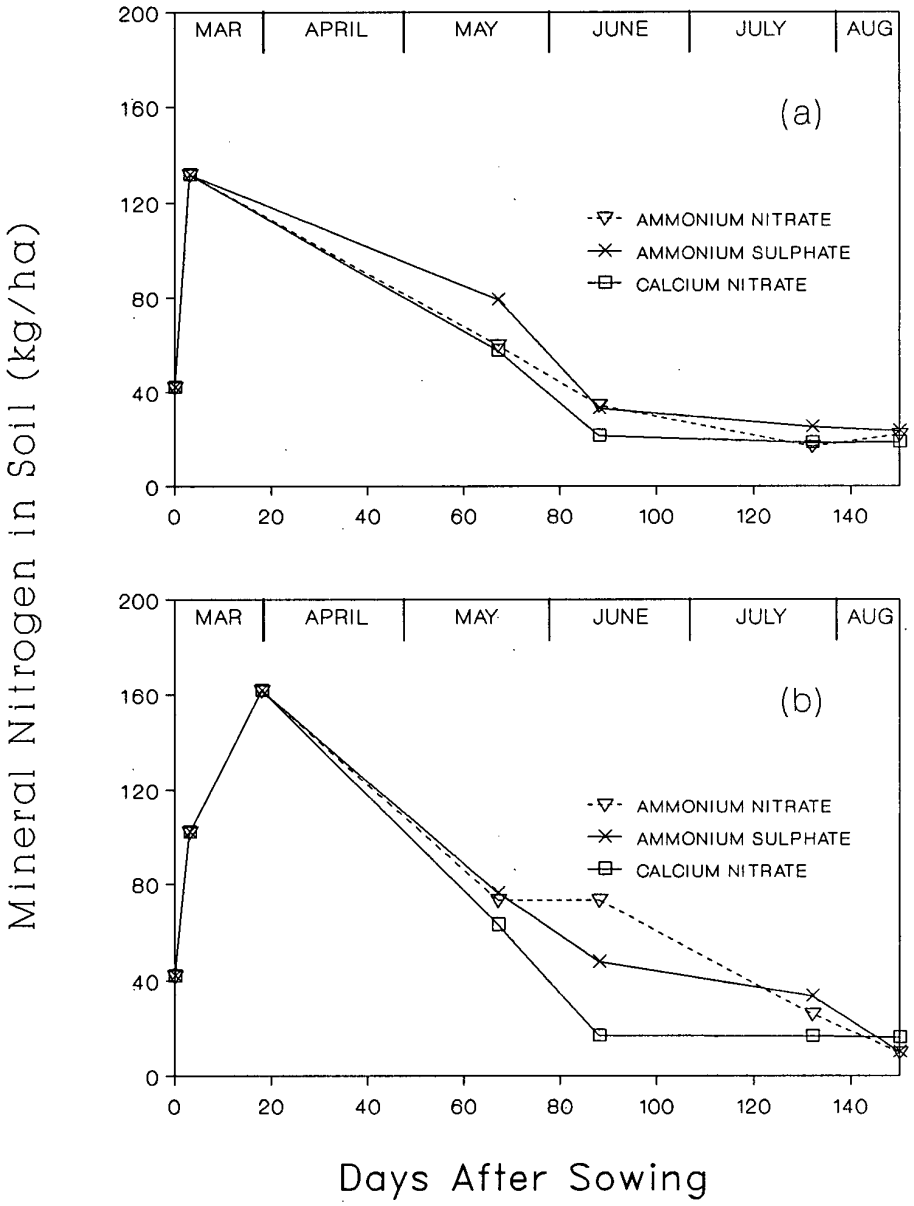


Figure A22. Changes in mineral nitrogen in the soil (0-40 cm) over the growing season, under spring barley, with fertiliser nitrogen applied (a) 90 kg/ha at sowing and (b) 60 kg/ha at sowing and 60 kg/ha at emergence, Middlestot 1988

