HGCA

PROJECT REPORT No. 151

ASSESSMENTS OF WHEAT GROWTH TO SUPPORT ITS PRODUCTION AND IMPROVEMENT (VOLUME III)

VOLUME III: The Dataset

FEBRUARY 1998

Price £4.00

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ASSESSMENTS OF WHEAT GROWTH TO SUPPORT ITS PRODUCTION AND IMPROVEMENT

Edited
by

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VOLUME III: The Dataset

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This is the third of three volumes of the final report of a five year project which started in July 1991 and a three year project which started in April 1993. The work was funded by the Home-Grown Cereals Authority with grants of £156,614 to ADAS (Part A), £107,346 to University of Nottingham (Part B), £63,467 to Harper-Adams Agricultural College (Part C) and £30,317 to Edinburgh University (Part D), which are all parts of HGCA Project No 0044/1/91, and a grant of £39,971 to ADAS for HGCA Project Report No 0023/1/93.

CONTENTS

1. INTRODUCTION

Crop performance is highly dependent on both site and season (Church & Austin, 1983). In farming, site is only of major concern when a farm is bought, perhaps once in a generation, whereas the season is considered perpetually. Scientifically, on the other hand, effects of site and season must be considered together; differences between sites cannot be confidently proven without repetition over seasons, and vice versa. Some differences between sites arise through differences in climate which might recur in, and be understood through, comparisons of seasons. Additionally, effects of season are strongly mediated by soil type, and thus site, because the soil can strongly buffer the effects of varying rainfall.

In considering the variation in crop performance between sites and seasons in agronomic experiments Sylvester-Bradley & Scott (1990) concluded that 'on a range of soils, it has usually proved possible, with careful agronomy, to achieve yields of 10 tonnes per hectare with first wheats after a break crop.' However, the range in average whole-farm wheat yields between 8 experimental farms over the 10 seasons was from 6.2 at ADAS Gleadthorpe to 8.2 tonnes per hectare at ADAS Rosemaund. Between the 10 seasons of the 1980s the range in average wheat yield over the 8 farms was from 6.4 in 1981 (and 1982) to 8.6 tonnes per hectare in 1984 (Sylvester-Bradley & Scott, 1990; Table 3). Undoubtedly the crops on these farms were not all first wheats, and take all could not be controlled, so some shortfall in yield from the perceived potential yield of 10 tonnes per hectare was inevitable in all instances. However, as far as sites are concerned, given the extent of the yield shortfall and its site to site variation, it seems highly probable that there were many instances where performance of these crops could have been improved through adjustments to husbandry. These farms were managed in the full knowledge of current agronomic science; thus the shortfalls are unlikely to have arisen through ignorance. There appear to be four possible reasons that these adjustments were not made :

(i) The expense in overcoming some yield restrictions may not have been economically worthwhile.

This would often be the case where drought was a factor. Only one farm was equipped to irrigate, and even here, the economic return from irrigating wheat would seldom equate to that of irrigating crops such as potatoes and sugar beet. However, significant drought only affects a minority of wheat crops in the UK because these tend to be grown on moisture retentive soils.

Most yield restrictions other than drought are surmountable through husbandry at an economic cost significantly less than that resulting from a shortfall from the 'potential' yield of 10 tonnes per hectare. It is therefore unlikely that husbandry costs are a major cause of small yields.

(ii) The seasonal weather could not be predicted adequately.

The deficiencies of weather forecasting are patently clear. However, there are predictable differences due to time of year, region, altitude, aspect and exposure which make significant differences to the conditions in which crops must grow. It would seem that at least these predictable factors should be taken into account in crop husbandry.

Turning to the differences between seasons, it would seem wrong for the deficiencies in weather forecasting to obviate attempts to identify, understand and adjust for interactions between season, site, and husbandry. Many of the seasonal effects are apparent before husbandry decisions are made. Uncertainty about future weather will always confer a risk on the outcome of crop husbandry but, over a run of several sites and seasons, husbandry tailored to growing conditions must, almost inevitably, result in overall improvements in average crop performance.

(iii) There was insufficient consensus in the agronomic literature on the way that husbandry should be adjusted for seasonal differences.

Certainly there is a paucity of objective evidence for the way to adjust husbandry. This results from the difficulty and expense of conducting husbandry investigations over a sufficient number of seasons for confident generalisations to emerge.

For example, it is still uncertain whether crops which are 'backward' in spring merit larger or smaller investment in nutrition and protection than normal or 'forward' crops, because (a) the determination of crop state in spring adds considerably to the cost of running experiments and (b) the establishment of 'backward' and 'forward' crops tends to be unplanned and haphazard, hence is seldom open to straightforward comparison and investigation.

(iv) The determination of performance in wheat appeared too complex and uncertain to provide a sound basis for predicting effects of season or husbandry.

The complexity, and hence uncertainty, perceived to underlie yield determination of wheat partly arises because it must complete both vegetative and reproductive processes before harvest; the workings of crops which are harvested in the vegetative state are simpler and easier to appreciate (Hay & Walker, 1989). Since yield formation occurs in the ultimate six or eight weeks of a 40 or 50 week growing cycle, and since husbandry decisions are almost all made well before the yield forming period, the prospect of understanding the effects of husbandry on wheat performance is more daunting, and for some, defeating.

Thus, except where drought was a factor, shortfalls in crop performance on these well managed farms appear to have arisen through uncertainty in defining husbandry adjustments (iii above) and the difficulty in anticipating crop progress (iv above). Work to improve husbandry decisions in the light of seasonal variation in growth is being undertaken through a number of HGCA and MAFF funded projects associated with this Project, and these are shown in the table below :

Project Code	*Title*
0037/1/91	Exploitation of varieties for UK wheat production
0025/1/93	... Acquisition of data on fertiliser effects
0054/1/91	... Prediction of ... wheat development for management decisions
0023/1/93	Applying new concepts of wheat development
0070/1/92	Assessing risks and avoiding lodging in wheat
0050/1/91	An integrated approach to N nutrition of wheat
0024/1/93	Integrated N for wheat : breadmaking quality
0051/1/93	Matching crop management to crop growth and yield potential
0056/1/93	... Pre harvest prediction of Hagberg falling number and sprouting

The complimentary purpose of this Project has been to overcome the last of the possible deficiencies listed above, by generating information and protocols for decision-takers, so that they can clarify and appreciate the progress and functions of their wheat crops.

Of course there are already many crop models. However, crop models tend to be inaccessible at the level of the crop producer both through the technology of their presentation and through their complexity. They are also often inexact, and therefore potentially misleading to the lay user. Our approach here has been to observe. And to provide as simple a summary of these observations as possible, overlaid with the slightest of theoretic interpretations. First we just intended to make a qualitative description of the data. Secondly we hoped to draw some quantitative relationships from the patterns in the data. Undoubtedly the natural consequence of publishing these observations will be a desire to interpret and explain them more fully, and we have made initial attempts at this through the work of Macbeth (1996) and Gillett (1997) and Kirby *et al.* (1997), but there is much more which could be done in future.

Our initial approach was to divide the growing cycle of wheat into a series of phases in which successive attributes of the crop are thought to be determined (Figure 1).

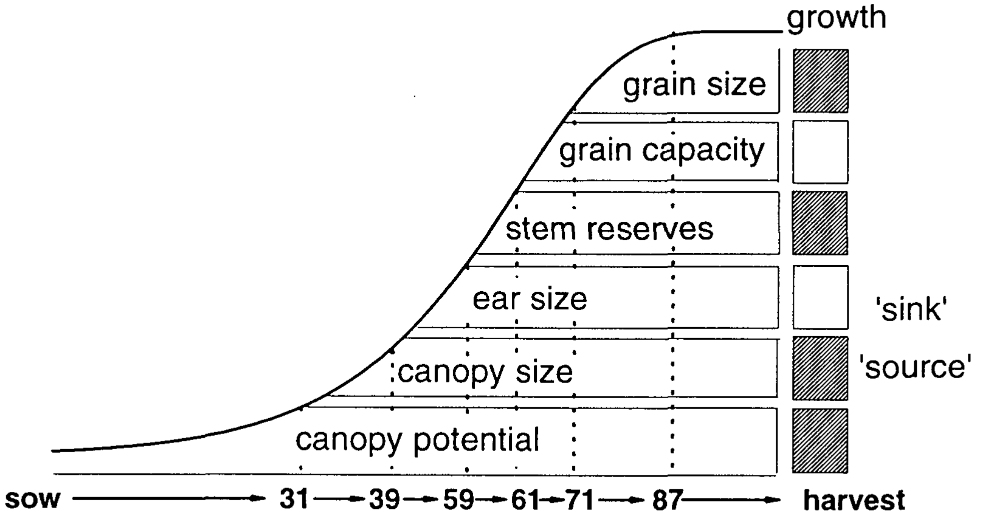

Fig. 1. Diagram showing the relationship between development and growth of wheat. The x axis indicates the sequence of stages (defined by the Decimal Code; Tottman 1987) from sowing to harvest, and the y axis indicates the component of final crop performance that is primarily affected by growth in each phase.

Progress through the phases of crop development was taken to be primarily affected by temperature, and modified by daylength. The rate of growth was taken to be primarily affected by the daily amounts of solar radiation intercepted by the crop's photosynthetic canopy. Since development is hastened in warm conditions and growth is 'fastest' in bright conditions, growth in any phase was expected to be maximised by a combination of cool and bright weather, and variations in growth were expected to be predictable from measurements of temperature and sunshine. The success of growth in each of the phases was expected to dictate one attribute of final crop performance. Thus :

a) the period until the start of stem extension was taken to determine, partly through establishment of a number of plants and then through tillering of those plants, the potential number of shoots and thus a *potential* green canopy that would undertake photosynthesis during the ultimate stage of grain filling.

