HGCA

PROJECT REPORT No. 48

INTEPRETATION OF SITE/TREATMENT EFFECTS ON GROWTH AND N UPTAKE OF WINTER BARLEY IN RELATION TO QUALITY CRITERIA, PARTICULARLY %N IN BARLEY FOR MALTING

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by

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Final report of a three year project which was co-ordinated by R. A. Leigh, AFRC Institute of Arable Crops Research, Rothamsted Experimental Station, Harpenden, Herts., AL5 2JQ. The work commenced in April 1988 and was funded by a grant of £86,772 from the Home-Grown Cereals Authority (Project No. 0080/2/87).

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ABSTRACT

Measurements were made of crop and ear dry matter production and of the uptake of nitrogen and its distribution to the ear in winter barley crops grown with no nitrogen fertiliser or with standard amounts at sites in England and Northern Ireland between 1988 and 1990 in order to develop a better understanding of the site and seasonal variation in the nitrogen percentages in grain for malting.

Crops without nitrogen fertiliser were grown as a guide to the background levels of N available to the crop from non-fertiliser sources in the soil. Large differences in grain yield occurred between sites and years in both these and standardly-fertilised crops. Responses to applied nitrogen were greater where the yields of unfertilised crops were small. Differences in yield were largely attributable to differences in numbers of grain m^{-2} which resulted from differences in the numbers of ears m^{-2}. Differences also occurred between sites and seasons in the nitrogen percentages of the harvested grain, but the responses to applied N were much smaller than for yield.

Large differences occurred in post-anthesis dry matter growth, both in the ears and the whole crop, and in nitrogen uptake. These did not explain the observed large site and season differences in the nitrogen concentrations of grain, indicating that the latter was influenced more by pre-anthesis growth and nitrogen uptake. There was evidence that N and dry matter accumulation are closely coupled in developing ears of barley when nitrogen supplies are not excessive.

OBJECTIVES

To determine the patterns of growth and nitrogen uptake of winter barley grown with different treatments at several sites. To analyse the results in relation to current knowledge of the relationships between N content and growth. To assess the consequences of different supplies of N in the soil and patterns of N uptake for the N content of the grain particularly in relation to its use for malting.

INTRODUCTION

Differences in soil, weather and plant factors between sites and seasons influence the patterns of crop growth and N uptake to different extents, with consequent effects on the N content of the grain. For instance, in recent HGCA-funded research on spring barley, Smith & Taggart (1990) concluded that varying the form, rate and timing of fertiliser N applications had only small effects on %N in the grain compared with those of site and season. Soil moisture and N in soil organic matter were considered to be major factors in the latter effects. Similarly, Vaughan (1990) showed that winter barley had smaller grain N concentrations when grown on clay rather than sandy soils but the relationships of grain N to the mineral N content of the soil in autumn and to applied N were not consistent from one year to another. Clearly, crop growth and N supply interact differently to affect grain N in different growing seasons and an understanding is needed of the underlying processes if grain of malting quality is to be consistently produced from winter barley.

The two factors that determine the percentage of N in the grain are grain size and the amount of N the grain contains. These in turn are determined, respectively, by the amounts carbohydrate produced and of N taken up by the crop and the relative proportions of each that are allocated to the grain. Much of the nitrogen in grain tends to be derived from pre-anthesis uptake whereas much of the carbohydrate is derived from post-anthesis photosynthesis (Carreck & Christian, 1987). N content may be affected by conditions that affect the supply and uptake of both soil and fertiliser-derived nitrate while growth will be influenced by the effects of seasonal weather on photosynthesis and the duration of grain growth.

The aim of this analysis was to collect, from on-going HGCA-funded experiments, minimum sets of data that would allow an initial assessment of how far the effects of site and season on the malting quality of winter barley could be explained by differences in the pre- and post-anthesis acquisition of carbohydrate and nitrogen and differences in their partitioning to grain.

MATERIALS AND METHODS

The data were collected from existing experiments which tested different nitrogen fertiliser practices at a range of sites between 1988 and 1990. Details of these experiments are given in Table 1. The measurements were confined to plots given no fertiliser N (N_0) since these provided an indication of the soil supply, and to plots given a application of N considered to be optimum for the site. The standard N applications (N_S) ranged from 85 to 125 kg N ha^{-1} depending on site and year. Different varieties were studied in the three years. Pipkin, Magie and Igri were studied in 1988 since these experiments were already sown. Magie was grown at all sites in 1989 and 1990 except for the ADAS site at Potton in 1989 which had Pipkin and Rothamsted in 1990 which grew Halcyon. There was no experiment at the Potton site in 1990. All crops were fully protected against disease and received a growth regulator if necessary. The following minimum set of measurements were made on each crop:

1. Total crop dry mass and ear dry mass, and the N contents of both fortnightly from N application to anthesis and weekly thereafter.

2. Grain yield, estimates of the components of grain yield, and grain N.

Additional, optional measurements included shoot numbers, patterns of grain growth, projected green area index and intercepted radiation.

The nitrogen treatments were applied at GS 30 just prior to the start of stem extension. In the present analysis, the following parameters of crop growth and N utilisation were calculated and related to yield and grain N% :-

a) crop dry mass and N content at GS 30 as a measure of over-winter growth and N uptake;

b) crop dry mass and N content at anthesis and the changes between GS 30 and anthesis as measures of pre-anthesis growth and N uptake;

c) final crop dry mass and N content at harvest and the changes between anthesis and harvest as measures of post-anthesis growth and N uptake; and

d) ear dry mass and N content at anthesis and harvest and the increments in both as measures of the amounts of dry matter and N partitioned to the ear during pre- and post-anthesis growth.

RESULTS AND DISCUSSION

Data for crop yields and components of yield for the two N treatments at each site and in each year are given in Tables 2 and 3, the seasonal patterns of growth and N uptake in Figs 1-5, and the derived pre- and post-anthesis dry matter and nitrogen increments in Tables 4-9.

Grain Yield and Grain N

Combine yields were not always taken. Grain yields from hand-harvested samples generally correlated well with combine yields at those sites where both were measured. Hand-harvest yields are used here. On average, yields were larger in 1989 and 1990 than 1988 especially in the N_0 crops. Across sites, yields of N_0 crops ranged from 1.5 to 3.0 t ha^{-1} in 1988, from 4.0 to 5.6 t ha^{-1} in 1989, and from 3.4 to 7.0 t ha^{-1} in 1990. The average response in grain yield to applied N was larger in 1988 (2.7 t ha^{-1}) than 1989 (1.9 t ha^{-1}) and 1990 (2.1 t ha^{-1}). Responses to applied N at individual sites ranged from 1.6 to 4.0 t ha^{-1} in 1988, from 1.2 to 3.0 t ha^{-1} in 1989 and from 0.8 to 3.0 t ha^{-1} in 1990 (Tables 2 and 3).

Averaged across all sites, the N_0 crops had higher grain N concentrations in 1989 and 1990 than in 1988 (1.52, 1.50% and 1.38%, respectively). Applied fertiliser N increased concentrations by 0.30% in 1988 and 1989 and by only 0.13% in 1990 (Table 3). At individual sites, the N_0 grain N concentrations ranged from 1.26 to 1.58% in 1988, from 1.25 to 1.77% in 1989 and from 1.26 to 1.61% in 1990, and the responses to applied N ranged from nil at Belfast in any year to an increase of 0.60% at Sutton Bonington in all three years (Table 2). Only four out of the six N_S crops would have met the malting requirement of 1.6% N in 1988 (two of Pipkin and two of Magie), three out of the six in 1989 (all Magie), and one out the six in 1990. There was no consistent difference between varieties. Of the three varieties tested in 1988 with standard rates of fertiliser, only the Igri grown at Sutton Bonington would have failed to meet an upper grain limit of 1.8% N, but in 1990 samples of Magie from Sutton Bonington and Halcyon from Rothamsted would also have failed.

The N_0 crops were grown and analysed to provide background information on the inherent capacities of the soils at the different sites to supply the crop with nitrogen from mineral N remaining from previous crops or mineralised from soil organic matter. If basal levels of soil N were a major factor that affected grain yields and %N, then the responses of both to applied N would be expected to be greater at sites where N_0 yields and %N values were low.

The growth of the N_0 crops was almost certainly restricted by the capacities of the soil at the different sites to supply N. In these crops, yield was generally proportional to their total N uptake (Fig. 6*a*) and the greatest responses to applied fertiliser were obtained at sites and in years where the yields of the N_0 crops were small (Fig. 6*b*). Yields were not increased by additional N at Sutton Bonington in 1989 because of a heavy infection with BYDV. Larger yields of grain, whether due to site, season or N application, resulted from an increase in the numbers of grain m^{-2} rather than grain size and the increased number of grains from more ears being present rather than each ear having more grains (Table 2).

Grain yields responded more to applications of fertiliser N than did the concentrations of N in the grain and larger yields of grain were not obviously associated with a low percentage of N, irrespective of whether the crops were or were not given fertiliser N (Fig. 7*a*). There was also no obvious relation between the percentage of N in the grain and the N content of the crop at anthesis (Fig. 7*b*). These two observations suggest that the extra N in fertilised crops was used to produce yield rather than grain protein.

Dry Matter Accumulation and Nitrogen Uptake

The main sources of carbon and nitrogen for the developing grain are dry matter and nitrogen accumulated before anthesis and relocated from other parts of the plant, and newly-assimilated photosynthate or soil nitrogen taken up after anthesis. The relative contributions of these to the harvested grain will differ with site and season and affect the nitrogen percentage.

The patterns of total and ear dry matter production and crop and ear N content are shown separately for the N_0 and N_s crops from each site in each year in Figs 3-5. The growth curves for crop dry matter were similar in shape with slow early growth, followed by linear growth from stem extension (GS 30) to anthesis and very little net increase in dry matter during the final stages. Growth in ear dry weight followed a similar sigmoid pattern but with very noticeable differences between sites and years, largely because of differences in ear number.

In an analysis of the relationships between crop dry matter production and N uptake and grain growth and N percentage, it is convenient to distinguish between the dry matter supply to developing ear that is accumulated in other parts of the plant prior to anthesis and subsequently relocated to the developing ears, and that which is produced following anthesis. Nitrogen supply can similarly be analysed in terms of that taken up before anthesis and that taken up after. The relative contributions of post-anthesis carbon and N accumulation to ear may differ between sites and seasons and underlie the differences in grain N concentrations. The results were analysed to test this possibility.

It has been suggested that N uptake ceases at anthesis in barley[3]. In most, but not all, of the crops in the present series of experiments, the N content increased after anthesis by amounts ranging from 8 to 144 kg ha^{-1}. The calculated values for ear and total dry matter and ear and total N at GS 30, anthesis and maturity and the increments in dry matter and N between GS 30 and anthesis and anthesis and maturity are given in Tables 4-9. In healthy N_0 crops, the increase in ear dry matter between anthesis and maturity ranged from 154 g m^{-2} at Rothamsted in 1988 to 870 g m^{-2} at Sutton Bonington in 1990, and in healthy N_S crops from 250 g m^{-2} in 1989 to 961 g m^{-2} in 1990, both at Sutton Bonington. During the same time, the increase in ear nitrogen at sites for which data is available ranged, in N_0 crops, from 1.86 g m^{-2} at Potton in 1988 to 12.23 g m^{-2} at Sutton Bonington in 1990, and in the N_S crops from 6.75 g m^{-2} at Belfast to 15.49 g m^{-2} at Sutton Bonington, both in 1990. Despite the large differences in both dry matter and nitrogen accumulation in the ear during post-anthesis growth, the ratio of nitrogen:dry matter in all crops ranged only between 13 and 18 mg N g^{-1} dry matter. Neither the differences in post-anthesis N uptake or dry matter growth either in the ear or the crop as a whole appeared to be obviously relatable to the nitrogen percentage of the grain (Figs 8*a* and 8*b*). This suggests that N and dry matter accumulation are closely coupled in developing ears of barley when nitrogen supplies are not excessive.