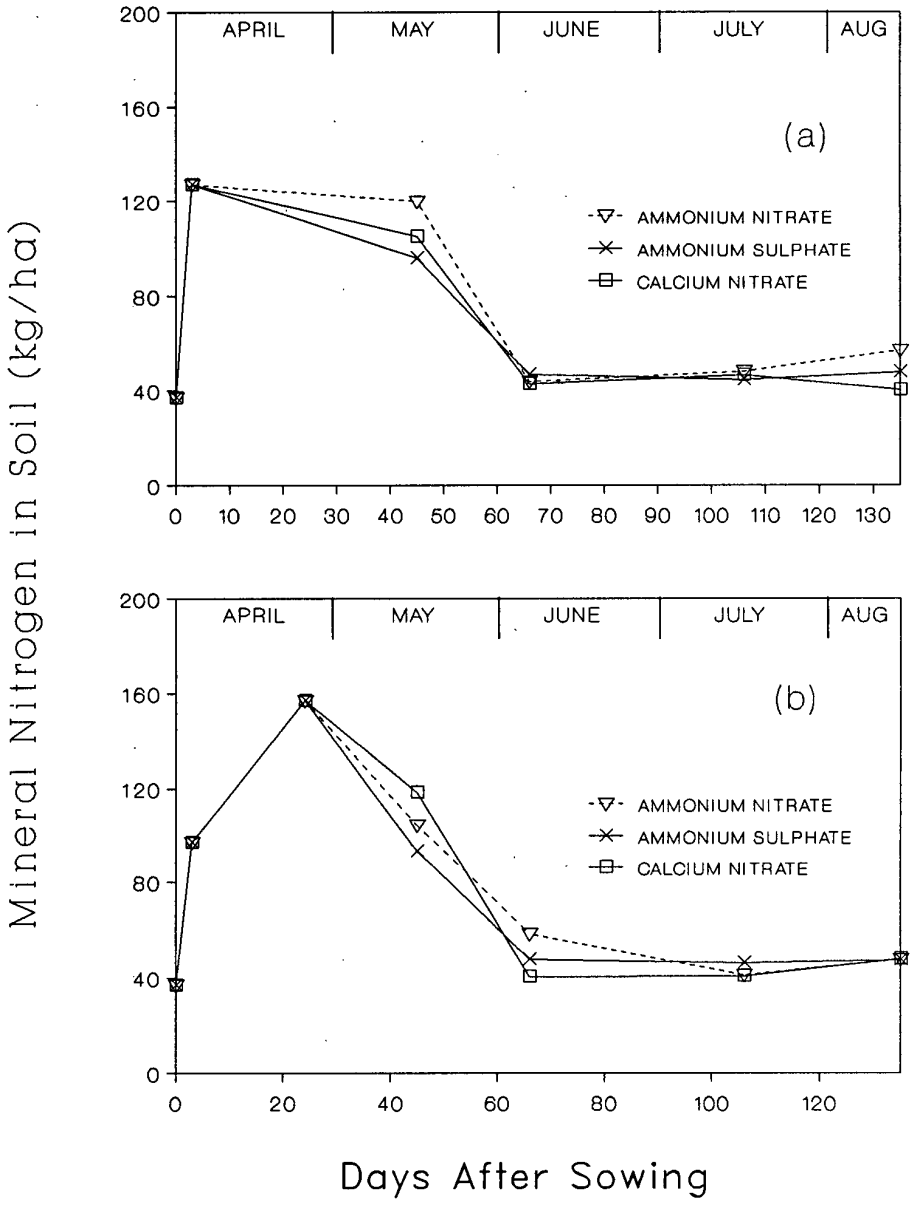


Figure A23. Changes in mineral nitrogen in the soil (0-40 cm) over the growing season, under spring barley, with fertiliser nitrogen applied (a) 90 kg/ha at sowing and (b) 60 kg/ha at sowing and 60 kg/ha at emergence, Bush 1989