   Rooting was not explicitly considered in the scheme, but extension of the primary root axes and thus most soil exploration is also primarily determined during this period before stem extension (Gregory *et al* 1978, Barraclough and Leigh 1984).

b) Internode formation, and thus stem extension, was taken to cause emergence of the 'yield-forming leaves' and thus partial realisation of the potential canopy size (Thorne & Wood, 1988). This phase coincides with, and was taken to be very dependent on, rapid N uptake.

c) After emergence of the flag leaf the ear rapidly swells in the "boot" and eventually emerges. The success of this stage can be taken to dictate the potential number of grains per ear (Fischer 1985).

d) Between ear emergence and flowering there is a period during which there is ostensibly no growth, despite the presence of a full photosynthetic canopy coincident with maximum amounts of sunlight. This phase was taken to give rise to reserves of carbohydrate in the stem, which could subsequently be re-mobilised if photosynthesis proved inadequate during grain-filling.

e) After flowering, the fertilised florets form grains, first by cell division, which can be taken to set their potential size (Brocklehurst *et al.* 1978).

f) Then the grains fill, depending on the amount of assimilate available from both current photosynthesis and from reserves accumulated before anthesis, mainly in the stem.

In summary, this initial scheme separated wheat development into six discrete phases, each one affecting either the 'source' of assimilate for grain formation, or the 'sink', the capacity of the grain to store that assimilate (indicated by the histogram on the right of Figure 1). An element of simplification was accepted in this; there was expected to be some overlap between the functions deemed to occur in successive phases. However, the scheme was set up as a feasible basis by which wheat growers might view progress of their crops and then infer appropriate action in terms of husbandry. It should be noted that this approach is incompatible with the approach which regards crop yield as resulting from the accumulation of dry weight, of which a stable proportion (the 'harvest index') is harvestable, in the case of wheat as grain. Our approach leads to an expectation of variation in both dry matter accumulation and harvest index as a result of variation in weather.

The main purpose of this section of the report is therefore to examine the changes in each crop attribute over a range of sites and seasons and to test the extent to which these conformed with the simplified scheme. The data described here were also used to formulate Volume I Part 1: '*The Wheat Growth Digest*' and Volume I Part 3: '*Forecasting Crop Progress for Wheat*'. The variation in many of the crop attributes was considerable. The extent of the variation in many attributes has been shown in '*The Wheat Growth Digest*' and the causes and patterns of variation have, to some extent, been examined and accounted for in the tables and equations of '*Forecasting Crop Progress for Wheat*'. The data themselves are extensive and will continue to be a valuable resource for further research. A further purpose of this section of the report is thus to present the principal data, site by site and season by season, for those who also wish to inspect the basis for the summaries and generalisations in the accompanying Sections, and who may wish to refer to the data for other purposes.

The crops summarised here have come to be termed 'Reference Crops'; the variety Mercia was used throughout, and one standard husbandry, specified in a detailed protocol, was used at all sites to provide, as near as possible, maximum expression of yield potential. The variety Mercia was chosen at the outset of this Project as it had been recommended for the longest period and was a reasonable yielding bread wheat although it is now considered as outclassed. The Reference Crops were monitored through the early spring and every week from the beginning of rapid growth until after harvest. Methods of husbandry and measurement in the detailed protocol used were almost identical to those described fully in the Volume II of this report, '*How to run a Reference Crop*'. The details are thus not repeated here.

This Section first describes the conditions in which the Reference Crops were grown, then describes their progress from sowing to harvest, and last describes their performance at harvest in terms of both quantity and quality. Tables and graphs have been used for presentation of the data. The sampling errors (two standard errors) are indicated on the graphs by the full length of the vertical lines attached to each respective point. In order to minimise the need for cross referencing between the five Sections of the Report, there is an element of repetition between Sections.

2. GROWING CONDITIONS

Mercia winter wheat was grown at 6 locations in England and Scotland in each of the seasons 1992-3, 1993-4 and 1994-5. Five locations were in England and one in Scotland. There were no locations in the south or in the north of England, or in the north of Scotland (Table 1.1). All of the locations were at experimental Centres, with the intention that attention to detail could be maximised. The locations were selected to include those giving extremes of low (Gleadthorpe) and high (Rosemaund) yield, as discussed in the Introduction. The crops were established at sites within each location each year but on different fields in order that they should be in a similar position in the rotation. The soil type at each location was thus not exactly the same each year. The principal difference between the sites in the dataset was between the sites in Scotland and those in England (Table 1.1). The sites in England were almost within one degree of latitude and were all of relatively low altitude. The sites in Scotland were about three degrees further north and were at 100 to 150 m greater altitude (Table 1.2).

Soils and husbandry

Other than weather, which is described in the next sub-section, the differences between sites were mainly due to soil type. These are summarised in the Table 1.2. There was a wide range of soils from clay to sand. No soil was shallow, although shallow soils over chalk or limestone do represent a significant portion of the UK wheat acreage. Soil organic matter contents were generally typical for each of the soil types. Only at Harper Adams in 1992-3 was the soil organic matter content particularly high; grass had not been grown recently at any site.

Table 1.1 Latitudes and altitudes of the six reference sites

			Latitude			
Site	Boxworth	Edinburgh	Gleadthorpe	Harper Adams	Rosemaund	Sutton Bonington
Latitude (°N)	52.3	55.9	53.2	52.8	52.1	52.8

A standard husbandry system was used to provide (internally) comparable crops. These were not necessarily representative of crops in the UK. The policy adopted was to ensure that growth and yield were not inhibited by nutrient supply, or by weeds, pests, lodging or controllable diseases. However, the effects of weather on crop development and growth were allowed to have full play. Thus, although targets were set for establishment date and rate, these varied as a result of autumn weather and, even in the relatively dry summers of 1994 and 1995, no crop was irrigated.

No significant levels of leaf disease were noted. No soil was sufficiently acid, or low in phosphate, potash or magnesium, for growth effects to be expected, and there were no serious cultural problems except for orange blossom midge and aphid infestations at Boxworth in 1994 and 1995 respectively, and the appearance of temporary manganese deficiency and then some take all in the crop at Harper Adams in 1992-3. Growth and yield of these crops were not considered sufficiently distinct for the data to be omitted from the set. Most crops were grown after break crops in order to minimise the risk of take all. At Rosemaund in 1995 the soil nitrogen supplies were greater than normal so applications of fertiliser N were reduced accordingly.

Table 1.2 Site conditions

1992-3

Site	Boxworth	Edinburgh	Gleadthorpe	H. Adams	Rosemaund	S. Bonington
Altitude (m)	54	195	50	70	98	50
Sowing Date	1 Oct	7 Oct	13 Oct	2 Oct	16 Oct	7 Oct
Harvest Date	14 Aug	14 Oct	26 Aug	26 Aug	20 Aug	20 Aug
Previous Crop	Spring OSR	Winter OSR	Potatoes	Beans	Winter OSR	Winter Oats
Soil Type	Clay loam over clay	Sandy loam over sandy clay loam	Medium sandy loam over medium sand	Loamy sand over medium sand	Sandy clay loam over sandy clay loam	Sandy clay loam over loamy sand
% OM	3.4	3.1	2.3	3.3	2.8	-
SMN (0-90 cm, kg/ha)	85 (Feb)	-	49 (Apr)	57	62	62
Soil N Supply	95	-	81	74	73	81
Total N applied (kg/ha)	190	180	200	210	215	210
Yield Constraints						
Soil pH, P, K, Mg	None	None	None	Mn deficiency	None	None
Pest or diseases	OB Midge	Aphids	None	Take-all	None	None
Weeds	None	None	None	None	None	None
Lodging	None	None	None	None	None	None

1993-4

Site	Boxworth	Edinburgh	Gleadthorpe	H. Adams	Rosemaund	S. Bonington
Altitude (m)	53	200	50	130	90	25
Sowing Date	18 Oct	2 Nov	28 Oct	23 Sept	23 Oct	2 Nov
Harvest Date	15 Aug	23 Sept	10 Aug	22 Aug	9 Aug	19 Aug
Previous Crop	OSR	Winter OSR	Potatoes	Winter Oats	Winter OSR	OSR
Soil Type	Clay loam over clay	Sandy loam over sandy clay loam	Loamy sand over loamy sand	Sandy loam over silt loam	Sandy clay loam over sandy clay loam	Clay loam over sandy clay loam
% OM	3.7	-	2.2	2.3	3.4	-
SMN (0-90 cm, kg/ha)	88	88	37	59	115	88
Soil N Supply	98	90	43	65	117	92
Total N applied (kg/ha)	190	180	200	200	200	190
Yield Constraints*						
Soil pH, P, K, Mg	None	None	None	None	None	None
Pests or Diseases	OB Midge	None	None	None	None	None
Weeds	None	None	None	None	None	None
Lodging	None	None	None	None	None	None

1994-5

Site	Boxworth	Edinburgh	Gleadthorpe	H. Adams	Rosemaund	S. Bonington
Altitude (m)	57	200	50	130	75	38
Sowing Date	6 Oct	30 Sept	10 Oct	5 Oct	23 Sept	6 Oct
Harvest Date	4 Aug	23 Aug	5 Aug	17 Aug	11 Aug	10 Aug
Previous Crop	Winter OSR	Winter Barley	Potatoes	Spring OSR	Spring OSR	OSR
Soil Type	Clay loam over clay	Sandy loam over sandy clay	Loamy sand over loamy sand	Sandy loam over silt loam	Sandy clay loam over sandy clay loam	Clay loam over clay
% OM	3.1	-	2.0	3.4	2.8	-
SMN (0-90 cm, kg/ha)	22	39	29	17	77	14
Soil N Supply	47	55	48	30	121	45
Total N applied (kg/ha)	190	200	200	200	150	190
Yield Constraints						
Soil pH, P, K, Mg	None	None	None	None	None	None
Pests or Diseases	Aphids	None	None	None	None	None
Weeds	None	None	None	None	None	None
Lodging	None	None	None	None	None	None

* Yield constraints : Soil analysis: pH<6, P <15 mg/l (Index 0), K <120 mg/l (Index 0), Mg <20 mg/l; Pests, Diseases, Weeds and Lodging judged to have been of sufficient extent to cause a possible yield loss of >5%.

The weather

Most of the variation between the 18 crops must be attributable directly or indirectly to differences in the weather. The long term averages for the sites are summarised in Table 1.3 and the weather for the three individual seasons is reported in Tables 1.4-1.6.

The long term pattern of rainfall is very even throughout the year at the English sites but rainfall is more seasonal at the Edinburgh site, with wetter autumn months (August to January) than spring months (February to July). Boxworth is the driest of the English sites but in general the differences in rainfall are small.

The differences in temperature between Edinburgh and English sites tend to be larger in summer (about 3°C) than in winter (about 1°C). All the English sites have very similar temperatures.