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Table 1. Agronomic details of experimental crops of winter barley grown at different sites between 1988 and 1990

Institution :	Belfast University	Newcastle University	Nottingham University	IACR Rothamsted	ADAS Cambridge	
Collaborator:	E White	E J Evans	D Stokes	G Milford	R Sylvester-Bradley	
Site :	Crossna-creevy	Cockle Park	S Bonington	Rothamsted	Blunham	Potton
1987/88						
Variety	Pipkin	Magie	Igri	Magie	Magie	Pipkin
Sowing date	03-11-87	28-09-87	26-09-87	25-09-87	01-10-87	22-10-87
kgN/ha	0, 120	0, 100	0, 120	0, 125	0, 120	0, 120
N applied	07-04-88	05-04-88	31-03-88	14-03-88	17-03-88	16-03-88
PGR	Terpal 25-04-88	Terpal 27-05-88	None	None	Terpal 05-05-88	Terpal 07-05-88
ZGS 30	25-04-88	04-04-88	31-03-88	29-03-88		
50% Anthesis	01-06-88	31-05-88	04-06-88	01-06-88	10-05-88	07-05-88
Harvest	01-08-88	05-08-88	18-07-88	25-07-88	21-07-88	13-07-88
1988/9						
Variety	Magie	Magie	Magie	Magie	Magie	Pipkin
Sowing date	24-11-88	18-09-88		20-09-88	19-10-88	18-10-88
kgN/ha	0, 120	0, 100	0, 120	0, 85	0, 120	0, 120
N applied	31-03-89	15-03-89	27-04-89	14-03-89	15-03-89	
PGR	Terpal 10-5-89		None	None	Chlormequat 25-03-89	Terpal 01-05-89
ZGS 30	26-04-89	15-03-89	03-04-89	04-04-89	05-04-89	05-04-89
50% Anthesis	10-06-89	25-05-89	06-06-89	18-05-89	21-05-89	16-05-89
Harvest	25-07-89	19-07-89	17-07-89	10-07-89	13-07-89	13-07-89
1989/90						
Variety	Magie	Magie	Magie	Halcyon	Pipkin	
Sowing date	17-10-89	15-09-89	02-10-89	21-09-89	19-09-89	
kgN/ha	0, 120	0, 100	0, 120	0, 100	0, 120	
N applied	16-03-90	12-03-90	19-03-90	14-03-90	15-03-90	
PGR	Terpal 30-04-90	Terpal 12-05-90	None	None	Chlormequat 16-03-90	
ZGS 30	23-04-90	12-03-90	12-03-90	02-04-90	10-04-90	
50% Anthesis	24-05-90	21-05-90	24-05-90	21-05-90	09-05-90	
Harvest	23-07-90	23-07-90	31-07-90	26-07-90	17-07-90	

Table 2. Yields, components of yield and grain N of winter barley crops grown at different sites between 1988 and 1990 with no fertiliser N or with standard applications of fertiliser N

Site	Variety *	Year	kgN/ha applied	Total DM G/M²	Harvest Index %	Ear DM g/m²	Ear Number m⁻²	Grains/ ear	Grains/ m²	Means Grain Height mg	Grain yield g/m²	Combine g/m²	Grain N %	Grain N g/m²
Belfast	P	1988	0	296.5	49.9	*	333.0	14.0	4659	31.2	145.9	176.0	1.32	1.93
	M	1989	0	921.0	44.9	473.7	602.3	15.3	9220	40.7	412.0	*	1.45	5.97
	M	1990	0	767.6	52.0	460.6	748.0	15.5	11538	34.6	399.9	384.4	1.43	5.72
Newcastle	M	1988	0	549.0	57.2	*	462.3	15.7	7266	40.7	295.8	*	1.40	4.14
	M	1989	0	691.8	68.9	473.0	724.3	18.0	12676	37.6	483.3	*	1.44	6.96
	M	1990	0	854.9	57.8	*	832.1	16.1	13261	40.0	493.9	546.1	1.34	6.62
Sutton B	I	1988	0	453.7	35.8	187.5	431.5	14.5	6242	27.6	161.8	181.5	1.58	2.56
	M	1989	0	975.7	47.3	517.2	919.5	16.2	14887	33.7	460.2	442.5	1.77	8.15
	M	1990	0	1360.4	51.2	777.6	853.0	20.0	17076	40.8	697.6	564.0	1.49	10.39
Rothamsted	M	1988	0	394.8	53.4	373.6	343.1	16.4	5703	36.7	215.0	*	1.37	2.95
	M	1989	0	686.0	58.6	469.7	632.9	19.2	12160	33.0	401.0	345.0	1.62	6.50
	H	1990	0	426.3	79.4	297.7	418.1	15.2	6433	38.1	339.6	*	1.53	5.20
Blunham	M	1988	0	602.4	49.8	369.2	527.2	17.3	9075	33.1	299.0	266.1	1.37	4.10
	M	1989	0	1009.2	55.6	641.2	1005.5	16.3	16361	34.2	561.0	455.6	1.60	8.98
	P	1990	0	1296.7	27.5	441.6	1347.3	9.1	12241	29.1	355.9	*	1.73	6.16
Potton	P	1988	0	289.2	57.1	167.8	413.9	12.5	5196	31.2	164.7	136.9	1.26	2.08
	P	1989	0	786.0	54.5	510.8	1041.2	15.0	14535	29.4	429.1	318.8	1.25	5.36
		Year.site SED		82.70			67.40	1.360	1234	1.410	45.80		0.09700	
Belfast	P	1988	120	1108.3	36.4	*	854.7	14.5	12049	33.3	402.3	502.0	1.35	5.43
	M	1989	120	1575.3	43.1	757.0	803.7	17.2	13864	42.4	674.7	*	1.54	10.30
	M	1990	120	1082.8	53.5	588.2	979.2	17.9	17567	34.0	576.5	568.7	1.37	7.90
Newcastle	M	1988	120	1114.0	52.5	*	689.3	18.0	12291	43.8	538.6	*	1.81	9.75
	M	1989	120	1417.0	54.6	891.6	970.3	19.0	18493	41.6	790.0	*	1.52	12.01
	M	1990	120	1263.3	57.1	*	1074.4	18.1	19376	38.7	720.7	750.3	1.58	11.39
Sutton B	I	1988	120	806.5	40.2	370.0	663.5	16.2	10742	30.4	324.0	374.7	2.18	7.06
	M	1989	120	988.2	47.8	533.5	1001.3	15.5	15519	33.2	471.2	505.0	2.41	11.36
	M	1990	120	1561.9	49.6	861.8	1037.0	19.9	20625	37.5	774.6	569.8	1.88	14.56
Rothamsted	M	1988	120	1005.7	52.0	892.4	611.1	20.4	12398	42.3	526.7	*	1.60	8.43
	M	1989	120	1160.8	55.7	730.9	836.2	21.7	18119	35.6	643.5	657.0	1.55	9.97
	H	1990	120	901.7	70.7	554.7	609.8	18.0	10967	42.0	639.6	*	1.87	11.96
Blunham	M	1988	120	1245.6	46.4	641.9	768.6	21.3	16306	34.9	568.5	494.7	1.46	8.30
	M	1989	120	1383.6	49.4	790.7	1277.9	18.7	24014	28.9	683.3	639.2	1.93	13.19
	P	1990	120	1730.3	35.5	562.7	1186.3	19.7	23245	26.2	610.3	*	1.47	8.97
Potton	P	1988	120	1146.4	49.1	604.8	918.2	18.5	16912	33.3	562.4	440.3	1.67	9.39
	P	1989	120	1208.0	50.2	692.0	1239.1	15.7	19491	30.9	610.3	474.3	1.88	11.47
		Year.site SED		109.0			74.10	1.420	1410	1.380	54.00		0.1120	

* Varieties: P = Pipkin; M = Magie; I = Igri; H = Halcyon

Table 3. Differences betwen sites and years in yield, components of yield and grain N of winter barley grown with no fertiliser (No) or with standard applications of fertiliser N (Ns)

	Yield g/m²		Grain %N		Ear No. m²		Grains per ear		Grain No. m²		Grain wt mg	
N Applied	No	Ns	No	Ns	No	Ns	No	Ns	No	Ns	No	Ns
Site												
Belfast	319.3	551.2	1.40	1.42	561	879	14.9	16.5	8472	14493	35.5	36.5
Newcastle	424.3	683.1	1.39	1.64	673	911	16.6	18.4	11101	16720	39.4	41.4
Sutton Bonington	439.9	523.3	1.61	2.16	735	901	16.9	17.2	12735	15629	34.0	33.7
Rothamsted	318.5	603.3	1.51	1.67	465	686	16.9	20.0	8099	14161	35.9	40.0
Blunham	405.3	620.7	1.57	1.62	960	1078	14.2	19.9	12559	21188	32.1	30.0
* Potton	295.9	586.4	1.26	1.78	728	1079	13.8	17.1	9866	18202	30.3	32.1
SED	30.96	36.49	0.0656	0.0757	45.6	50.1	0.916	0.956	834.2	953.2	0.950	0.932
Year												
1988	213.7	487.1	1.38	1.68	419	751	15.1	18.2	6357	13450	33.4	36.3
1989	457.8	645.5	1.52	1.81	821	1021	16.7	18.0	13307	18250	34.8	35.4
+ 1990	397.4	664.3	1.50	1.63	840	977	15.2	18.7	12110	18356	36.5	35.7
SED	20.69	24.39	0.0439	0.0506	30.4	33.5	0.612	0.639	557.5	637.1	0.635	0.623

* 1988/1989 only
+ excludes Potton

Table 4. Crop dry weight at GS 30 and anthesis and the corresponding increments in dry weight of winter barley crops grwon with no fertiliser N (No) or standard applciations of fertiliser (Ns) at different sites between 1988 and 1990)

	Date - Julian days		No		Ns	
	GS 30	50% Anthesis	ZGS 30 (G/M^2)	50% Anth. (g/m^2)	ZGS 30 (g/m^2)	50% Anth. (g/m^2)
1988						
Belfast	116					
Blunham	*	158	44.8	269.8	75.9	953.5
Newcastle	97	128	*	345.4	*	701.4
Potton	*	152	98.3	404.4	98.3	831.9
Rothamsted	89	128	*	132.1	*	470.3
Sutton Bonington	91	153	80.4	237.5	85.1	744.6
		156	95.0	610.2	95.0	846.7
1989						
Belfast	116	165	127.3	578.3	200.0	1206.7
Blunham	95	142	74.9	524.3	101.2	762.9
Newcastle	80	146	138.4	649.3	142.3	961.5
Potton	95	137	52.9	374.4	49.2	568.9
Rothamsted	94	142	182.0	395.6	285.0	858.5
Sutton Bonington	93	156	87.9	988.2	110.7	110.7
1990						
Belfast	113	148	234.6	564.6	314.7	1082.9
Blunham	100	129	305.4	405.0	379.2	701.6
Newcastle	71	141	120.7	511.6	141.3	683.1
Potton	*	*	*	*	*	*
Rothamsted	93	141	83.2	266.9	115.5	650.1
Sutton Bonington	71	141	119.3	990.8	152.0	1115.6

Table 5. Crop dry weights at anthesis and maturity and the corresponding increments in dry weight of winter barley crops grown with no fertiliser N (No) or standard applications of fertiliser N (Ns) at different sites between 1988 and 1990

	Date - Julian days		No		Ns	
	50% Anthesis	Harvest	50% Anth. (g/m^2)	Harvest (g/m^2)	50% Anth. (g/m^2)	Harvest (g/m^2)
1988						
Belfast	158	214	269.8	349.9	953.53	1152.3
Blunham	128	203	345.4	602.5	701.4	1140.8
Newcastle	152	207	404.4	789.1	831.9	1340.5
Potton	128	195	132.1	289.2	470.3	1146.4
Rothamsted	153	196	237.5	330.3	744.6	1013.7
Sutton Bonington	156	210	610.2	453.7	846.7	806.5
1989						
Belfast	165	204	564.6	864.9	1082.9	1110.2
Blunham	142	198	405.0	1296.6	701.6	1730.7
Newcastle	146	183	511.6	813.1	683.1	1484.5
Potton	137	*	*	*	*	*
Rothamsted	142	207	266.9	426.2	650.1	901.5
Sutton Bonington	156	191	990.8	1599.8	1115.6	1797.3
1990						
Belfast	148	204	564.6	864.9	1082.9	1110.2
Blunham	129	198	405.0	1296.6	701.6	1730.7
Newcastle	141	183	511.6	813.1	683.1	1484.5
Potton	*	*	*	*	*	*
Rothamsted	141	207	266.9	426.2	650.1	901.5
Sutton Bonington	141	191	990.8	1599.8	1115.6	1797.3

Table 6 Crop nitrogen contents at GS 30 and anthesis and the corresponding increments in dry weight of winter barley crops grown with no fertiliser N (No) or stgandard applications of fertiliser N (No) at different sites between 1988 and 1990

	Date - Julian Days		No		Ns	
	ZGS 30	50% Anthesis	ZGS 30 (g/m²)	50% Anth. (g/m²)	ZGS 30 (g/m²)	50% Anth. (g/m²)
1988						
Belfast	116	158	1.11	2.07	3.86	9.30
Blunham	*	128	*	4.25	*	14.37
Newcastle	97	152	2.47	4.60	*	10.47
Potton	*	128	*	1.57	*	9.73
Rothamsted	89	146	2.17	3.11	7.26	13.19
Sutton Bonington	91	156	*	*	*	*
1989						
Belfast	116	165	2.77	3.48	8.92	9.93
Blunham	95	142	1.86	7.15	4.04	13.51
Newcastle	80	146	*	4.91	*	10.63
Potton	95	137	1.29	3.47	2.15	8.90
Rothamsted	94	142	3.54	4.36	11.69	10.89
Sutton Bonington	93	156	9.12	10.66	1.15	15.60
1990						
Belfast	113	148	4.35	7.20	10.48	14.75
Blunham	100	129	3.89	3.00	11.18	8.94
Newcastle	71	141	5.61	5.87	11.73	9.67
Potton	*	*	*	*	*	*
Rothamsted	93	141	*	*	*	*
Sutton Bonington	71	141	6.33	10.97	7.34	15.01