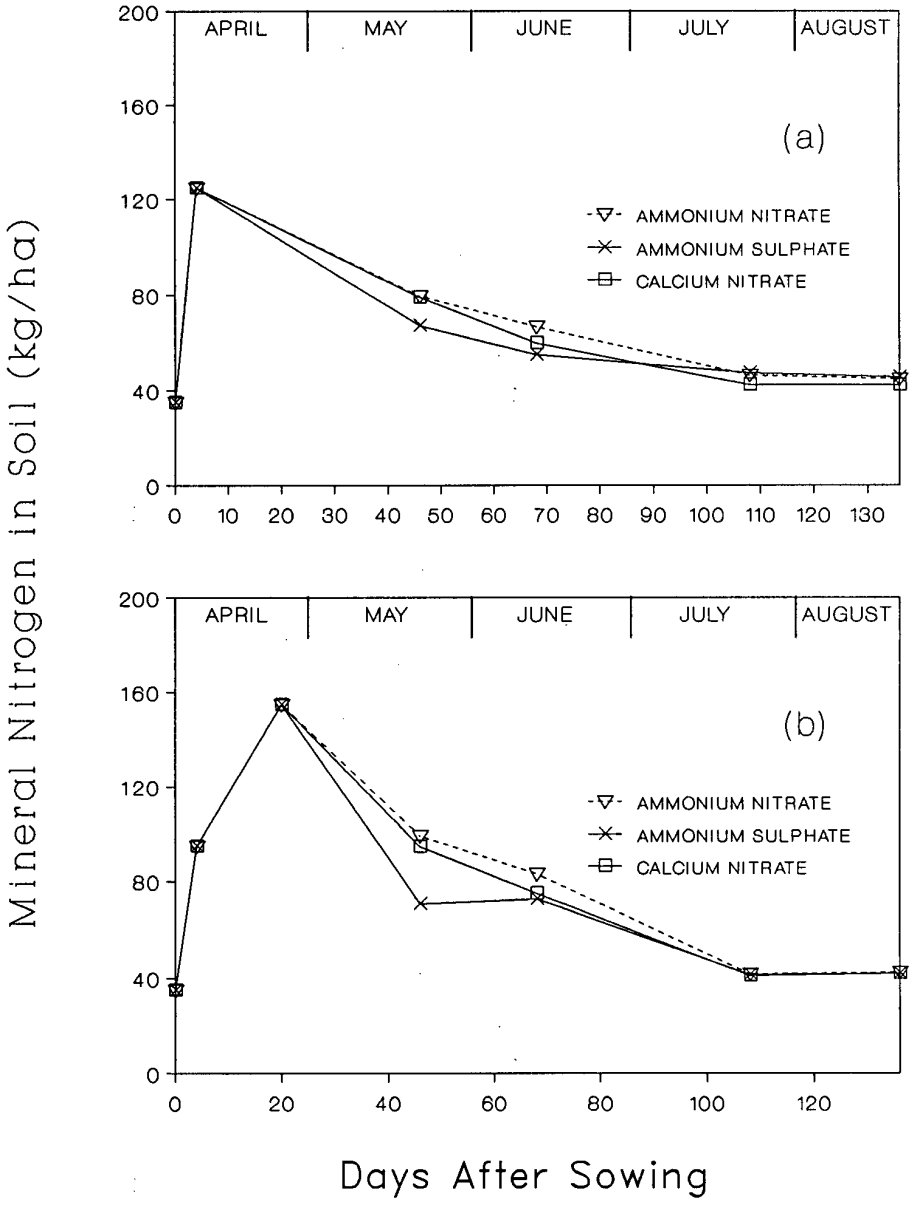


Figure A24. Changes in mineral nitrogen in the soil (0-40 cm) over the growing season, under spring barley, with fertiliser nitrogen applied (a) 90 kg/ha at sowing and (b) 60 kg/ha at sowing and 60 kg/ha at emergence, Upper Cairnie 1989