As well as being the wettest and coolest site, Edinburgh is also the dullest in terms of hours of sunshine. The pattern of sunshine is very similar at all sites with most sunshine hours occurring in the months of May, June and July. The most significant differences in long term weather records between the English sites appear to be in sunshine. In particular Harper Adams appears to have significantly duller conditions than Boxworth.

Generally, the differences in weather between seasons were as great as the differences between sites. The seasons can be summarised as follows :

1992-3

The autumn of 1992 was sufficiently open and mild to allow timely sowing and good establishment. It was colder than normal in October and December. Over-winter rain was sufficient to rewet the soil and to cause drainage. The spring was particularly warm, which would be expected to encourage tillering. However there was much less rain in February and March than normal and this may have restricted the availability of nutrients in the topsoil e.g. manganese deficiency was noted at Harper Adams. Summer rainfall was greater than the long term average, so that growth was not expected to be restricted by moisture supply except on the very lightest soils. Sunshine was close to normal for the English sites but May and June were particularly dull at Edinburgh, possibly restricting shoot survival.

1993-4

The autumn of 1993 was sufficiently wet for drilling to be delayed and establishment to be inhibited at most sites. Cool weather in October and November exacerbated the slow and unsatisfactory establishment. At Edinburgh rainfall from October to March was particularly high; total rainfall over-winter at the other sites was also greater than normal and could have caused significant losses of soil nitrogen, where there were significant residues. December, and particularly January were warm months, but February was colder than average. The spring of 1994 was bright in March and April, and was followed by a dry June and July, with particularly sunny and hot weather in July at the English sites. However, this period was dull at Edinburgh.

1994-5

The autumn of 1994 was wet in some places but not sufficient to prevent good crop establishment. The whole winter was again relatively wet, and sufficient to both replenish the soils with water to field capacity and to cause N losses. The whole period from November to February was warm, resulting in crops looking generally 'forward' and 'lush'. As in 1994, the spring of 1995 was bright in March and April. However, the spring and summer were drier even than in 1994, with sub-average rainfall through from April to August. The summer was also very warm and bright; August was particularly sunny.

Table 1.3 Long term average weather records from the six reference sites for 1961-1990.

Rainfall (mm)

Site	Boxworth	Edinburgh	Gleadthorpe	Harper Adams	Rosemaund	Sutton Bonington	**Average**
September	46	80	51	56	58	49	57
October	48	87	51	52	57	48	57
November	51	86	56	62	59	52	61
December	50	76	58	64	66	56	62
January	45	78	53	56	62	50	57
February	35	55	45	43	46	43	45
March	44	73	51	50	52	45	53
April	45	52	53	48	46	46	48
May	50	65	53	57	55	47	55
June	53	61	56	54	51	55	55
July	44	68	50	49	47	48	51
August	56	80	52	60	54	61	61
Total	567	861	629	651	653	600	660

Temperature (°C)

Site	Boxworth	Edinburgh	Gleadthorpe	Harper Adams	Rosemaund	Sutton Bonington	**Average**
September	14.1	11.5	13.1	13.1	13.1	13.5	13.1
October	10.9	8.8	10.0	10.1	10.1	10.4	10.0
November	6.3	4.9	6.0	6.0	6.2	6.3	5.9
December	4.3	3.4	4.0	4.1	4.3	4.4	4.1
January	3.3	2.6	3.3	3.3	3.5	3.6	3.3
February	3.4	2.5	3.4	3.5	3.6	3.7	3.3
March	5.5	4.2	5.3	5.4	5.5	5.6	5.2
April	7.7	6.2	7.4	7.6	7.7	7.8	7.4
May	11.0	9.0	10.5	10.8	10.7	10.9	10.5
June	14.2	12.0	13.6	13.8	13.7	14.0	13.5
July	16.2	13.6	15.5	15.6	15.7	15.8	15.4
August	16.3	13.4	15.2	15.4	15.4	15.7	15.2
Average	9.4	7.7	8.9	9.0	9.1	9.3	8.9

Sunshine (hours)

Site	Boxworth	Edinburgh	Gleadthorpe	Harper Adams	Rosemaund	Sutton Bonington	**Average**
September	144	109	130	121	132	133	128
October	108	88	95	89	91	97	95
November	67	59	63	58	64	60	62
December	46	35	44	40	45	42	42
January	54	42	49	47	51	48	48
February	68	65	60	58	64	62	63
March	108	98	101	96	107	102	102
April	142	131	126	127	144	129	133
May	192	159	179	175	182	178	178
June	194	161	182	174	184	172	178
July	184	158	170	174	187	173	174
August	179	143	164	159	170	169	164
Total	1486	1247	1362	1318	1422	1363	1366

Table 1.4 Weather at the six reference sites for 1992-3 as % of the long term average (see Table 1.3).

Rainfall (%)

Site	Boxworth	Edinburgh	Gleadthorpe	Harper Adams	Rosemaund	Sutton Bonington	**Average**
September	235	162	166	90	90	159	148
October	159	67	121	121	72	142	107
November	160	127	146	133	155	150	143
December	55	65	84	58	94	70	71
January	112	212	100	92	110	105	128
February	32	19	23	13	8	15	18
March	44	68	16	27	29	21	37
April	199	166	155	74	123	143	143
May	109	211	107	172	113	97	139
June	103	117	150	128	86	108	116
July	143	70	165	151	111	168	131
August	74	53	82	73	40	75	66
Total	120	111	111	96	87	105	105

Temperature (%)

Site	Boxworth	Edinburgh	Gleadthorpe	Harper Adams	Rosemaund	Sutton Bonington	**Average**
September	99	94	98	99	100	100	98
October	74	68	73	72	75	75	73
November	116	106	113	116	118	116	114
December	81	83	73	65	79	75	76
January	172	160	159	166	168	161	165
February	120	215	143	125	130	133	141
March	118	124	116	121	119	121	120
April	121	109	127	122	120	123	121
May	106	97	105	103	104	105	103
June	105	102	105	106	108	105	105
July	96	96	97	96	96	97	96
August	95	93	92	90	93	92	93
Total	103	101	102	101	103	103	102

Sunshine (%)

Site	Boxworth	Edinburgh	Gleadthorpe	Harper Adams	Rosemaund	Sutton Bonington	**Average**
September	88	97	97	77	71	79	85
October	86	68	97	83	86	91	85
November	90	101	104	89	86	107	96
December	97	75	98	29	117	36	77
January	67	60	92	37	43	74	62
February	50	56	79	72	72	85	69
March	108	97	118	94	83	109	102
April	67	74	84	69	63	81	73
May	103	64	115	99	91	99	96
June	104	69	107	106	96	117	100
July	102	95	118	90	97	111	102
August	122	107	119	106	97	114	111
Total	95	82	106	87	86	98	92

Table 1.5 Weather at the six reference sites for 1993-4 as % of the long term average (see Table 1.3).

Rainfall (%)

Site	Boxworth	Edinburgh	Gleadthorpe	Harper Adams	Rosemaund	Sutton Bonington	**Average**
September	203	132	216	137	137	182	163
October	176	206	141	129	169	182	171
November	117	71	90	89	105	110	94
December	158	203	164	164	128	167	165
January	159	152	132	103	94	152	131
February	79	131	122	114	160	110	122
March	96	195	90	124	65	143	124
April	162	132	68	75	74	70	96
May	103	22	125	66	106	114	86
June	45	93	16	26	33	15	39
July	59	68	90	87	57	59	70
August	111	49	120	71	84	59	79
Total	122	123	114	99	102	112	113

Temperature (%)

Site	Boxworth	Edinburgh	Gleadthorpe	Harper Adams	Rosemaund	Sutton Bonington	**Average**
September	91	89	93	91	90	92	91
October	81	74	80	75	76	79	78
November	74	63	73	62	73	75	70
December	124	75	118	116	128	123	115
January	151	111	143	143	154	144	142
February	94	57	66	74	85	83	77
March	136	118	144	138	147	142	138
April	105	99	113	105	107	109	107
May	99	92	97	97	100	93	97
June	106	102	108	102	104	106	105
July	117	106	114	111	114	116	113
August	102	97	102	99	102	104	101
Total	103	93	103	99	103	103	101

Sunshine (%)

Site	Boxworth	Edinburgh	Gleadthorpe	Harper Adams	Rosemaund	Sutton Bonington	**Average**
September	67	107	66	57	64	62	69
October	103	105	117	104	108	94	105
November	91	83	62	76	63	71	74
December	82	73	127	108	120	120	106
January	133	93	145	127	156	143	134
February	110	78	134	72	87	97	96
March	117	112	118	119	117	119	117
April	126	101	148	128	99	122	120
May	79	116	83	71	70	72	81
June	132	108	119	97	107	115	113
July	138	89	137	128	118	124	123
August	108	88	118	97	102	94	102
Total	109	99	113	98	98	101	103

Table 1.6 Weather at the six reference sites for 1994-5 as % of the long term average (see Table 1.3).