Table 7 Crop nitrogen contents at anthesis and maturity and the corresponding increments in dry weight of winter barley crops grown with no fertiliser N (No) or standard applications of fertiser N (Ns) at different sites between 1988 and 1990

	Date - Julian days		No		Ns	
	50% Anthesis	Harvest	50% Anth. (g/m^2)	Harvest (g/m^2)	50% Anth. (g/m^2)	Harvest (g/m^2)
1988						
Belfast	158	214	2.07	2.78	9.30	7.84
Blunham	128	203	4.25	6.09	14.37	12.59
Newcastle	152	207	4.60	6.00	10.47	9.94
Potton	128	195	1.57	2.49	9.73	12.56
Rothamsted	153	196	3.11	*	13.19	*
Sutton Bonington	156	210	*	*	*	*
1989						
Belfast	165	200	3.48	2.44	9.93	5.90
Blunham	142	193	7.15	*	13.51	*
Newcastle	146	195	4.91	6.66	10.63	14.18
Potton	137	193	3.47	*	8.90	*
Rothamsted	142	186	4.36	6.53	10.89	14.35
Sutton Bonington	156	198	10.66	*	15.60	*
1990						
Belfast	148	204	7.22	9.61	14.75	11.77
Blunham	129	198	3.00	10.14	8.94	13.70
Newcastle	141	183	5.87	*	9.67	*
Potton	*	*	*	*	*	*
Rothamsted	141	207	*	*	*	*
Sutton Bonington	141	191	10.97	18.05	15.01	23.70

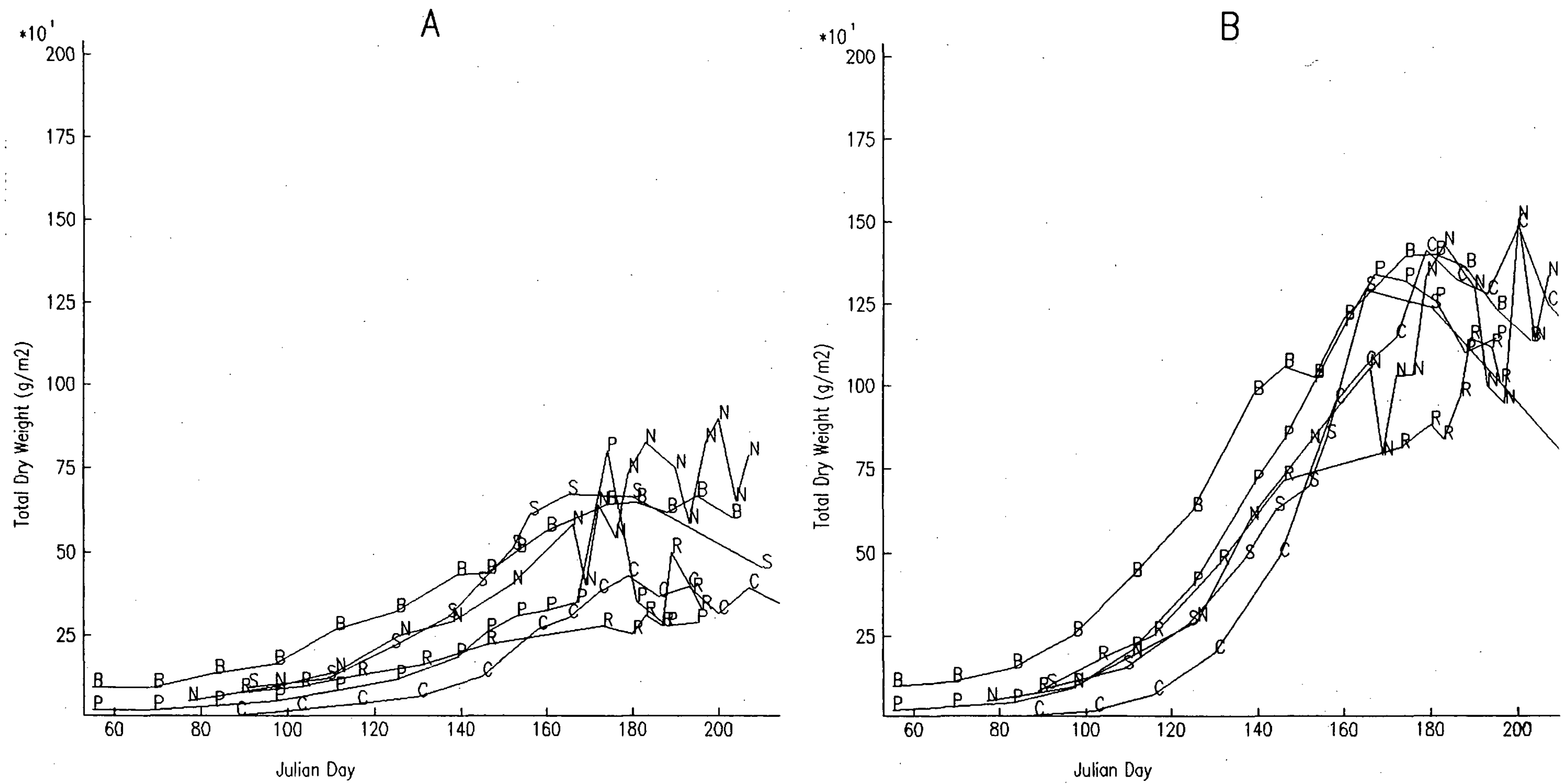
Table 8 Ear dry weights at anthesis and maturity and the coresponding increments in ear dry weight of winter barley crops grown with no fertiliser N (No) or stdanard applications of fertiliser N (Ns) at different sites between 1988 and 1990

	Date - Julian days		No		Ns	
	50% Anthesis	Harvest	50% Anth. (g/m^2)	Harvest (g/m^2)	50% Anth. (g/m^2)	Harvest (g/m^2)
1988						
Belfast	158	214	*	*	*	*
Blunham	128	203	40.6	369.2	106.7	641.9
Newcastle	152	207	83.2	562.8	121.9	921.0
Potton	128	195	8.7	167.7	44.4	604.9
Rothamsted	153	196	48.6	202.3	116.1	586.3
Sutton Bonington	156	210	119.3	187.5	153.3	370.0
1989						
Belfast	165	200	97.2	506.0	148.3	763.0
Blunham	142	193	43.8	641.2	32.5	790.7
Newcast;e	146	195	105.0	473.0	134.8	891.6
Potton	137	193	35.0	510.8	101.1	692.0
Rothamsted	142	186	95.7	432.8	172.4	844.0
Sutton Bonington	156	198	259.5	516.7	283.7	533.5
1990						
Belfast	148	204	76.4	519.9	117.4	563.2
Blunham	129	198	56.5	441.6	107.8	562.7
Newcastle	141	183	*	*	*	*
Potton	*	*	*	*	*	*
Rothamsted	141	207	13.0	297.5	55.9	554.7
Sutton Bonington	141	191	145.8	1016.2	195.2	1156.5

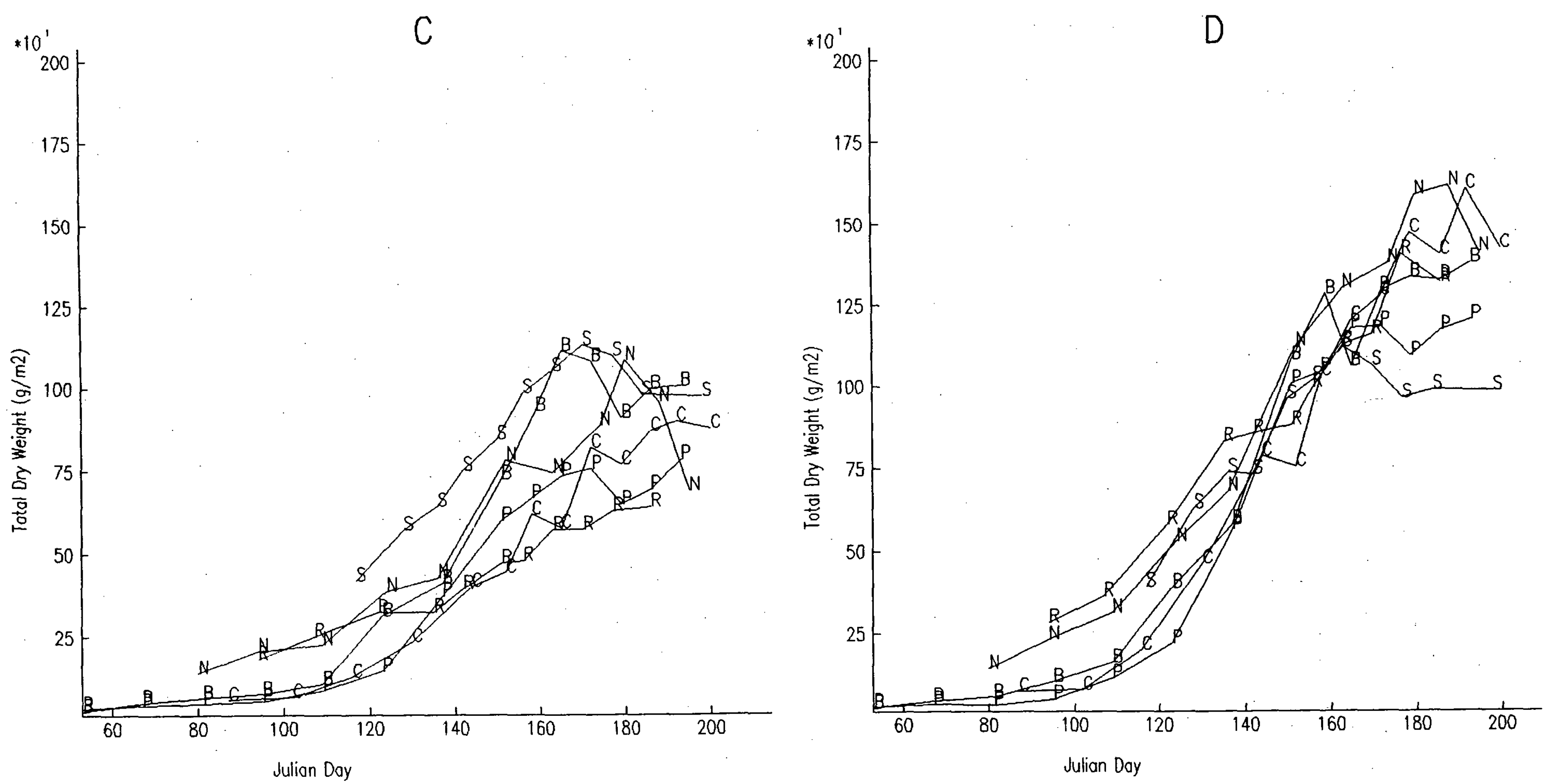
Table 9. Ear nitrogen contents at anthesis and maturity and the correspondong increments in ear N of winter barley crops grown with no fertiliser N (No) or standard fertiliser N (Ns) at different sites between 1988 and 1990 (No)

	Date - Julian days		Ns		Ns	
	50% Anthesis	Harvest	50% Anth. (g/m^2)	Harvest (g/m^2)	50% Anth. (g/m^2)	Harvest (g/m^2)
1988						
Belfast	158	214	*	*	*	*
Blunham	128	203	0.69	5.06	1.94	9.36
Newcastle	152	207	0.46	2.66	0.11	11.11
Potton	128	195	0.22	2.08	0.56	10.09
Rothamsted	153	196	0.49	*	1.13	*
Sutton Bonington	156	210	*	*	*	*
1989						
Belfast	165	200	1.48	7.04	2.38	11.55
Blunham	142	193	0.87	*	1.43	*
Newcastle	146	195	0.98	5.62	1.86	11.52
Potton	137	193	0.04	*	2.27	*
Rothamsted	142	186	1.37	5.81	3.04	12.67
Sutton Bonington	156	198	4.00	*	5.57	*
1990						
Belfast	148	204	1.05	7.48	1.75	8.50
Blunham	129	198	2.20	7.69	0.27	8.35
Newcastle	141	183	*	*	*	*
Potton	*	*	*	*	*	*
Rothamsted	141	207	*	*	*	*
Sutton Bonington	141	191	2.40	14.63	3.93	19.42