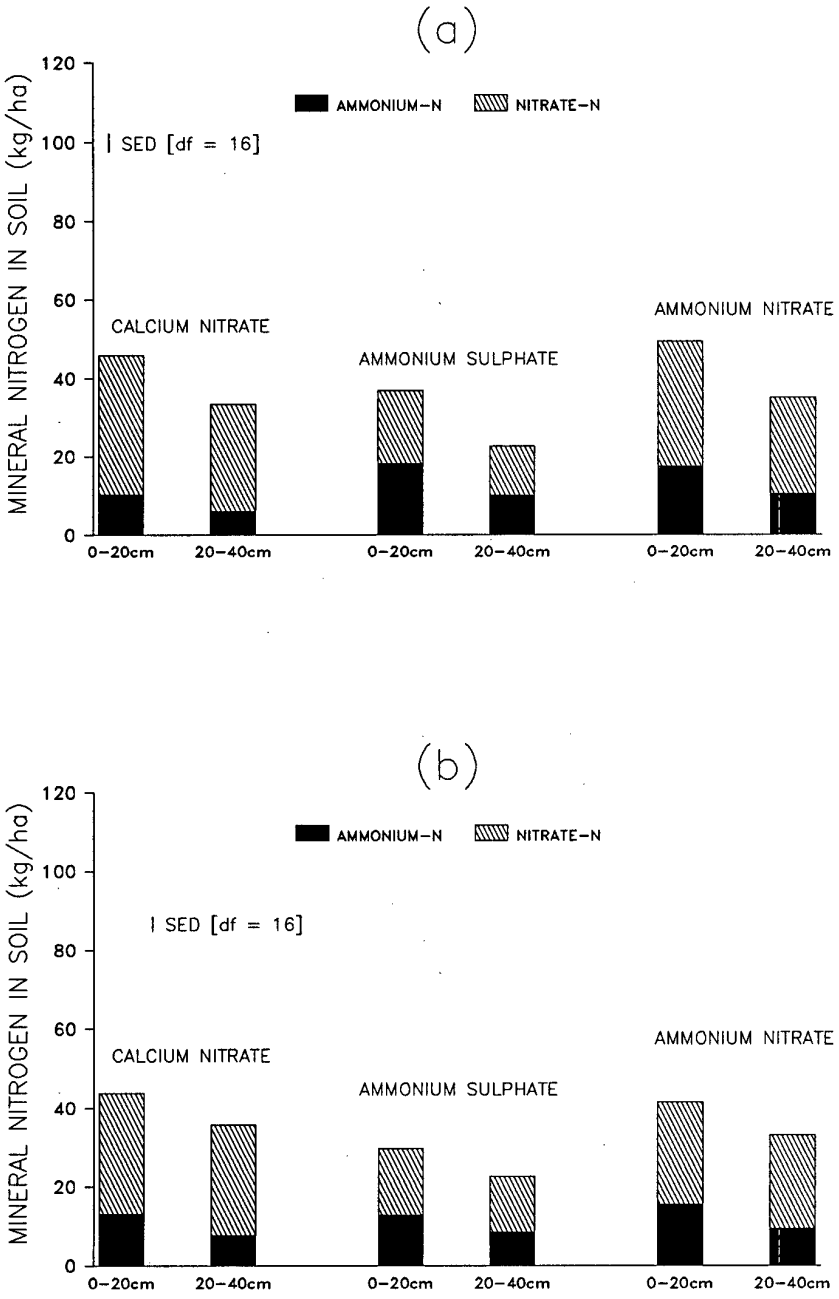
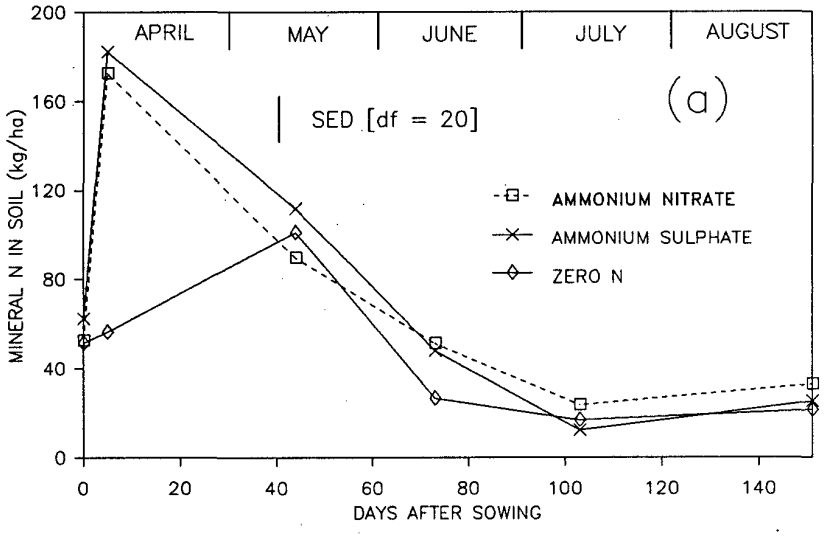


Figure A25. Quantities of nitrate- and ammonium-N at different depths in the soil at first two sampling dates, under spring barley fertilised with 120 kg/ha N fertiliser at sowing, (a) after 48 days (b) after 68 days, Upper Cairnie 1989