Rainfall (%)

Site	Boxworth	Edinburgh	Gleadthorpe	Harper Adams	Rosemaund	Sutton Bonington	**Average**
September	148	90	99	82	117	222	122
October	169	59	287	182	211	87	156
November	60	86	111	85	98	129	94
December	79	214	136	135	150	168	151
January	174	132	184	166	182	209	171
February	152	193	124	149	132	128	148
March	103	71	70	76	74	77	77
April	24	64	34	28	37	29	36
May	46	90	106	65	113	50	80
June	38	30	27	27	14	21	27
July	41	77	19	56	13	22	41
August	14	25	9	13	33	9	18
Total	84	93	100	88	102	95	94

Temperature (%)

Site	Boxworth	Edinburgh	Gleadthorpe	Harper Adams	Rosemaund	Sutton Bonington	**Average**
September	72	72	73	74	73	95	76
October	121	120	124	122	124	93	117
November	154	167	151	159	163	156	158
December	137	131	146	142	149	143	142
January	131	96	129	128	143	128	127
February	182	155	185	174	186	177	177
March	98	84	100	95	101	99	96
April	117	114	117	116	117	114	116
May	109	107	106	105	105	107	106
June	99	102	101	101	102	102	101
July	122	111	121	118	117	119	118
August	120	118	116	125	124	120	121
Total	114	110	114	114	117	115	114

Sunshine (%)

Site	Boxworth	Edinburgh	Gleadthorpe	Harper Adams	Rosemaund	Sutton Bonington	**Average**
September	84	76	77	86	78	75	79
October	104	113	125	110	111	98	110
November	61	74	97	66	42	73	69
December	143	88	150	86	102	124	117
January	106	106	126	103	101	121	110
February	124	98	143	114	107	120	118
March	173	114	182	151	160	158	157
April	114	100	130	128	122	133	121
May	105	104	111	95	101	100	103
June	82	105	101	103	103	76	95
July	128	117	150	129	95	129	124
August	136	129	159	168	167	145	151
Total	112	105	128	116	111	112	114

3. CROP PROGRESS

Crop development or 'growth stages'

The dates at which growth stages (Tottman 1987) first occurred are shown in Table 2.1. Despite their common variety (Mercia) and standard husbandry protocol, crops showed considerable variation in development. There was more variation in dates of early stages than in dates of late stages; GS30 and GS31 showed a range of almost two months whereas GS87 showed a range of about one month. The difficulties in achieving target sowing dates in autumn 1993 and the cold autumn conditions resulted in relatively late dates for the first recorded stages in 1994, but warm conditions in the summer of 1994 resulted in rapid development and earlier grain ripening than in the summer of 1993. The considerably cooler conditions at the Edinburgh sites resulted in consistently later dates for each stage of development than at the English sites. Of the English sites, Boxworth & Rosemaund, the two southern most sites, were generally earliest; they reached flowering a few days earlier than Gleadthorpe, Harper Adams or Sutton Bonington.

Stem extension was the first process for which dates were recorded. It began in late March or early April and ceased with the full emergence of the ear in early June. The period of most rapid stem extension was during May when extension of the fourth-, third- and second-last internodes assisted emergence of the last three leaves. The intervals between emergence of each of these leaves were usually between seven and fourteen days with the shorter intervals for those leaves experiencing higher temperatures. Emergence of the flag leaf was complete by late May. Thus it took a little over a month for formation of the most important leaves of the canopy on which the majority of subsequent growth must depend.

The components of the inflorescence developed and the ear emerged concurrent with extension of the last few internodes, although early stages of ear development were not recorded. Development of the ear was initially noted as 'boots swollen' (GS45) which occurred at the end of May. It then took about 5 days for ears to become half exerted above the flag leaf ligule (GS55), and it took almost as long again for the ears to become fully emerged (GS59); thus ear emergence was not complete at any site until June, about three weeks after emergence of the flag leaf. There was usually a short interval of two to four days at between full emergence of the ear and flowering (GS61). In only three crops was there a longer interval of seven or more days, and in five crops the interval was less than two days; with one notable crop at Rosemaund in 1994 anthesis commenced before the ear was fully emerged. The closeness of these dates emphasises the need for very frequent observations of these growth stages if accurate assessments of time intervals between stages are going to be made.

Grain filling stages were more difficult to identify accurately than stages identified by morphological features. The period between flowering and 'watery ripe' (GS71) was not directly recorded at most sites in 1993. In 1994 it took between seven and twelve days and in 1995 it took about 2 weeks. Subsequent development to the 'hard dough' stage (GS87) took about a month in all years. It was reached a few days earlier after the warm summers of 1994 and 1995 than after the cooler summer of 1993. It was reached about three weeks later at Edinburgh than at the English sites.

Table 2.1 Dates for Growth Stages of winter wheat at six sites in three seasons. Dates in *italics* were not observed and are estimated on the basis that intervals in terms of thermal time between successive stages would have been similar to those observed at other sites. Dates for GS39 were estimated from leaf growth data as described under "Leaf production" below.

Growth Stage				**1992-93**			
	Boxworth	Edinburgh	Gleadthorpe	Harper Adams	Rosemaund	Sutton Bonington	Median
GS 30	***13-Apr***	20-Apr	24-Apr	07-Apr	06-Apr	***07-Apr***	10-Apr
GS 31	20-Apr	10-May	28-Apr	14-Apr	13-Apr	***14-Apr***	17-Apr
GS 32	27-Apr	18-May	05-May	26-Apr	26-Apr	26-Apr	26-Apr
GS 39	18-May	01-Jun	21-May	30-May	24-May	23-May	23-May
GS 45	24-May	07-Jun	02-Jun	30-May	27-May	01-Jun	31-May
GS 55	02-Jun	22-Jun	02-Jun	05-Jun	04-Jun	04-Jun	04-Jun
GS 59	***03-Jun***	28-Jun	08-Jun	08-Jun	07-Jun	07-Jun	07-Jun
GS 61	04-Jun	02-Jul	16-Jun	10-Jun	09-Jun	11-Jun	10-Jun
GS 71	21-Jun	***15-Jul***	***22-Jun***	***26-Jun***	***24-Jun***	***24-Jun***	24-Jun
GS 75	28-Jun	19-Jul	***02-Jul***	12-Jul	05-Jul	05-Jul	05-Jul
GS 85	19-Jul	09-Aug	***20-Jul***	26-Jul	26-Jul	19-Jul	23-Jul
GS 87	***30-Jul***	23-Aug	09-Aug	02-Aug	02-Aug	***30-Jul***	02-Aug

Growth Stage				**1993-94**			
	Boxworth	Edinburgh	Gleadthorpe	Harper Adams	Rosemaund	Sutton Bonington	Median
GS 30	18-Apr	10-May	18-Apr	26-Apr	25-Apr	18-Apr	21-Apr
GS 31	***27-Apr***	25-May	27-Apr	02-May	02-May	29-Apr	30-Apr
GS 32	03-May	30-May	03-May	10-May	09-May	03-May	06-May
GS 39	22-May	10-Jun	26-May	30-May	24-May	24-May	25-May
GS 45	30-May	23-Jun	06-Jun	06-Jun	05-Jun	06-Jun	06-Jun
GS 55	07-Jun	27-Jun	11-Jun	11-Jun	11-Jun	10-Jun	11-Jun
GS 59	13-Jun	04-Jul	20-Jun	***22-Jun***	18-Jun	17-Jun	19-Jun
GS 61	17-Jun	04-Jul	20-Jun	23-Jun	17-Jun	19-Jun	19-Jun
GS 71	28-Jun	15-Jul	27-Jun	02-Jul	27-Jun	27-Jun	27-Jun
GS 75	01-Jul	25-Jul	04-Jul	12-Jul	11-Jul	04-Jul	07-Jul
GS 85	18-Jul	15-Aug	25-Jul	18-Jul	18-Jul	25-Jul	21-Jul
GS 87	25-Jul	22-Aug	25-Jul	01-Aug	25-Jul	25-Jul	25-Jul

Growth Stage				**1994-95**			
	Boxworth	Edinburgh	Gleadthorpe	Harper Adams	Rosemaund	Sutton Bonington	Median
GS 30	27-Mar	24-Apr	27-Mar	10-Apr	13-Mar	27-Mar	27-Mar
GS 31	10-Apr	***30-Apr***	10-Apr	19-Apr	27-Mar	10-Apr	10-Apr
GS 32	24-Apr	08-May	01-May	01-May	24-Apr	01-May	01-May
GS 39	14-May	30-May	19-May	26-May	09-May	16-May	17-May
GS 45	22-May	12-Jun	26-May	30-May	22-May	30-May	28-May
GS 55	27-May	19-Jun	03-Jun	06-Jun	02-Jun	05-Jun	04-Jun
GS 59	04-Jun	22-Jun	12-Jun	12-Jun	05-Jun	05-Jun	08-Jun
GS 61	07-Jun	24-Jun	19-Jun	16-Jun	08-Jun	14-Jun	15-Jun
GS 71	17-Jun	08-Jul	03-Jul	01-Jul	26-Jun	26-Jun	28-Jun
GS 75	23-Jun	14-Jul	10-Jul	10-Jul	07-Jul	03-Jul	08-Jul
GS 85	17-Jul	24-Jul	24-Jul	24-Jul	17-Jul	17-Jul	20-Jul
GS 87	20-Jul	07-Aug	28-Jul	26-Jul	26-Jul	24-Jul	26-Jul

Leaf and shoot production

Leaf production

Progress in emergence of successive leaves on the mainstem is shown in Fig. 2. The overall pattern of leaf production was similar for all crops. Leaf production would have started in autumn with emergence of the seedling, and it can be inferred to have continued at a low rate through the winter, due to the low winter temperatures. By mid February, when records began, most crops had produced only one to two fifths of their final number of leaves. Thus most mainstem leaves were produced in spring and early summer. However, the variation between sites and seasons in the number of leaves in February was considerable, due to variations in sowing and emergence dates and winter temperatures. The number of leaves produced by the end of the winter varied from two (Edinburgh, 1994) to seven (Boxworth and Sutton Bonington 1995). There were also high leaf numbers at Sutton Bonington in 1993, Rosemaund in 1995, and Boxworth in 1993, and low, but not the lowest, leaf numbers at Rosemaund in 1993 and Sutton Bonington in 1994.

After the end of the winter the rate of leaf production increased, with leaves appearing at successively shorter intervals as temperature increased, although the onset of the more rapid rate of leaf production was considerably delayed at Edinburgh. When examined in detail, all sites had a near linear relation between leaf number and accumulated thermal time above 0°C until the flag leaf ligule appeared. This implies that, by our definition, the phyllochron (the thermal time interval between the same stage of growth of successive leaves) was constant. The values calculated according to this definition (method detailed below) are shown in Table 2.2.

Table 2.2. Mean phyllochron (°C d) from February to flag leaf appearance for wheat crops over the three seasons at six sites.