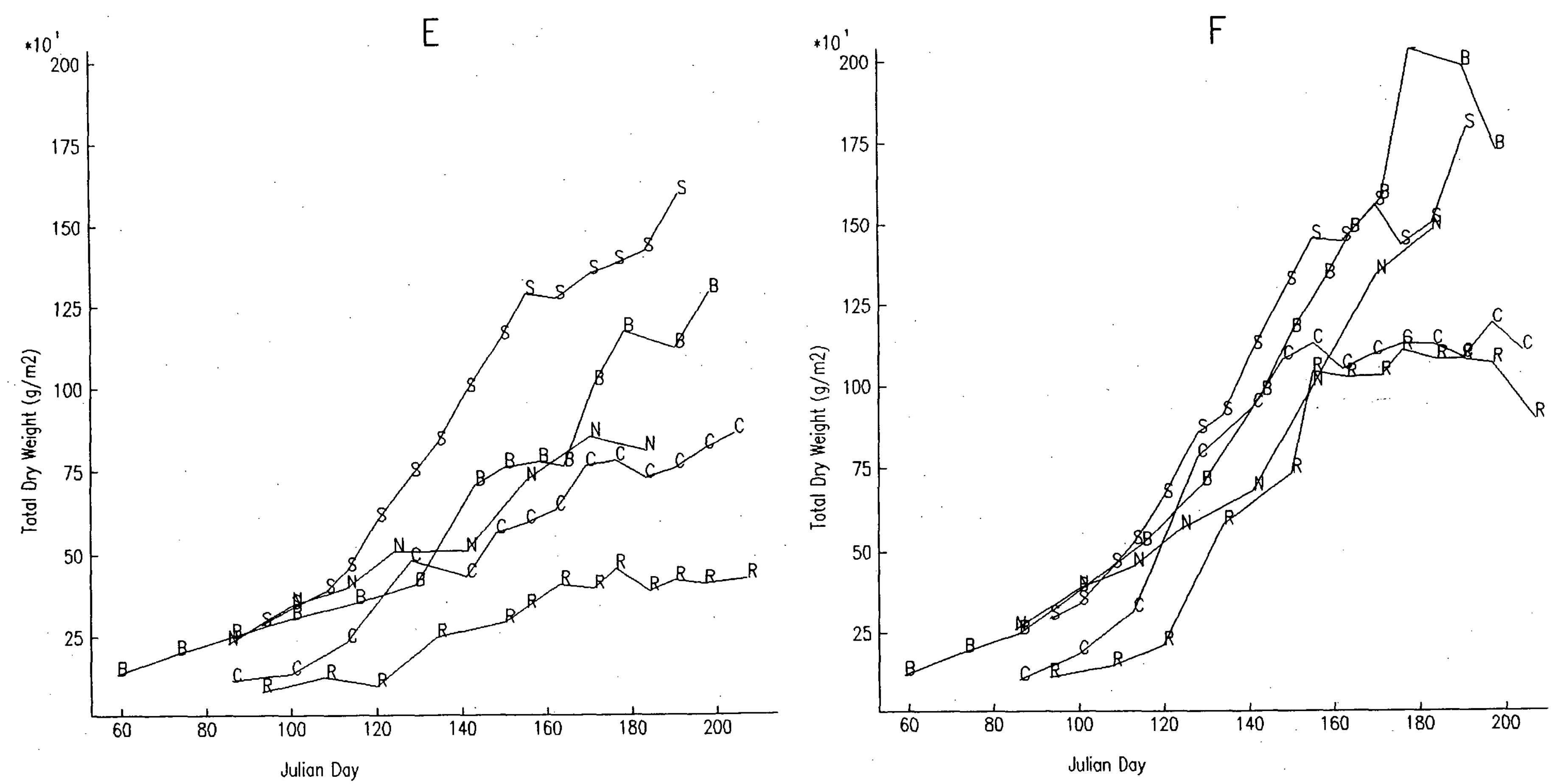
Figs. 1a and 1b. Patterns of crop dry matter accumulation of winter barley grown at Blunham (B), Crossnacreevy near Belfast (C), Newcastle (N), Potton (P), Rothamsted (R), and Sutton Bonington (S) in 1988 with none (Fig.A) or standard (Fig.B) applications of fertiliser N.



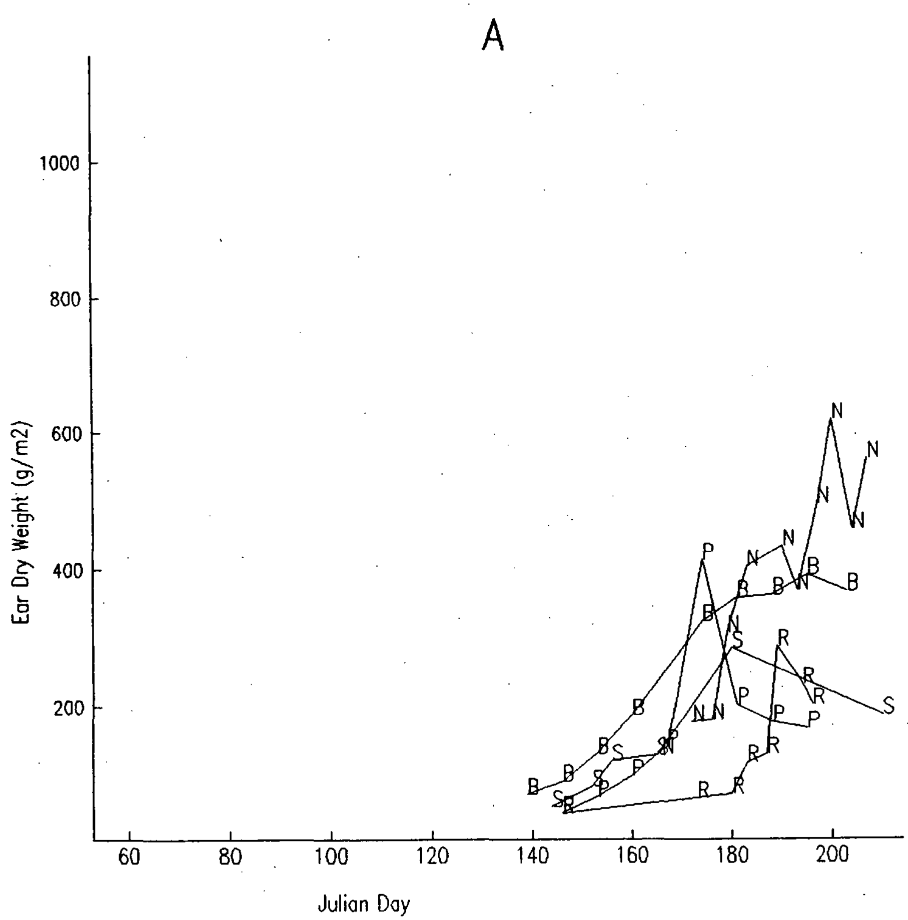
Figs. 1c and 1d. Patterns of crop dry matter accumulation of winter barley grown at Blunham (B), Crossnacreevy near Belfast (C), Newcastle (N), Potton (P), Rothamsted (R), and Sutton Bonington (S) in 1989 with none (Fig.C) or standard (Fig.D) applications of fertiliser N.

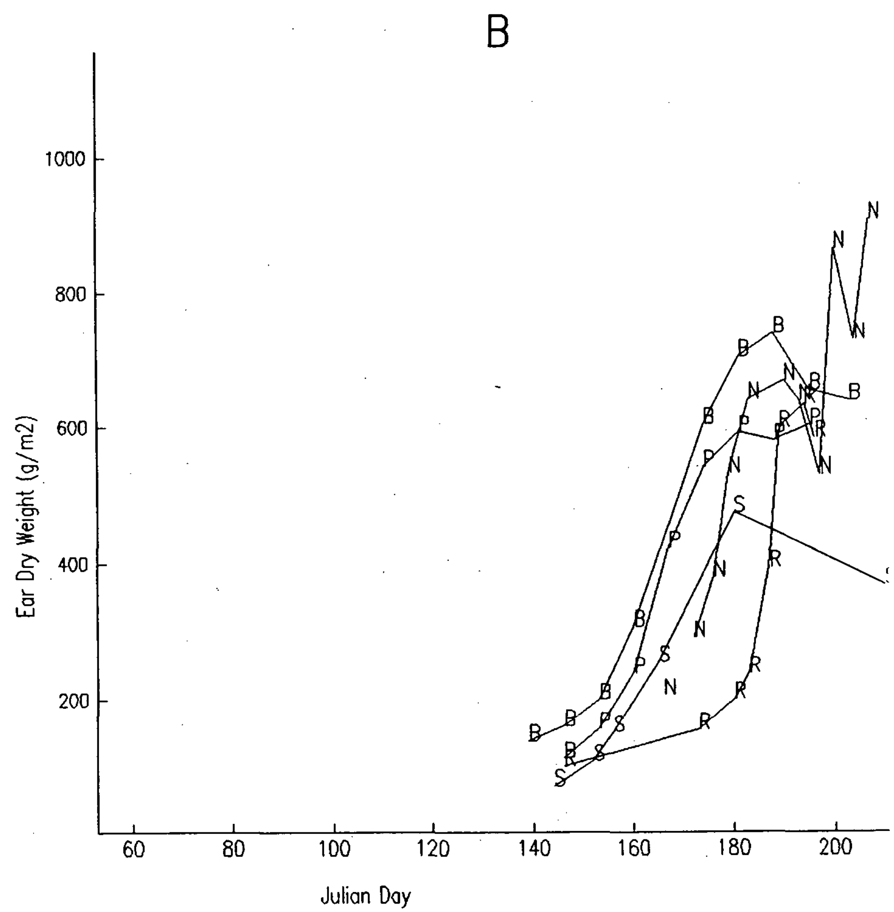


Figs. 1e and 1f. Patterns of crop dry matter accumulation of winter barley grown at Blunham (B), Crossnacreevy near Belfast (C), Newcastle (N), Potton (P), Rothamsted (R), and Sutton Bonington (S) in 1990 with none (Fig.E) or standard (Fig.F) applications of fertiliser N.

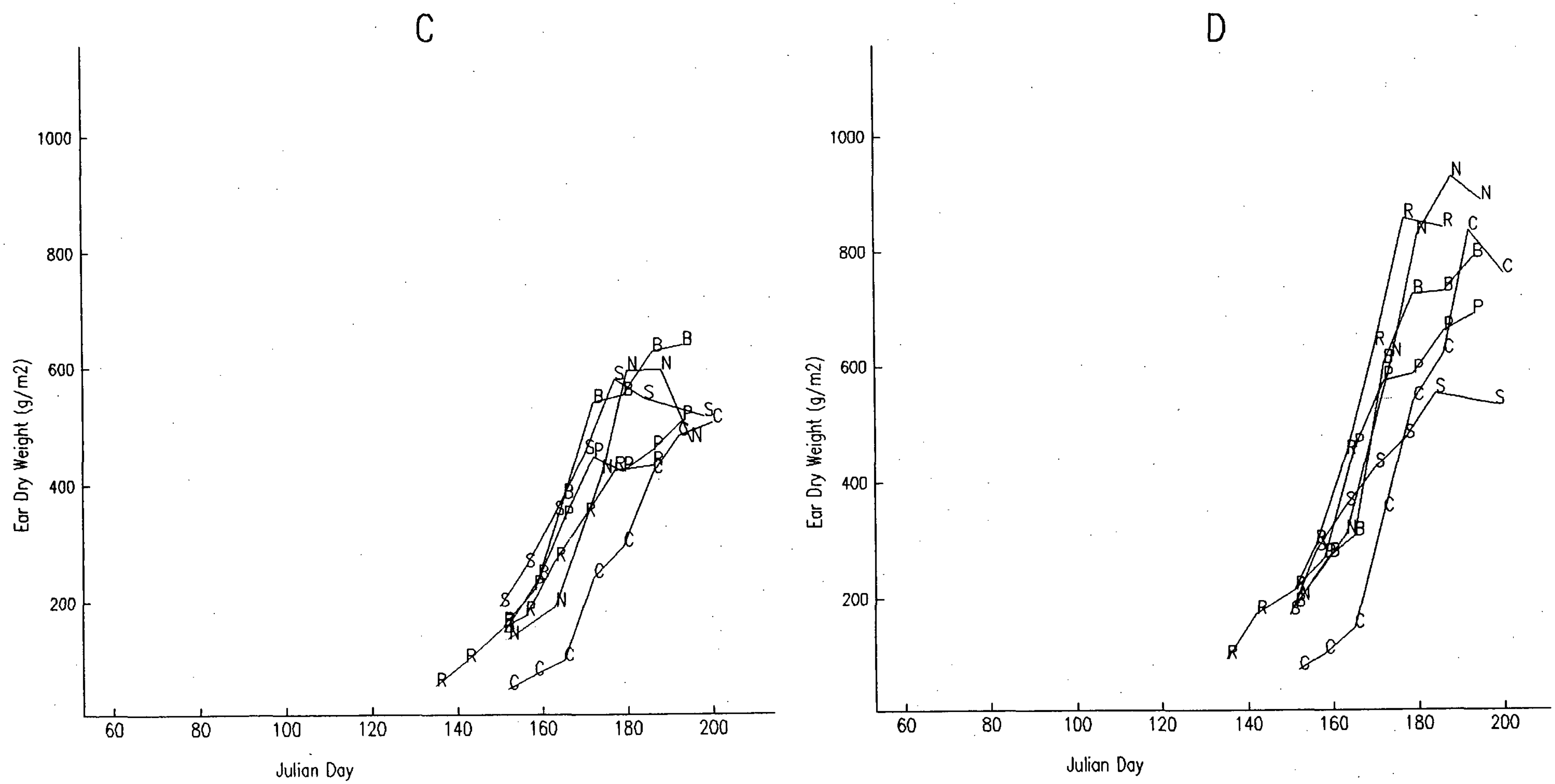


Figs. 2a and 2b. Patterns of ear dry matter accumulation of winter barley grown at Blunham (B), Crossnacreevy near Belfast (C), Newcastle (N), Potton (P), Rothamsted (R), and Sutton Bonington (S) in 1988 with none (Fig.A) or standard (Fig.B) applications of fertiliser N.