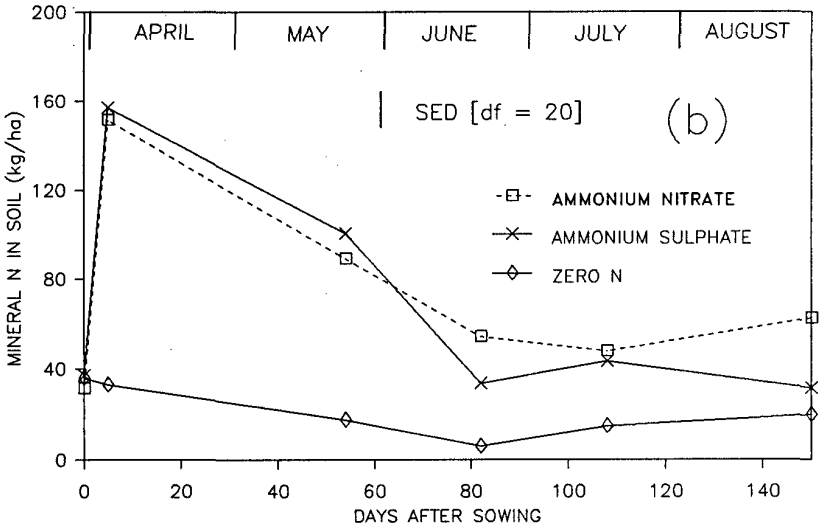


Figure A26. Changes in mineral nitrogen in the soil (0-30 cm) over the growing season, under spring barley, grown with zero or 120 kg/ha fertiliser nitrogen applied at sowing (a) Quixwood and (b) Bush (Crofts), 1990

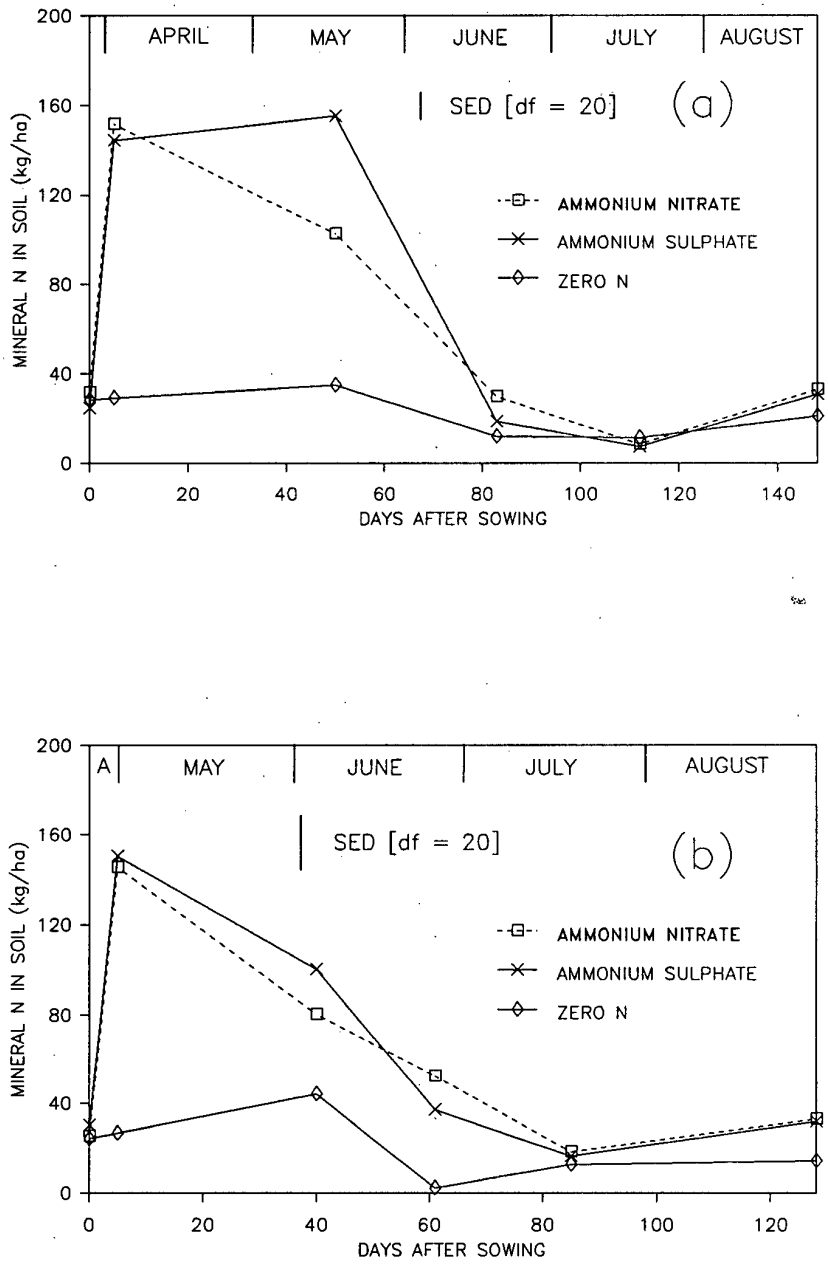


Figure A27. Changes in mineral nitrogen in the soil (0-30 cm) over the growing season, under spring barley, grown with zero or 120 kg/ha fertiliser nitrogen applied at sowing (a) Treaton and (b) Kettle, 1990