Site	1993	1994	1995
Boxworth	133	108	109
Edinburgh	92	89	116
Gleadthorpe	119	102	106
Harper Adams	121	121	133
Rosemaund	111	96	97
Sutton Bonington	148	108	102

The range of values for the phyllochron was quite large and varied in a complex manner between sites and seasons. In most years the range of values was large enough to imply that it would take at least 30% longer at a given temperature to produce a leaf at the sites with the greatest phyllochron compared with the sites with the shortest phyllochron. This large range in phyllochron in the present variety, Mercia, and the large number of factors known to influence phyllochron such as variety, daylength at time of emergence, latitude

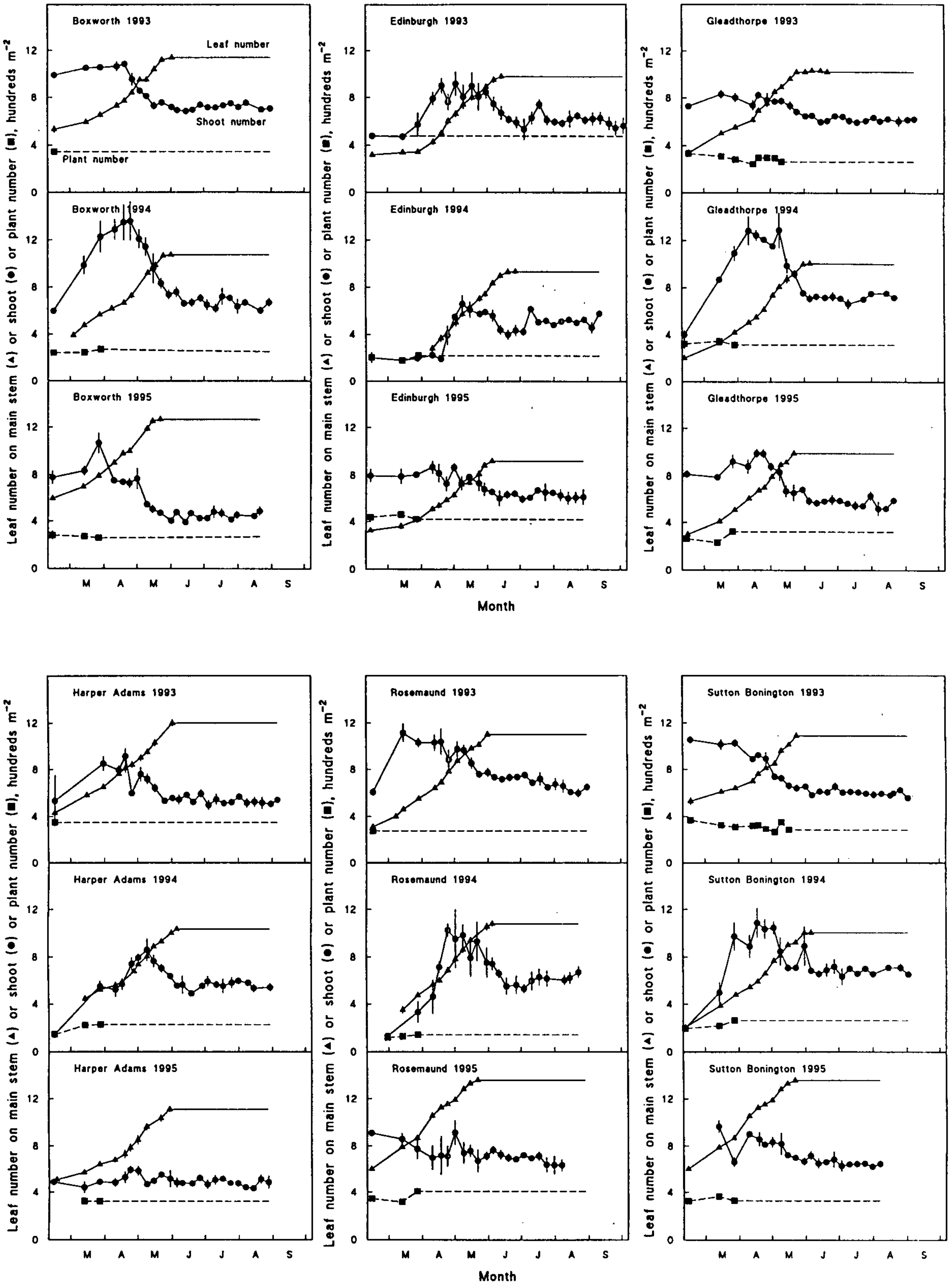

Fig. 2. Time course of leaf number on mainstem (▲) and shoot number per m^2 (●) or plant number per m^2 (■) for Mercia grown at six sites in harvest years 1993, 1994 and 1995. Vertical bars are standard error of mean.

and vernalisation, suggests that generally, where a knowledge of phyllochron is required for a particular crop, it should be confirmed by measurement. Accurate knowledge of the phyllochron of a crop may be useful for estimating the dates of appearance of future culm leaves.

Determination of phyllochron and dates of ligule appearance. Estimation of phyllochron and interpolations of dates of ligule appearance on the last four leaves were made from lines fitted to mean leaf number (over ten plants in each of three replicates) against thermal time. The thermal time of flag leaf emergence was estimated by fitting a second horizontal line to mean *final* leaf number against thermal time, and determining the intersection with the first line. Fitting of both lines was performed simultaneously as a spline function using a Maximum Likelihood Program (Ross, 1987). The result is illustrated in Fig 3.

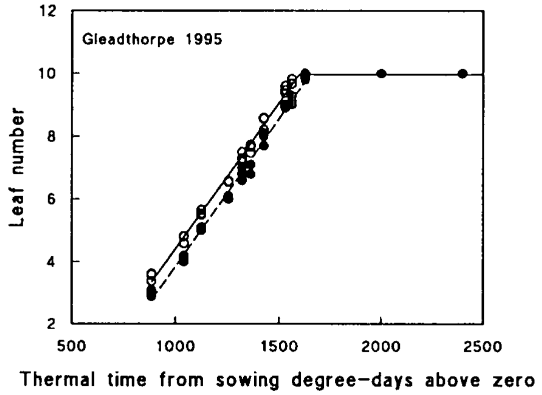

Figure 3. *Example data and fitted lines as used to estimate phyllochron in thermal time. The data are total leaf number including length of expanding leaf divided by length of expanding leaf when fully expanded (○), and total fully expanded leaf number (●). The lines are fitted to the fractional leaf data (—) or to fully expanded leaf number only (- -) as splines.*

For 1994 and 1995 the data used in the fitting process for calculation of mean leaf numbers for each time point were the number of fully expanded leaves plus the current length of the expanding leaf divided by it's length when fully expanded. For 1993 lengths of expanding leaves were not recorded, so a correction was made: when interpolating dates of ligule appearance, 0.5 was subtracted from the values of mean leaf number for all leaves including the flag leaf to correct for this. This correction was tested on the 1994 and 1995 data, truncated to whole leaf data; the results were very similar to those obtained using the full data. Phyllochrons (day-degrees per leaf) were estimated as the reciprocal of the slope (leaves per degree-day), and thermal times were converted to dates using the daily course of thermal time for each site and season (Table 2.3).

Crops that were early in producing the third from last leaf were often those that produced the earliest flag leaves. However, the relationship was not completely reliable, because the actual course of temperatures experienced at a particular site in the variable weather of late spring, and differences in phyllochron between sites, significantly altered the rate of completion of leaves between sites.

Table 2.3. Calculated dates of ligule appearance on mainstem leaves of wheat crops over three seasons at six sites.

	1993	1994	1995
Third from last leaf			
Boxworth	9-Apr	24-Apr	10-Apr
Edinburgh	1-May	12-May	19-Apr
Gleadthorpe	18-Apr	28-Apr	13-Apr
Harper Adams	27-Apr	27-Apr	15-Apr
Rosemaund	24-Apr	28-Apr	9-Apr
Sutton Bonington	12-Apr	25-Apr	13-Apr
Second from last leaf			
Boxworth	23-Apr	02-May	24-Apr
Edinburgh	2-May	23-May	4-May
Gleadthorpe	28-Apr	6-May	27-Apr
Harper Adams	10-May	7-May	2-May
Rosemaund	5-May	6-May	22-Apr
Sutton Bonington	26-Apr	3-May	22-Apr
Penultimate leaf			
Boxworth	6-May	12-May	4-May
Edinburgh	23-May	3-Jun	20-May
Gleadthorpe	10-May	15-May	6-May
Harper Adams	21-May	17-May	14-May
Rosemaund	15-May	15-May	2-May
Sutton Bonington	10-May	13-May	5-May
Last (flag) leaf			
Boxworth	18-May	22-May	14-May
Edinburgh	1-Jun	10-Jun	30-May
Gleadthorpe	21-May	26-May	19-May
Harper Adams	30-May	30-May	26-May
Rosemaund	24-May	24-May	9-May
Sutton Bonington	23-May	24-May	16-May

These data demonstrate the problem in timing fungicide applications to protect the last three 'leaf layers' of the crop. The recommended timing for protection of leaf 3 (flag leaf numbered as 1) is often to spray at GS32. If the mean date of GS32 is compared with the mean date of ligule emergence on leaf three, they are very close. (within one standard error of each other). However, there were six site-season combinations where ligule emergence was more than seven days before or after GS32, and on two of the crops ligule emergence was more than 13 days earlier or later than GS32. We have to conclude that, when timing fungicide applications for a particular crop, it is important to observe leaf emergence rather than stem extension stage, as the latter is not a good indicator of the former.

The timing of the production of the last (flag) leaf varied by over a month across the sites and seasons. The delayed start of leaf production at Edinburgh in 1993 and 1994, led to a delay in the production of the flag leaf compared to most of the other sites, in spite of the very low phyllochron in these years. The delay in completion at Edinburgh was also related to the lower temperatures experienced at this site, rather than an intrinsic feature of the site, since leaf expansion was completed at Edinburgh earlier in 1995 than at Harper Adams in 1993 and Rosemaund in 1993 and 1994. Overall flag leaf emergence was earlier in 1995 than in the other years (Table 2.3).

The maximum number of leaves produced on the mainstem varied from 9.2 to 13.6 with lower numbers occurring at Edinburgh and higher numbers occurring at Rosemaund, Sutton Bonington and Boxworth in 1995. As maximum leaf number is determined as soon as the apex switches from producing vegetative to reproductive primordia, these differences largely reflect variation in development before crop records began. The overall pattern of fewer mainstem leaves at the most northerly site and more mainstem leaves in the more southerly sites was consistent with the other work showing this to be affected by date of emergence and the latitude (Kirby 1992).

In summary, the overall pattern of leaf production across sites was consistent; the differences between sites and seasons were primarily in the timing of the start of rapid leaf production in spring, and in final leaf number.

Plant establishment and shoot production

The total numbers of plants and shoots per square metre are shown in Figure 2. Where the number of plants was monitored from early spring the numbers remained relatively stable. Numbers increased slightly at Edinburgh in 1993 and at most sites in 1994 where late sowing or cold conditions in autumn had delayed emergence. Some plant death was noted due to frost damage between the first and second measurements at Edinburgh in 1994 but the overall effect on plant population was small.