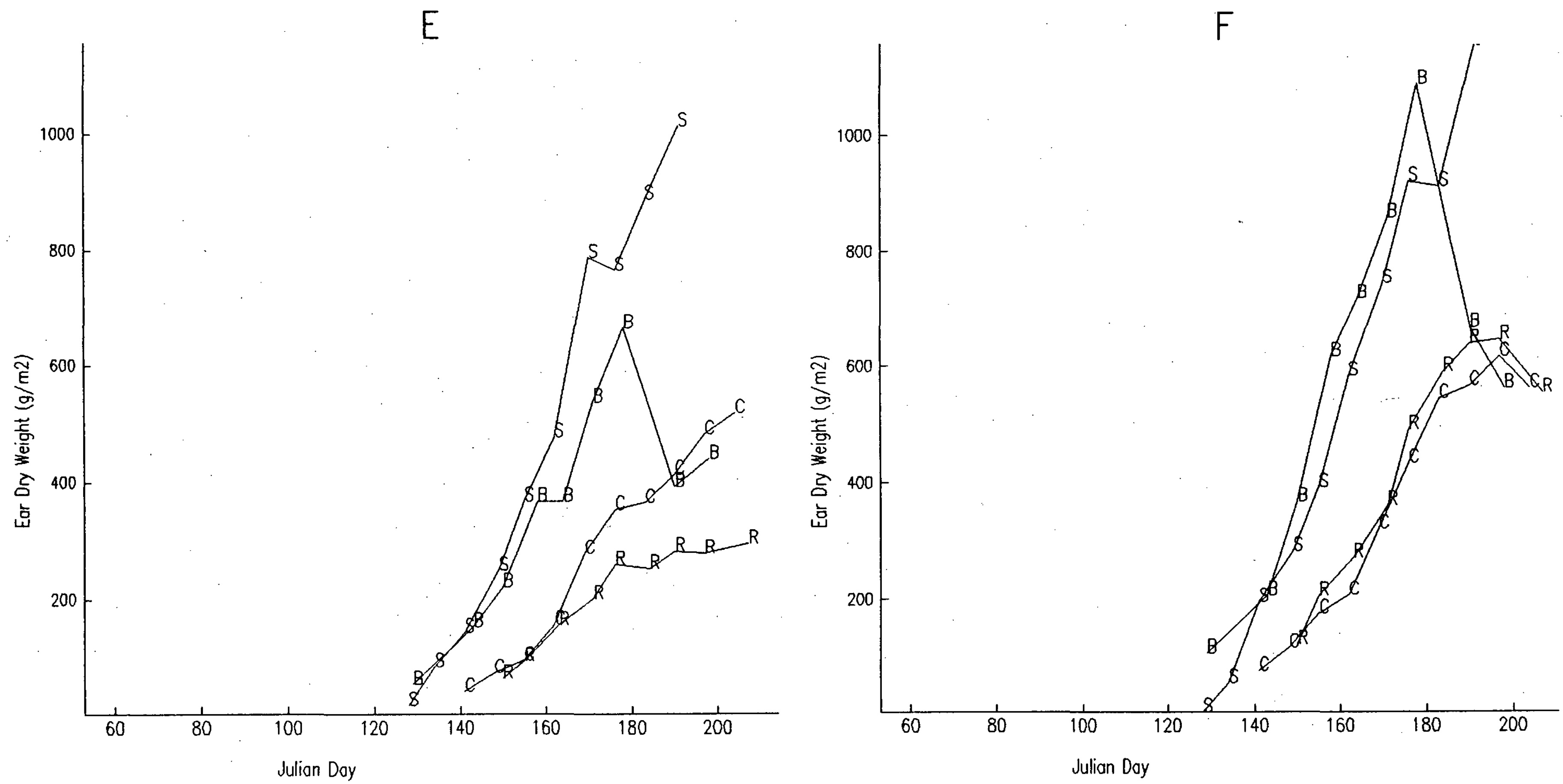




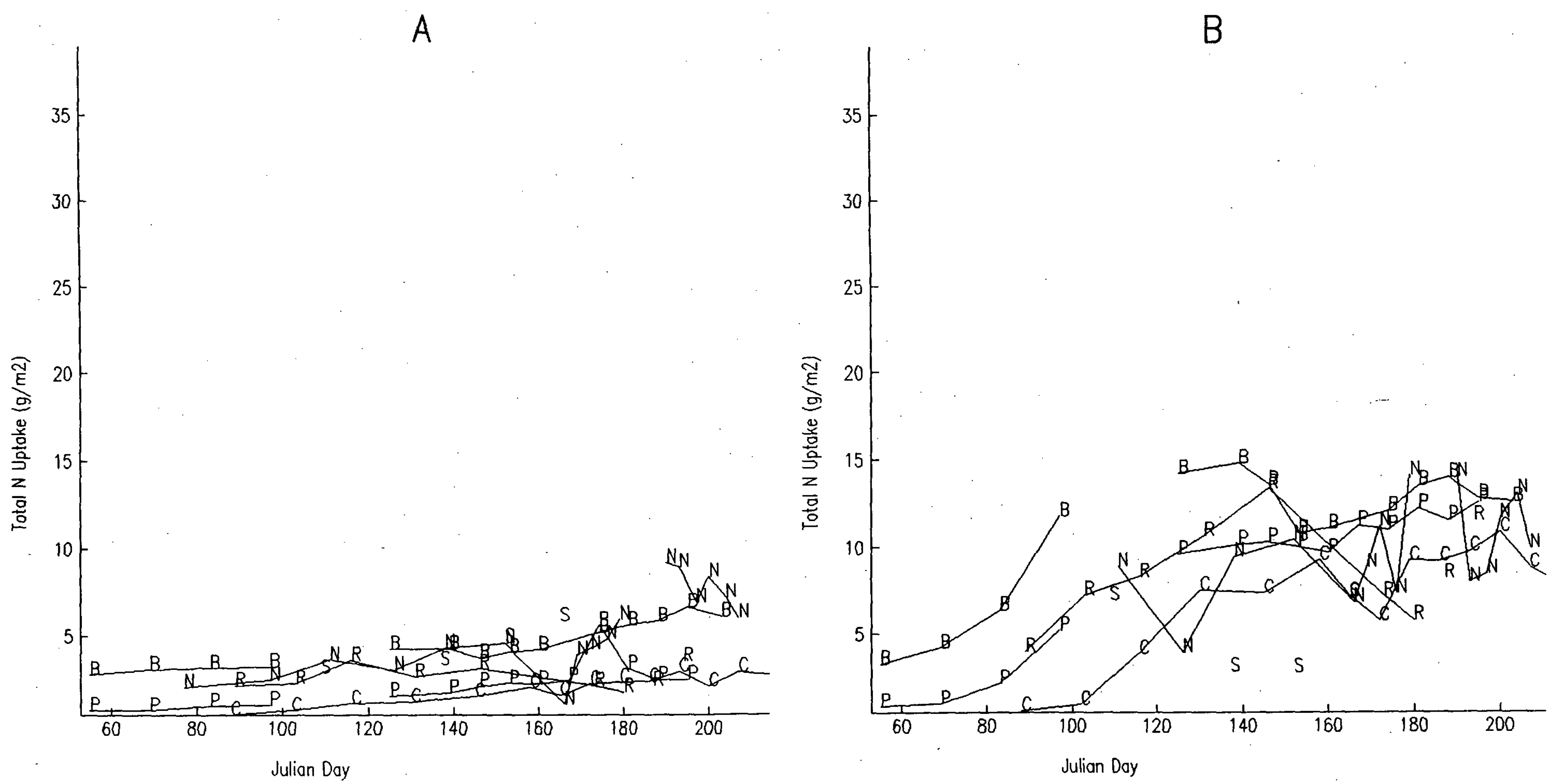
Figs. 2c and 2d. Patterns of ear dry matter accumulation of winter barley grown at Blunham (B), Crossnacreevy near Belfast (C), Newcastle (N), Potton (P), Rothamsted (R), and Sutton Bonington (S) in 1989 with none (Fig.C) or standard (Fig.D) applications of fertiliser N.



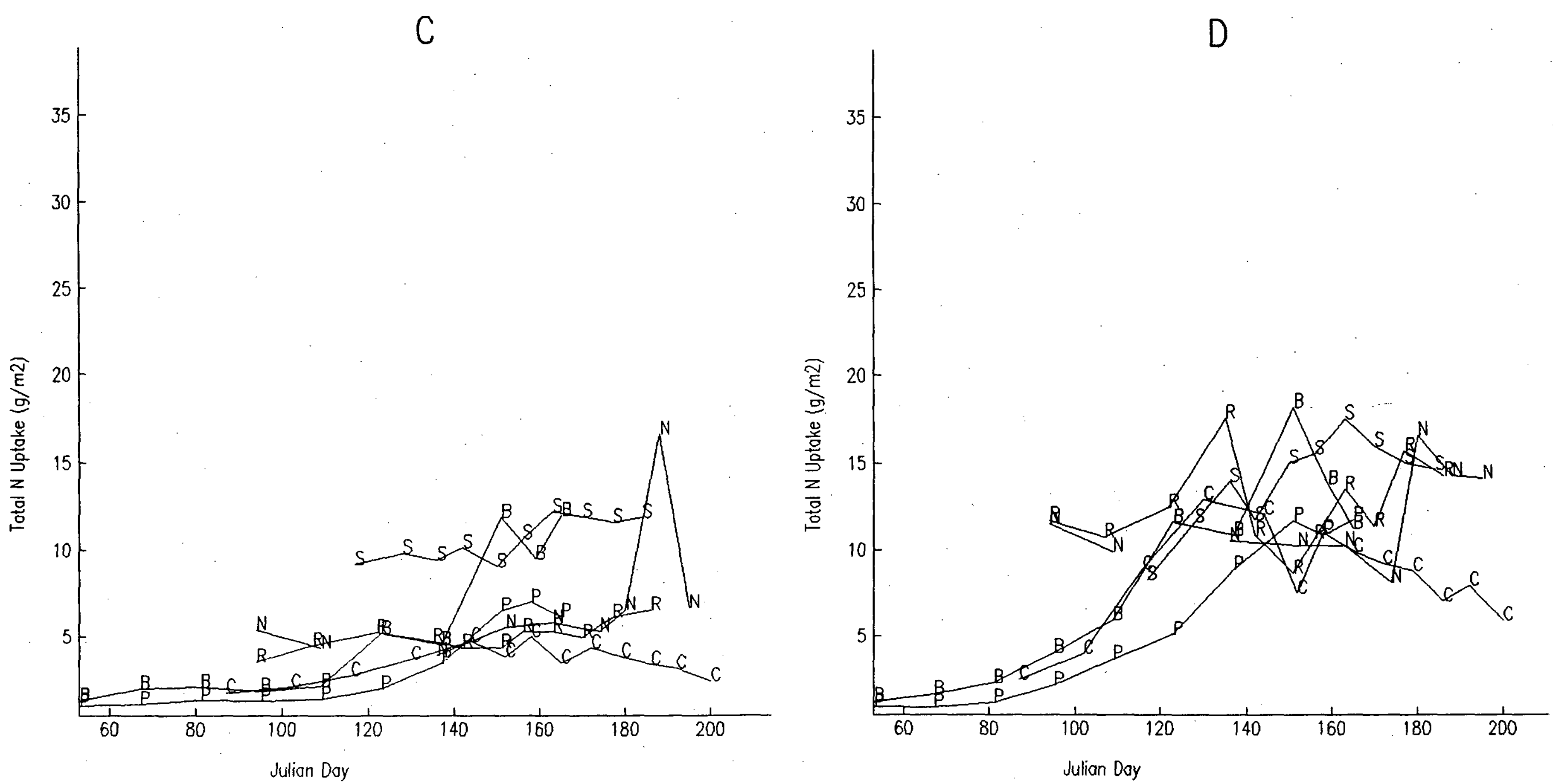
Figs. 2e and 2f. Patterns of ear dry matter accumulation of winter barley grown at Blunham (B), Crossnacreevy near Belfast (C), Newcastle (N), Potton (P), Rothamsted (R), and Sutton Bonington (S) in 1990 with none (Fig.E) or standard (Fig.F) applications of fertiliser N.



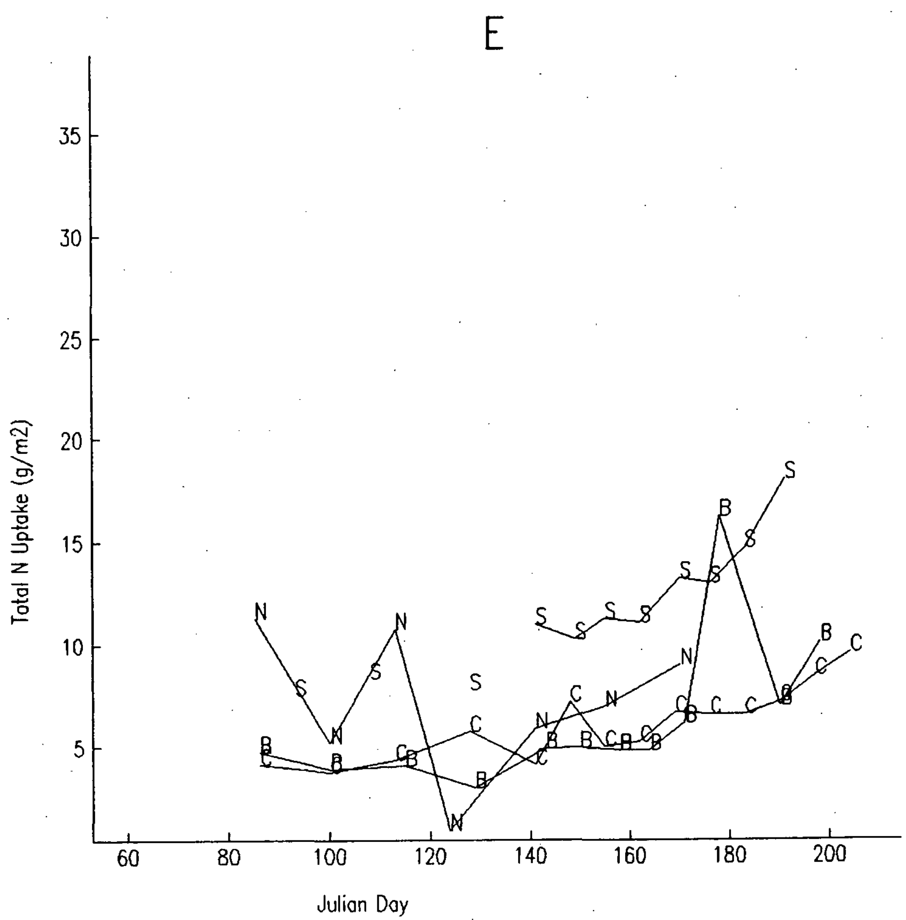
Figs. 3a and 3b. Patterns of crop N uptake of winter barley grown at Blunham (B), Crossnacreevy near Belfast (C), Newcastle (N), Potton (P), Rothamsted (R), and Sutton Bonington (S) in 1988 with none (Fig.A) or standard (Fig.B) applications of fertiliser N.

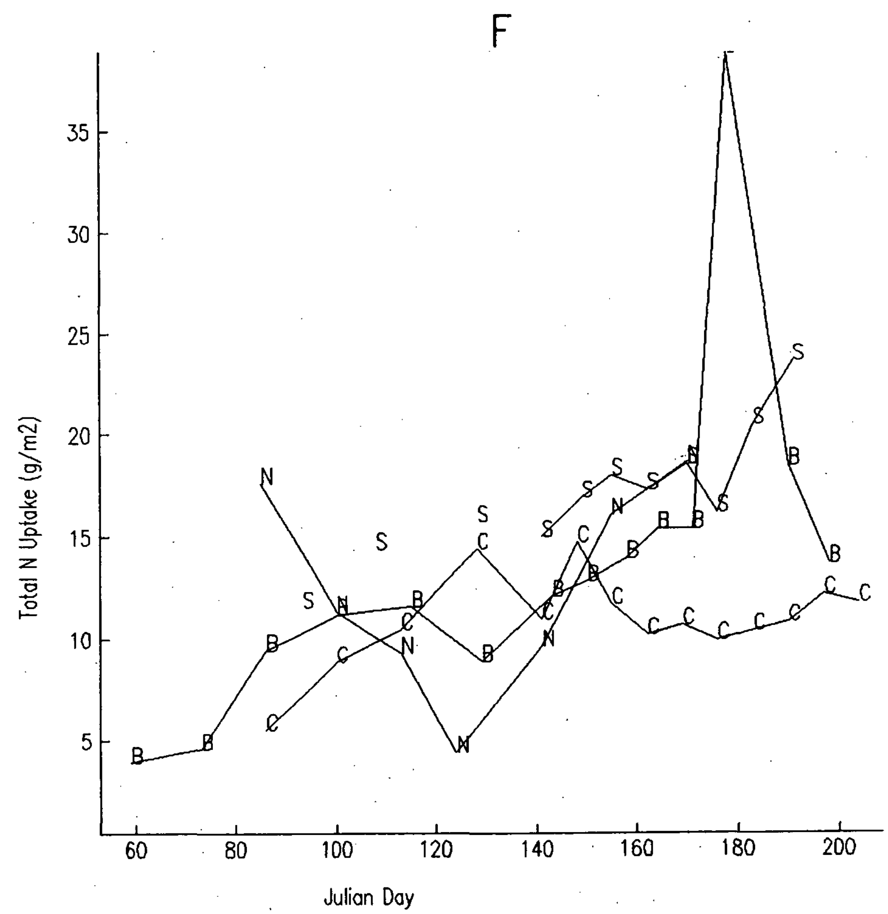


Figs. 3c and 3d. Patterns of crop N uptake of winter barley grown at Blunham (B), Crossnacreevy near Belfast (C), Newcastle (N), Potton (P), Rothamsted (R), and Sutton Bonington (S) in 1989 with none (Fig.C) or standard (Fig.D) applications of fertiliser N.

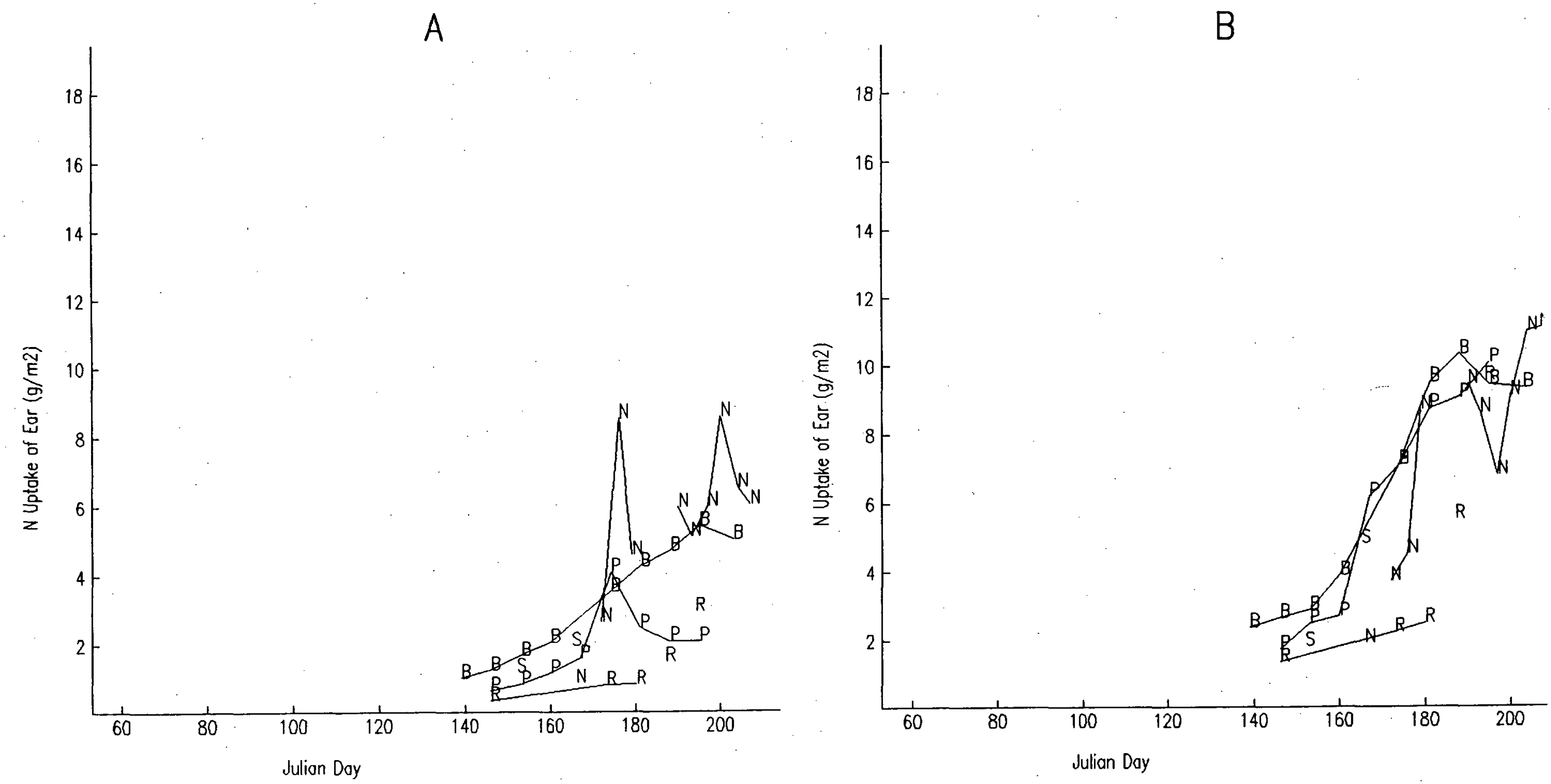


Figs. 3e and 3f. Patterns of crop N uptake of winter barley grown at Blunham (B), Crossnacreevy near Belfast (C), Newcastle (N), Potton (P), Rothamsted (R), and Sutton Bonington (S) in 1990 with none (Fig.E) or standard (Fig.F) applications of fertiliser N.