The patterns of shoot number were very variable and only showed a few common features. At all sites the initial number of mainshoots (equivalent to the number of plants) was augmented significantly by the end of the season, when most shoots had become fertile, so determining the number of ears with harvestable grain. Tillering usually resulted in at least a doubling of the number of shoots, although there were a few crops with only a 50% increase in the number of shoots (Boxworth 1995, Edinburgh 1995 and Harper Adams 1993 and 1995).

The increase in shoot number through the season was achieved by different routes between sites and seasons, contrasting with the relatively similar time course of leaf production noted above. The only consistent features were the separation in time of shoot production from shoot death, and the relative stability of shoot numbers for a given crop after the end of June. Shoot production always ceased before leaf production ceased, and shoot death ceased at about the time that ear growth started (Figure 6).

There was a greater similarity in the pattern of shoot numbers across all sites within a season than at a site in successive years. The 1993 season showed either high shoot numbers at the start of measurements, or rapid, early tillering, with the exception of

Edinburgh where tillering was delayed. Also in 1993 the "overproduction" of tillers was relatively modest i.e. the extent of shoot death was relatively small. The 1994 season showed predominant spring tillering, even in the crop (at Boxworth) where there had been some over winter tillering. This was also a year in which, except at Edinburgh, "overproduction" of tillers was relatively large and shoot death in April was relatively high. In 1995 most tillering occurred over winter; spring tiller production was relatively small, probably because of dry spring conditions, and shoot death was relatively low at most sites.

The production of tillers occurred in two principal periods, either before the start of measurements in mid February or in spring. Sites where considerable tillering occurred before mid February were Boxworth and Gleadthorpe in 1993, Boxworth in 1994, and all sites in 1995. At some of these sites (Boxworth and Gleadthorpe in 1993, and Edinburgh, Harper Adams, Rosemaund and Sutton Bonington in 1995) there was little evidence of spring tillering and thus pre-winter tillering played an important role in determining final shoot number. At the other sites (Edinburgh, Harper Adams and Rosemaund in 1993, and all sites in 1995) the majority of tillering occurred in spring. The greatest maximum number of shoots resulted from spring tillering (at Boxworth and Gleadthorpe in 1994).

In determining the final number of fertile shoots, the death of shoots during May was important in most crops, and except in two crops (Edinburgh in 1994 and Harper Adams in 1995), the proportion of tiller death varied from a rapid halving of total shoots (e.g. Boxworth 1994) to a slow reduction over a longer period (e.g. Gleadthorpe in 1993). In most crops showing shoot death, numbers started to decrease at about the end of April, but the onset of shoot death was delayed by about 10 days at Rosemaund in 1994 and by about 30 days at Edinburgh in 1993 and 1994. There was little evidence of involvement of plant death in the decline of shoot numbers.

The result of the considerable variations in the timing and magnitude of the processes of shoot production and shoot death was that in some crops there were long periods of fairly stable shoot numbers, whilst in other crops there were almost continual changes in shoot number until shoot death stopped.

In summary, shoot production, was the most variable process studied. A particular feature was the overproduction of shoots in some crops in relation to the number of shoots that eventually survived. It is common to attribute the death of shoots to competition for resources within the plant, with the younger tillers being less able to compete, principally for nitrogen and light. Here, in some crops (e.g. Boxworth in 1994) the higher rates of shoot death were concurrent with marked increases in rates of nitrogen uptake (Figure 4) and canopy expansion (Figure 5), giving strong circumstantial evidence to support the idea that shoot death was related to competition for nitrogen. However, in other crops (e.g. Edinburgh in 1993) the period of shoot death occurred after the main period of canopy expansion and rapid nitrogen uptake, and at GAIs greater than four; thus competition for light may have had a more important role here. Further study is required to define more precisely the circumstances and resources primarily responsible for determining final shoot number.

Nitrogen uptake and distribution

The nitrogen uptake of the whole crop and the straw are shown in Figure 4. Overall no crop took up less than 200 kg per hectare of nitrogen and many crops took up about 300 kg per hectare. The general pattern of nitrogen uptake was for a small amount to be taken up slowly over the winter, then for an increasing rate of uptake through the spring leading to rapid nitrogen uptake during May. Then, after the ears emerged, there was slow further uptake, accompanied by transfer of nitrogen to the ears, so that most of the nitrogen was held in the ears as maturity approached. Cessation of nitrogen uptake by the crop showed two distinct patterns. At five sites (Boxworth in 1993 and 1994, Gleadthorpe in 1995, Harper Adams in 1995, and Sutton Bonington in 1995) crop nitrogen uptake appeared to stop as ear growth commenced, whilst at other sites it continued during ear growth. At just two sites (Rosemaund in 1993 and Edinburgh in 1995) there was apparent nitrogen loss from the crop as a whole; most crops were successful in retaining the nitrogen they acquired. The redistribution of nitrogen to the ear during development generally ceased at the same time as the canopy died (Figure 5).

Examining the sites individually, the uptake of nitrogen over the winter did vary between crops with Boxworth in 1993 and Rosemaund and Sutton Bonington in 1995 taking up the most. The higher nitrogen uptake seemed to be associated with greater dry weight of the crop and greater shoot numbers. The date of increase in the rate of nitrogen uptake in the spring also varied considerably, with a noticeably early start at Boxworth in 1993. The rates of acquisition of nitrogen also varied considerably; there appeared to be no clear relationship with crop growth, and full resolution of this would need to take into account the time course of nitrogen availability at the root, resulting from soil mineralisation and fertiliser application.

In general the steep line in Figure 4 between straw and ear nitrogen indicates rapid transfer of nitrogen within the plant, from straw to ears. In some cases (e.g. Boxworth in 1993 and 1994, Harper Adams in 1994 and 1995) transfer was very quick. In crops with relatively small initial nitrogen contents and continuing uptake as the ears are growing (e.g. Edinburgh in 1993 and 1994) it can be inferred that newly acquired nitrogen must be deposited directly in the ears as there was no concurrent increase in canopy nitrogen. Without this late nitrogen uptake in the Scottish crops it can be inferred that there would have been low grain nitrogen contents because the early nitrogen uptake was so small.

Crops with large amounts of nitrogen retained in their straw (Boxworth in 1993, Gleadthorpe in 1993, Rosemaund in 1993 and 1994, and Sutton Bonington in all years) tended to be those with highest nitrogen offtakes.

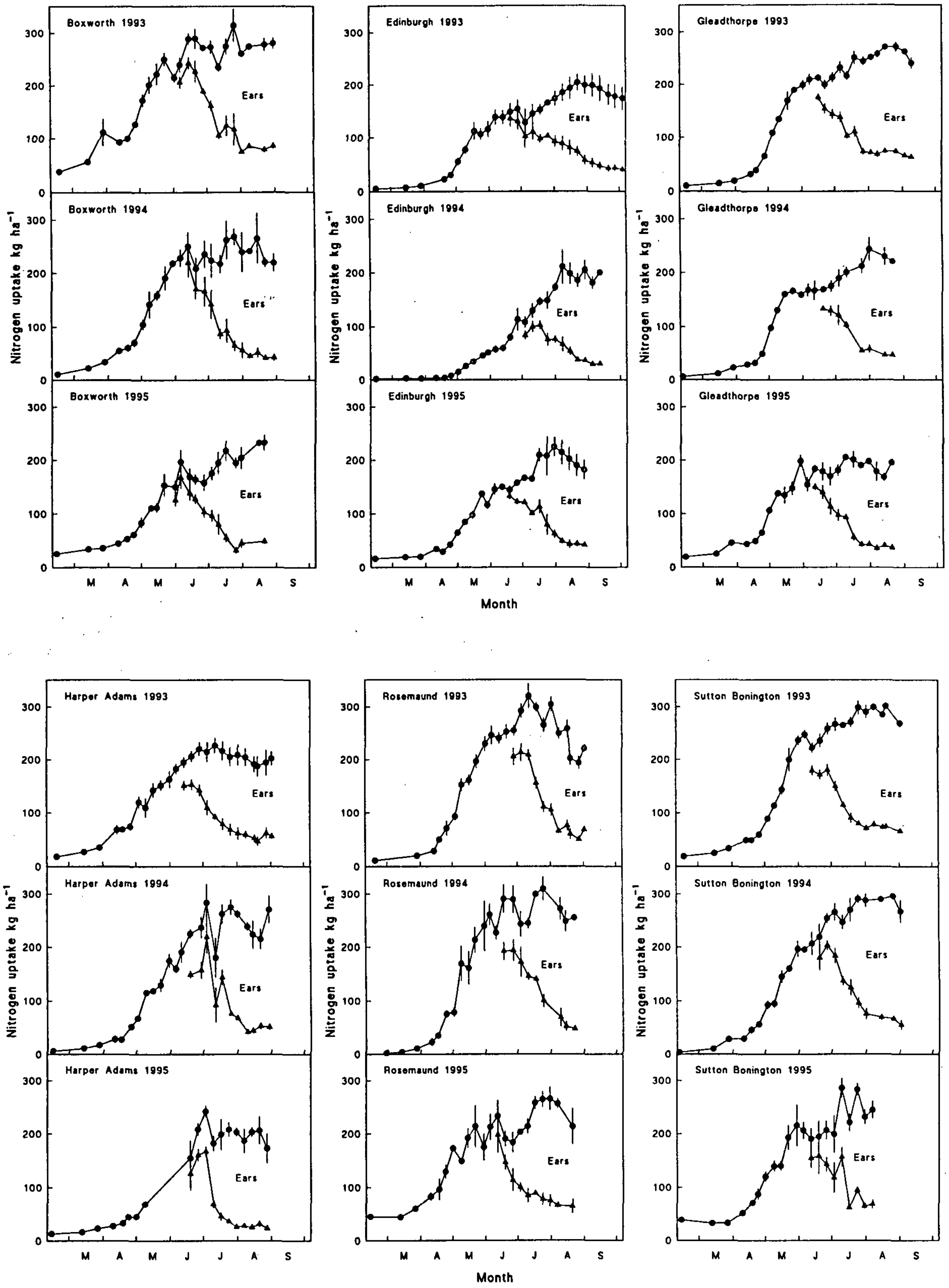

Fig. 4. Time course of nitrogen uptake by whole crop (●) or straw (▲) for Mercia grown at six sites in harvest years 1993, 1994 and 1995. Vertical bars are standard errors of mean.