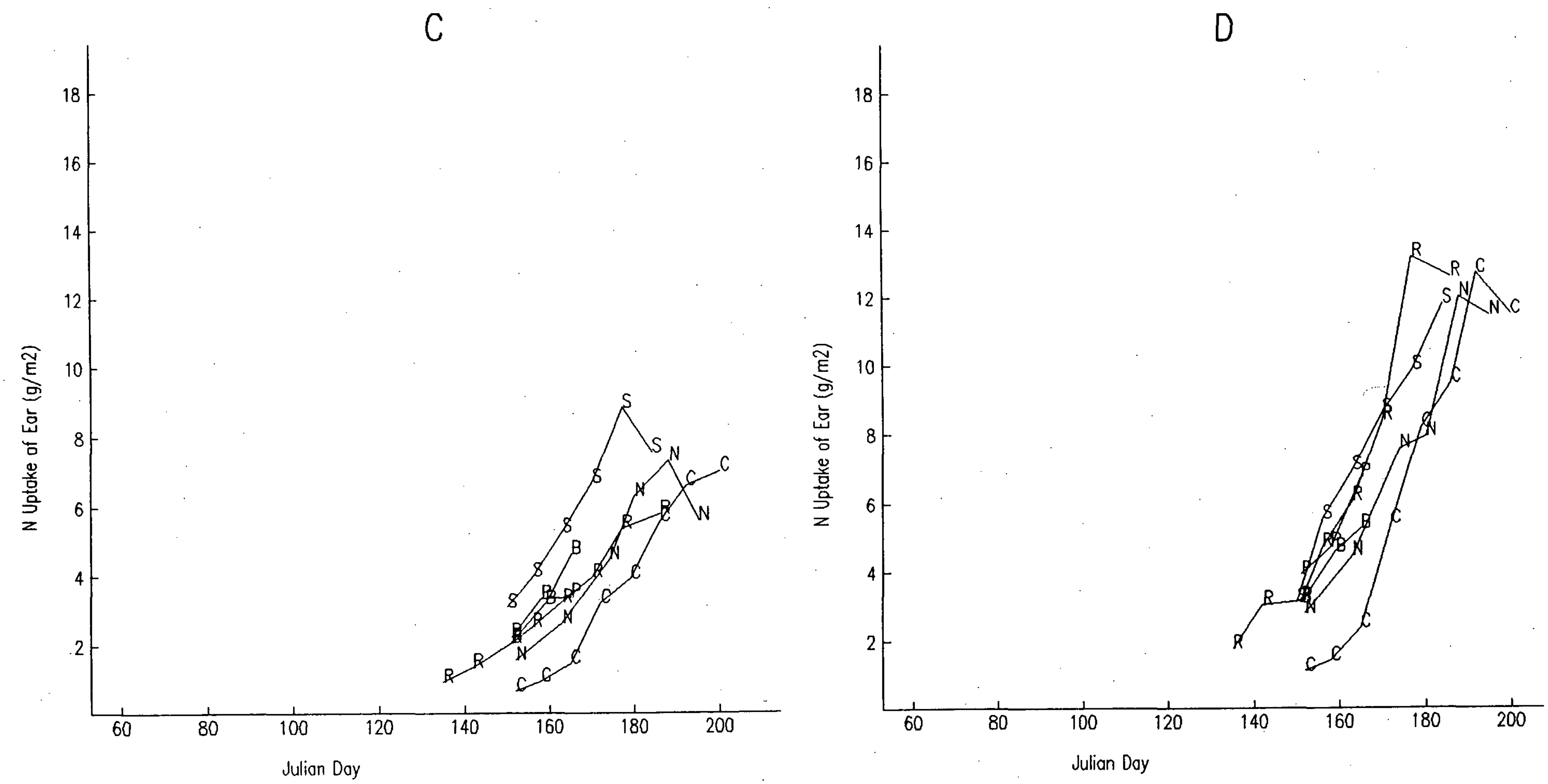




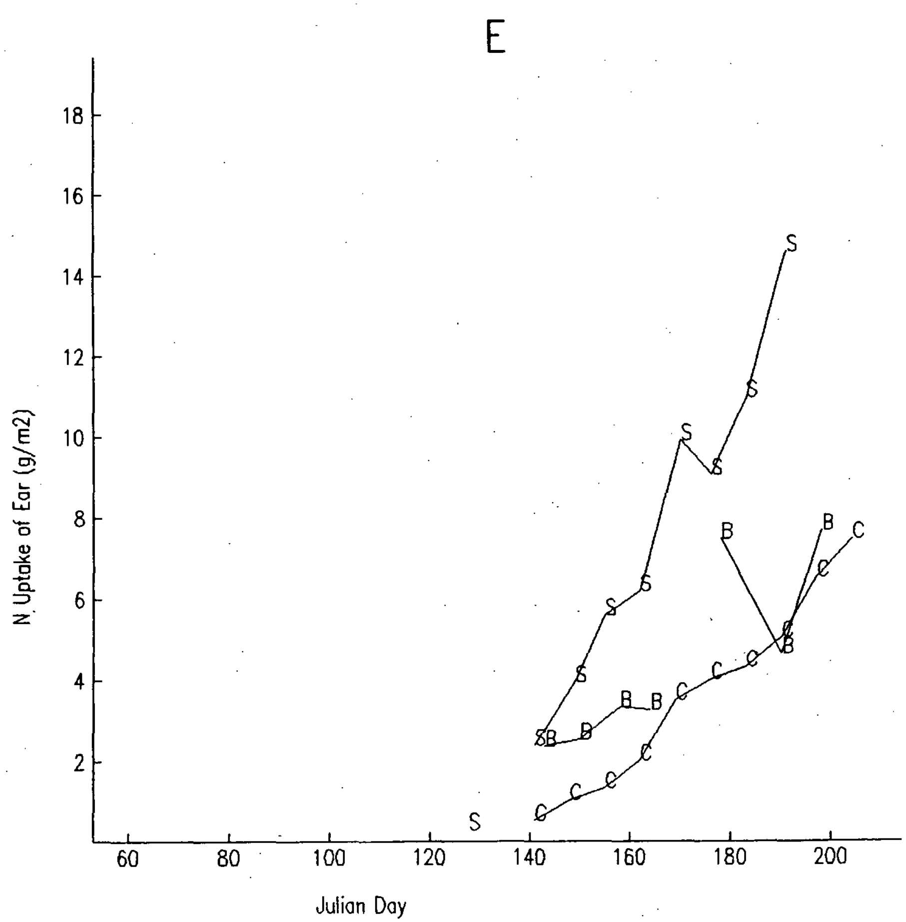
Figs. 4a and 4b. Patterns of N accumulation in the ears of winter barley grown at Blunham (B), Crossnacreevy near Belfast (C), Newcastle (N), Potton (P), Rothamsted (R), and Sutton Bonington (S) in 1988 with none (Fig.A) or standard (Fig.B) applications of fertiliser N.

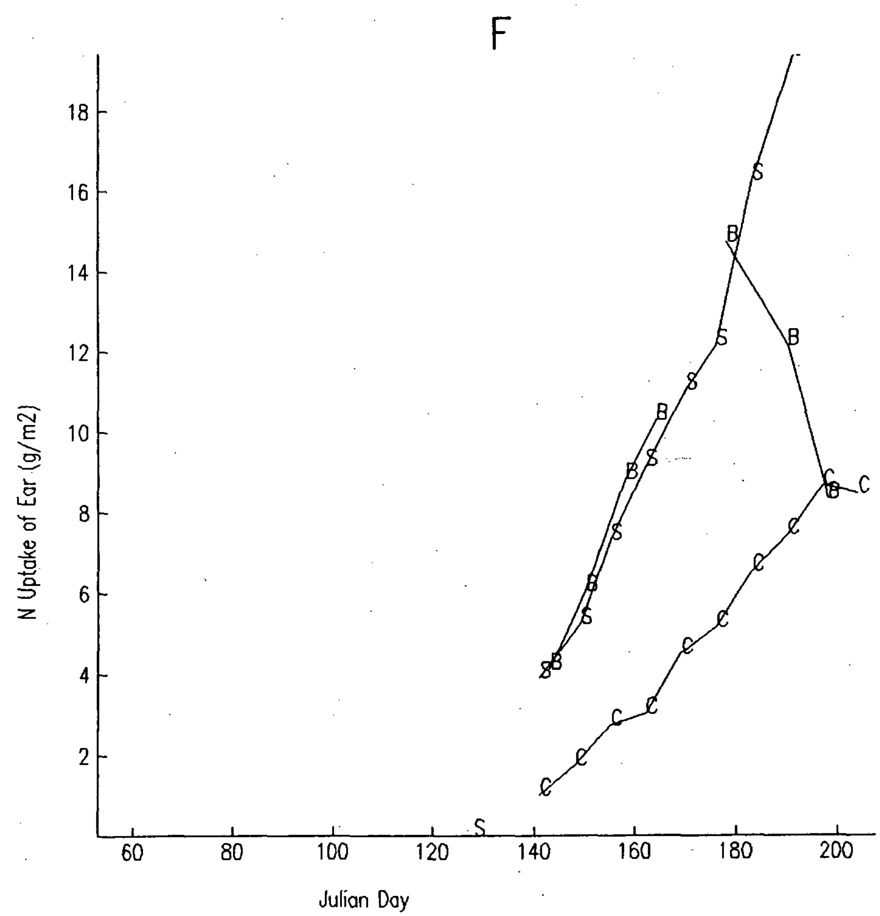


Figs. 4c and 4d. Patterns of N accumulation in the ears of winter barley grown at Blunham (B), Crossnacreevy near Belfast (C), Newcastle (N), Potton (P), Rothamsted (R), and Sutton Bonington (S) in 1989 with none (Fig.C) or standard (Fig.D) applications of fertiliser N.

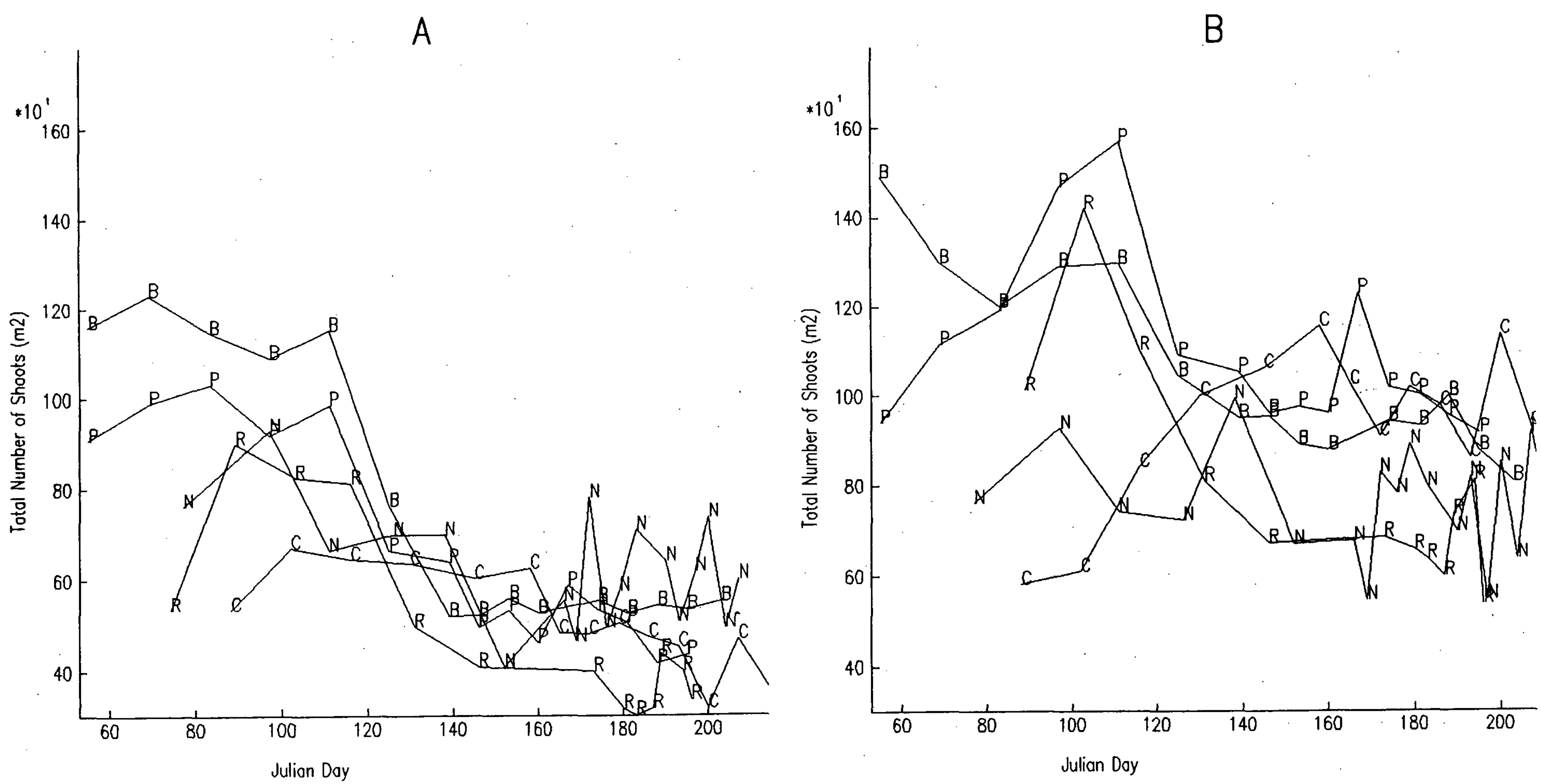


Figs. 4e and 4f. Patterns of N accumulation in the ears of winter barley grown at Blunham (B), Crossnacreevy near Belfast (C), Newcastle (N), Potton (P), Rothamsted (R), and Sutton Bonington (S) in 1990 with none (Fig.E) or standard (Fig.F) applications of fertiliser N.

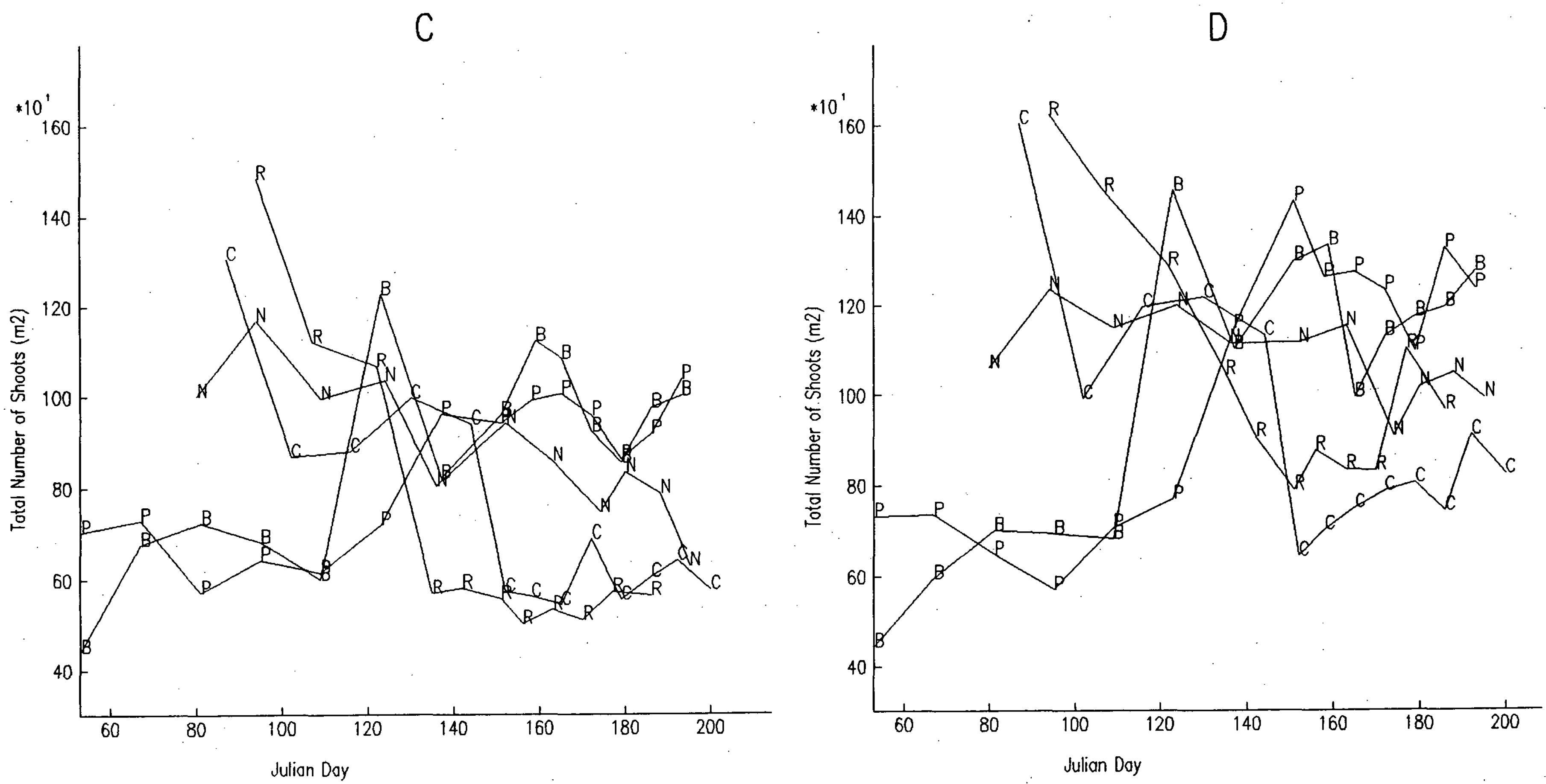




Figs. 5a and 5b. Changes in the number of shoots in winter barley grown at Blunham (B), Crossnacreevy near Belfast (C), Newcastle (N), Potton (P), Rothamsted (R), and Sutton Bonington (S) in 1988 with none (Fig.A) or standard (Fig.B) applications of fertiliser N.



Figs. 5c and 5d. Changes in the number of shoots in winter barley grown at Blunham (B), Crossnacreevy near Belfast (C), Newcastle (N), Potton (P), Rothamsted (R), and Sutton Bonington (S) in 1989 with none (Fig.C) or standard (Fig.D) applications of fertiliser N.



Figs. 5e and 5f. Changes in the number of shoots in winter barley grown at Blunham (B), Crossnacreevy near Belfast (C), Newcastle (N), Potton (P), Rothamsted (R), and Sutton Bonington (S) in 1990 with none (Fig.E) or standard (Fig.F) applications of fertiliser N.

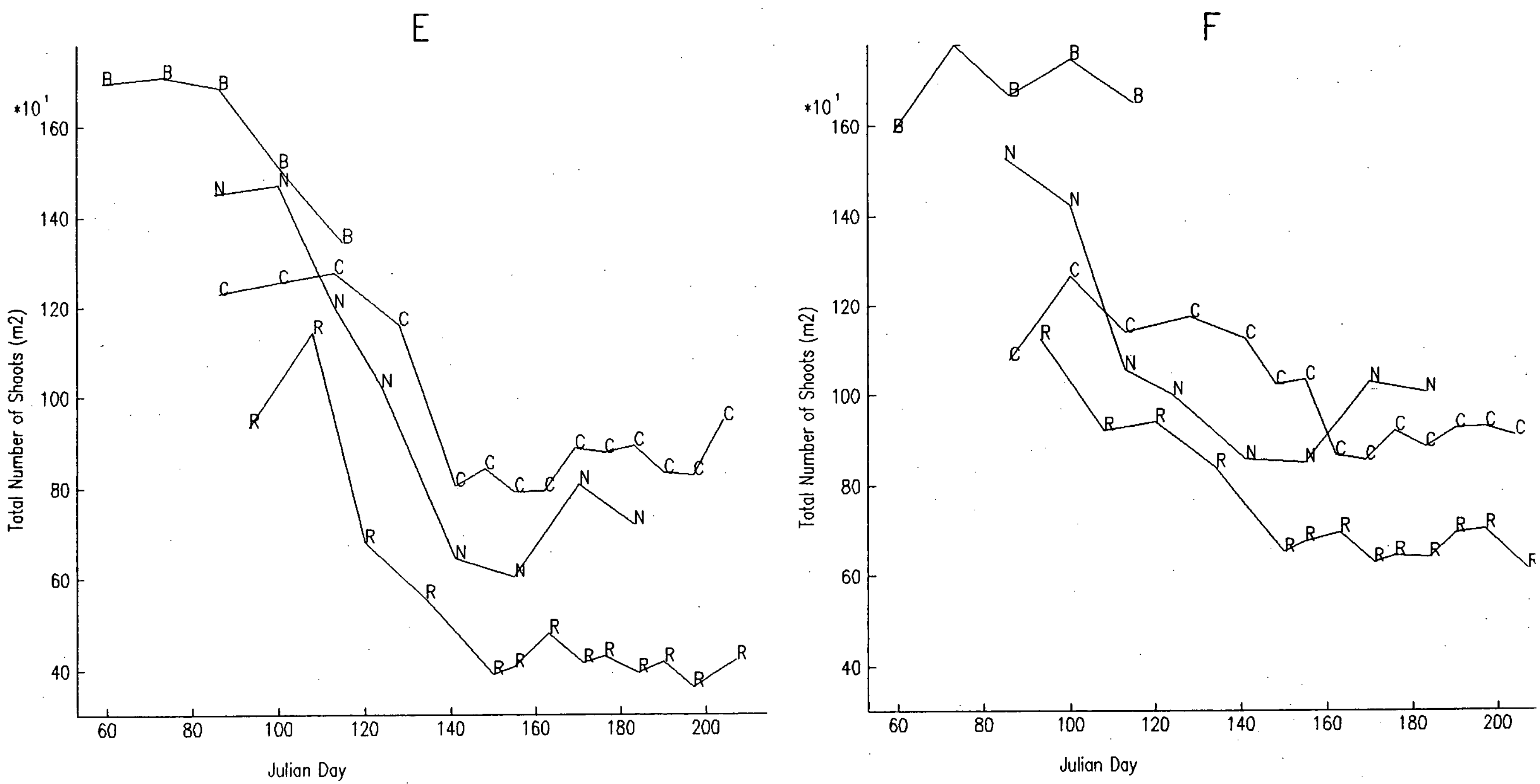


Fig. 6. (*a*) Yields of winter-barley crops given no N fertiliser plotted against crop N content at anthesis, and (*b*) the yields of crops given standard amounts of N fertiliser plotted against the yields of crops given no fertiliser N. Data are for crops grown at different sites in 1988 (○), 1989 (□) and 1990 (△).

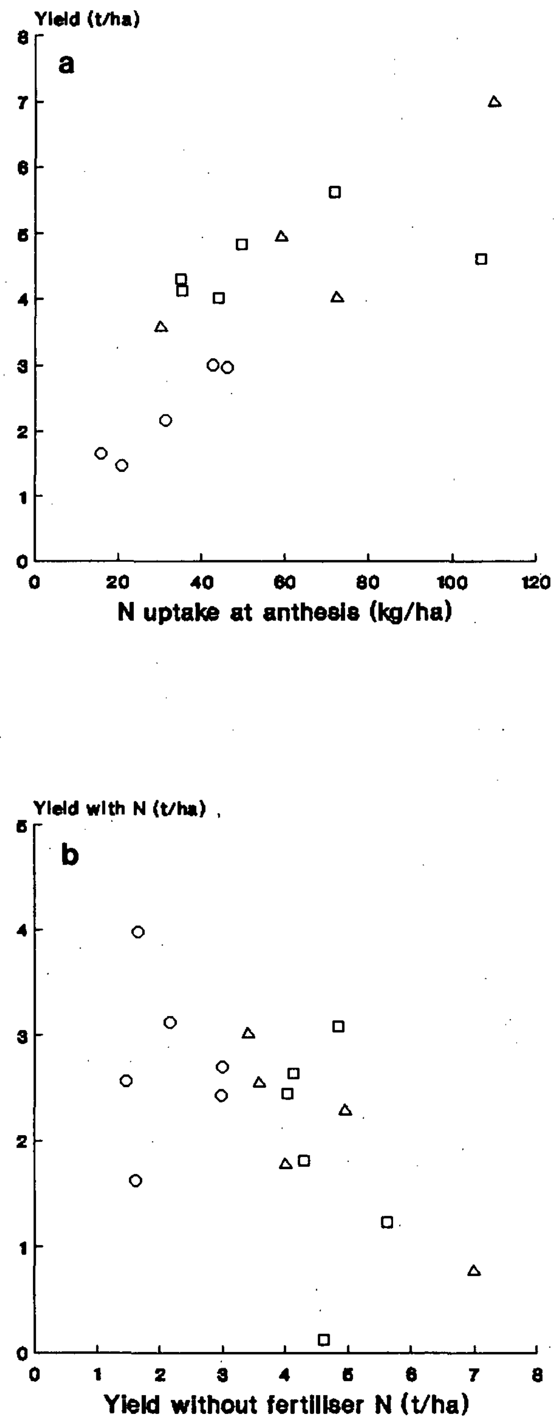


Fig. 7. Relationships between the %N in the grain at harvest and (*a*) yield and (*b*) N content at anthesis for winter-barley crops grown with (□) and without (○) fertiliser N at different sites between 1988 and 1990.

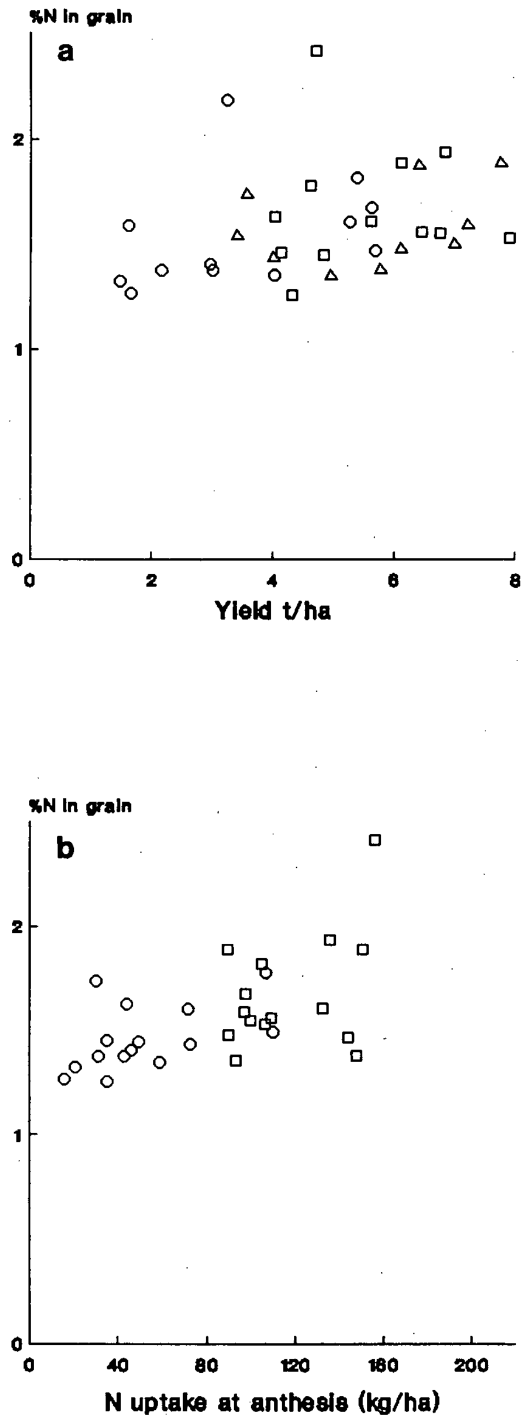


Fig. 8. Relationships between the %N in the grain at harvest and (*a*) post-anthesis dry matter growth and (*b*) post-anthesis N uptake for winter-barley crops grown with (□) and without (○) fertiliser N at different sites between 1988 and 1990.