Canopy expansion and senescence

Figure 5 shows how the expansion and senescence of the leaf blades affects the photosynthetic area of the crop. The area is expressed both as the main photosynthetic component of the canopy, green leaf area index (GLAI) and as the sum of the green leaves leaf sheaths, stems and ears, green area index (GAI). The general pattern was for the leaf canopy to grow at an increasing rate in the spring, until a maximum GLAI was attained in late May, with a maximum GAI being reached some ten days later. Maximum green area was maintained for only a short period. Initial senescence was relatively slow until GAI fell to about 4, after which GAI decreased rapidly to zero at about the end of July.

The green tissues of stems and ears can be taken to be equally effective in photosynthesis on an area basis as leaf blades. The contribution to GAI from stems and ears was small during canopy expansion but was more important in the latter half of the life of the canopy. In these crops, the period with GAI exceeding three was extended by about a week by the contribution from stems and ears. If for any reason the effectiveness of the leaf canopy is reduced, for example by leaf disease or drought, then the contribution by other components of the canopy must assume greater importance.

The largest canopies were present in those crops that had taken up the greatest amounts of nitrogen in the spring, particularly at Boxworth in 1993 (Figure 5). However, early canopy expansion appeared to depend on experiencing sufficient warm days in autumn as well as an adequate soil N supply (Table 1.2); for example, the crop at Edinburgh in 1994 had by far the smallest canopy in spite of an average nitrogen supply. Overall the only major seasonal factor that appeared to restrict canopy expansion in spring was the relative dryness at some sites in 1995; since at sites with slightly higher rainfall more normal sized canopies were produced, presumably through ensuring availability of fertiliser N or alleviating the direct effects of water shortage on leaf expansion. Generally the largest canopies were at Rosemaund, and the smallest at Edinburgh. However, site season interactions were very important in determining canopy size; canopies at Boxworth were particularly variable.

The period over which maximum GAI was maintained differed between crops; those with large maximum GAIs started senescing soonest. The rate of senescence was more rapid than the rate of expansion, perhaps partly due to the higher temperatures during senescence. Although senescence started sooner, and occurred at a higher rate in crops with large GAIs, these crops generally maintained canopies with a GAI greater than four for about the same length of time as other crops.

Although, as noted above, some crops showed nitrogen uptake during ear growth, their rates of canopy senescence were not noticeably reduced; nitrogen taken up in this phase must have been used directly by the ear. Leaf senescence was generally complete, and thus most of the nitrogen present in the leaves redistributed to the ears, well before any general nitrogen losses from the crop could be detected.

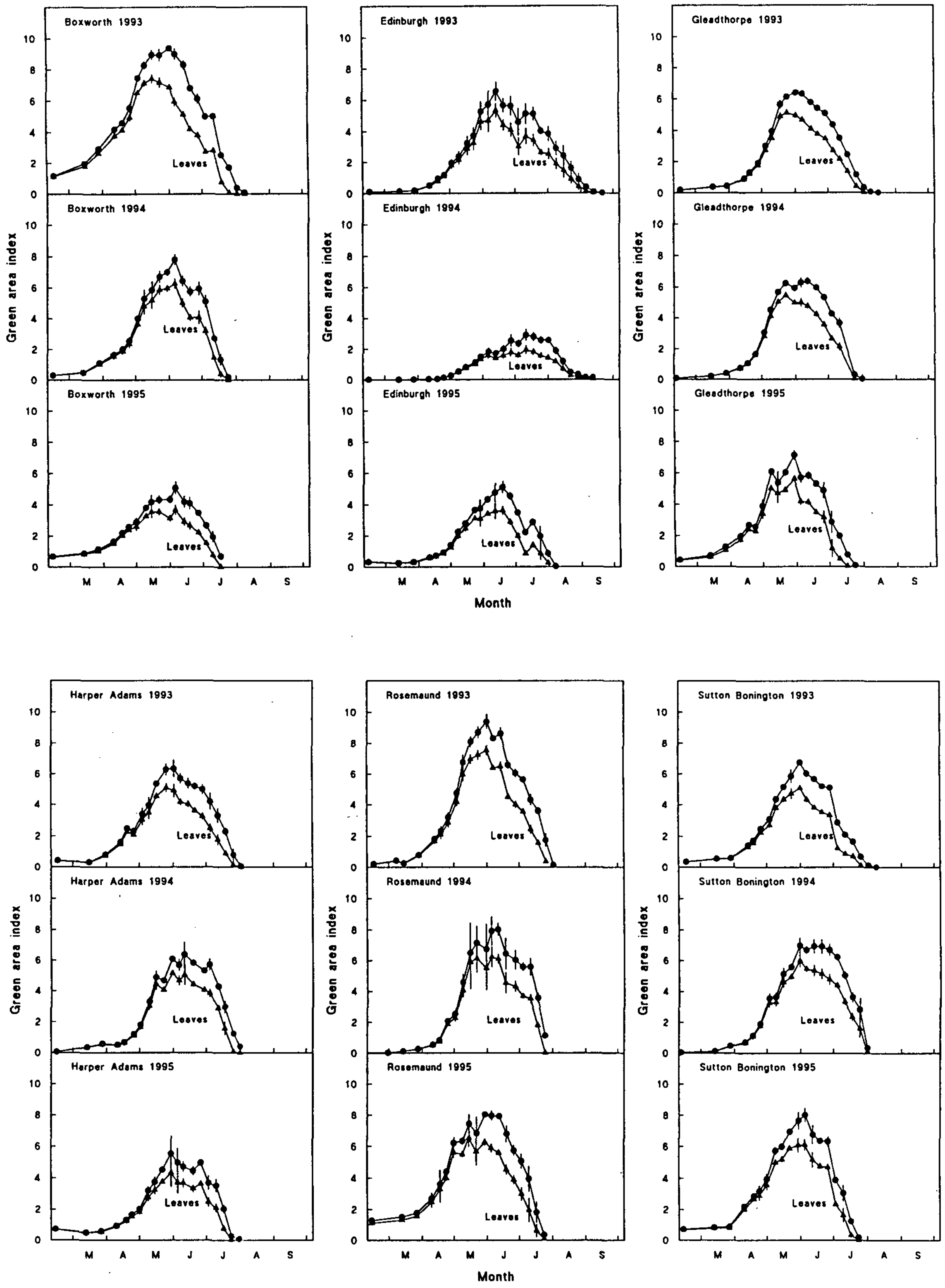

Fig. 5. Time course of green area index (●) or green lamina area index (▲) for Mercia grown at six sites in harvest years 1993, 1994 and 1995. Vertical bars are standard errors of mean.

Dry matter accumulation and distribution

Dry matter accumulation by the whole (above ground) crop and by the ears is shown in Figure 6. Very little dry matter accumulated over winter, and growth in dry matter was slow in early spring, presumably due to the small GAIs and dull light at this time. However, from April dry matter growth rate became almost linear with time, until a maximum crop dry weight was reached, coincident with canopy senescence. At a majority of sites (e.g. Sutton Bonington in 1993) there was some evidence for a short pause (or decrease) in rapid growth in the week or two before flowering. The cause is not clear but these events did not coincide with agrochemical sprays. After canopy senescence the dry weight of some crops decreased slightly, possibly due to the shedding of dead leaves and crop respiration

The apparently linear growth rate with time is often referred to as the 'grand growth' period and occurs when the canopy is intercepting most of the incident light, and here it is defined as that part of the dry weight growth occurring when GAI was above three. There was a two-fold variation in the duration of this phase, with usually a later start and finish in Edinburgh (Table 2.5). There was also considerable variation in the rates of growth, with the lower rates tending to occur in crops of lower GAI, a feature particularly noticeable at Edinburgh in 1994.

Generally the dry matter accumulation at most sites was very similar in 1993 and 1994 but there was a reduction in total dry weight accumulated at the drier sites in 1995. The crops at Rosemaund and Sutton Bonington had relatively high dry weights in all years; at other sites the total dry weights were much more variable between years. There was a small total dry weight at Edinburgh in 1994, but in other years the Edinburgh crops were not exceptionally small.

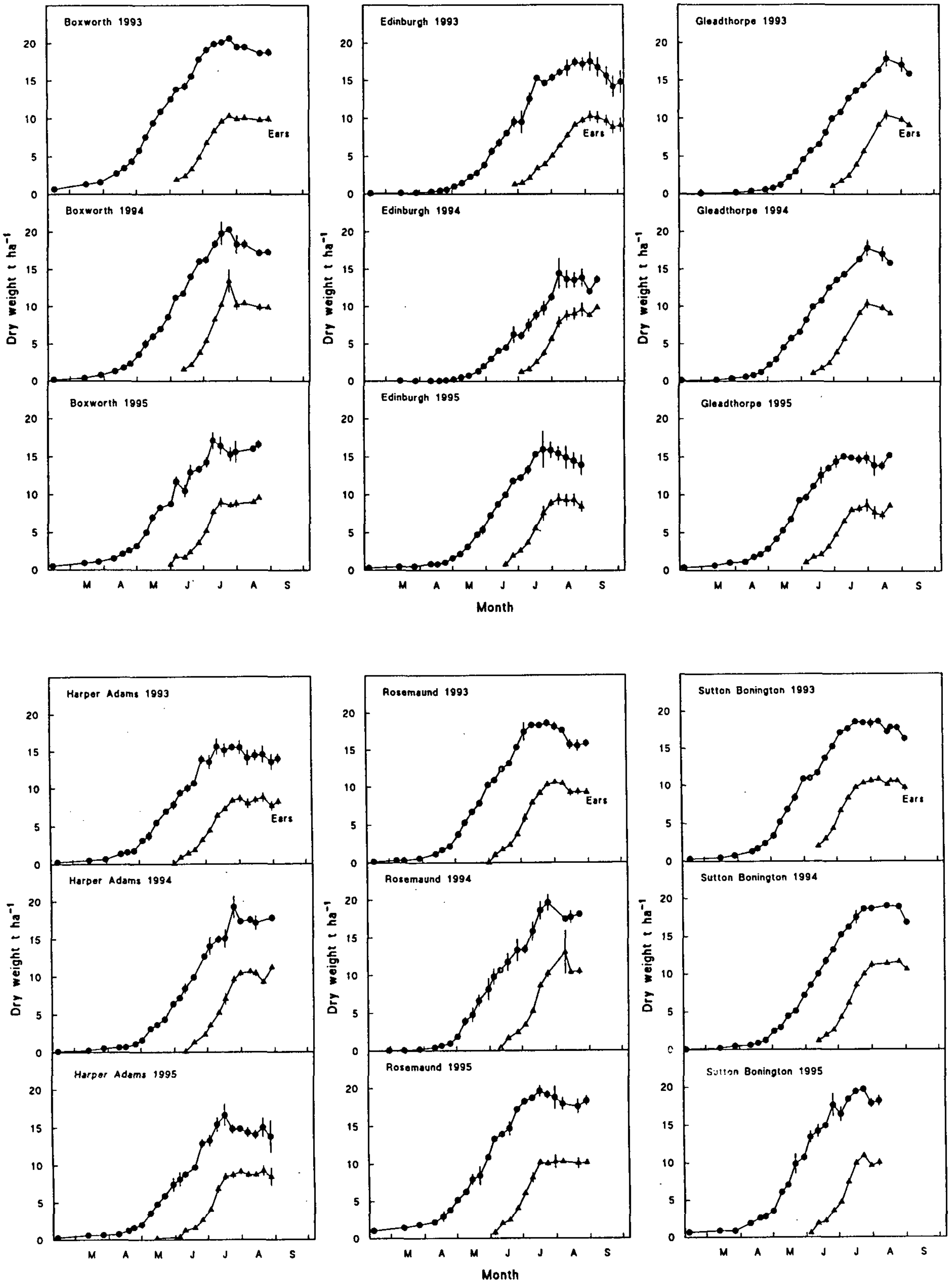

Fig. 6. Time course of total above ground (●) and ear (▲) dry weight for Mercia grown at six sites in harvest years 1993, 1994 and 1995. Vertical bars are standard errors of mean.

Table 2.5. Duration and rate of the 'grand growth' phase, where grand growth was taken as when GAI > 3 (for Edinburgh 1994 GAI > 1.5).

	1993	1994	1995
Duration days			
Boxworth	109	74	60
Edinburgh	84	74*	49
Gleadthorpe	71	72	67
Harper Adams	74	71	66
Rosemaund	88	77	91
Sutton Bonington	63	84	80
Growth rate kg per hectare d^{-1}			
Boxworth	201	216	166
Edinburgh	188	159*	201
Gleadthorpe	183	185	198
Harper Adams	179	202	183
Rosemaund	202	195	204
Sutton Bonington	208	210	213
Standard error of growth rate			
Boxworth	4.8	8.3	20.5
Edinburgh	9.5	25.3	10.0
Gleadthorpe	6.4	5.0	6.2
Harper Adams	7.6	7.9	9.5
Rosemaund	5.5	8.9	6.3
Sutton Bonington	8.7	5.2	11.6

Ear growth generally appeared to account for most of crop growth from just before flowering and generally continued after crop growth had stopped, with reserves from the rest of the plant being transferred to the ear. There was no clear evidence of losses from ears contributing to the losses in total dry weight observed in some crops just before harvest. At harvest, the amount of dry weight present in the ear seemed to be much more constant than the weight of the crop; for example, the relatively large crops at Boxworth in 1993 and 1994 (maximum dry weight of about 20 tonnes per hectare) and the relatively small crops at Edinburgh in 1994 and 1995 (maximum dry weights less than 16 tonnes per hectare) had very similar total ear weights.

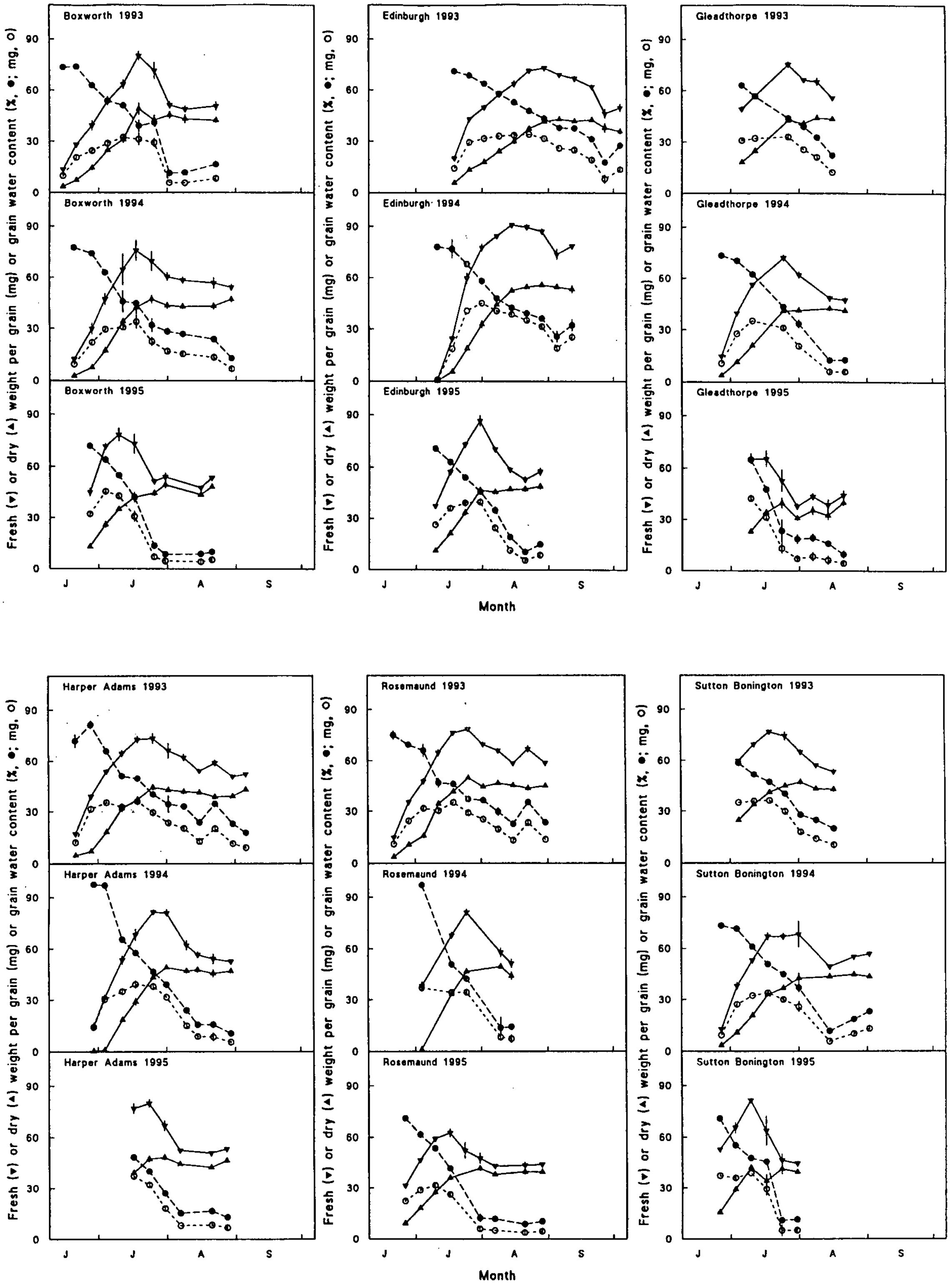

Fig. 7. Time course of filling and drying of central grains in the ear. Water content(%, ●; mg per grain, O*), dry (▲) and fresh (* ▼*) weight mg per grain for Mercia grown at six sites in harvest years 1993, 1994 and 1995. Vertical bars are standard errors of mean..*

Grain filling

The changes in weights (both fresh and dry) of grains taken from a central position in the ear, together with their moisture contents as a per cent, are shown in Figure 7. Generally, filling of these grains started immediately after anthesis, with the grain increasing rapidly in both fresh and dry weight for a period of five to six weeks. Then the flow of both water and dry materials into the grain then ceased, the grain lost water and, where weather remained dry, the rate of drying was maintained until harvest. The end of grain filling generally coincided with grain water content falling below 45%, and this point was often preceded by a week in which the fresh weight of the grain stopped increasing. Generally losses of dry weight from the grains were small, confirming that losses in total dry weight of the crop observed during this period (reported above) were unlikely to affect yield.

Comparing these data with equivalent data collected from whole ears in the two later years of the Project (data not shown), it appeared that, early in grain filling, water content of grains was higher than that of ears, and in about half of the crops studied, ear fresh weight continued to increase for about a week longer than grain fresh weight. However, the time of completion of grain and ear filling on a dry weight basis was very similar for grains and for ears, and it occurred at a similar moisture content. This observation is useful as it may be taken that a water content of 45% or less can be taken as indicative of completion of ear or grain filling and hence allow early estimation of grain yield.

The maximum fresh weight of grains can be taken as indicative of their volume and varied from about 70 mg at Gleadthorpe and Rosemaund in 1995, where drought was probably a factor, to 90 mg at Edinburgh in 1994. Final dry weight of grains varied from 40 mg to about 60 mg at Edinburgh in 1994; however, there was some evidence for stability in final grain weights across sites and seasons. Rates of moisture loss from grains were very variable, being particularly slow at Edinburgh in 1993 and fast at Rosemaund in 1994.

4. FINAL CROP PERFORMANCE

Grain yield

The management of these crops, almost free of detectable yield constraints, resulted in relatively high yields at all sites for the variety used, Mercia (Table 3.1). Undoubtedly the higher yielding 'feed' varieties, or higher yielding breadmaking varieties which are now available would have given greater yields. It is expected that studies of growth and development in parallel projects of wheat varieties (e.g. Project No. 0037/1/91) can be used to indicate the facets that mainly account for these improvements.

The protocol used was based on prophylactic treatments with agrochemicals, but it is unlikely that yields would have been substantially different if husbandry decisions had been made according to normal commercial criteria.

Table 3.1. Combine harvested yield from six sites in three seasons.

	1993	1994	1995
Yield tonnes per hectare at 15% moisture content			
Boxworth	8.61	9.35	7.67
Edinburgh	9.49	9.07	8.98
Gleadthorpe	9.08	8.72	7.40
Harper Adams	8.31	9.89	8.56
Rosemaund	9.73	8.89	9.61
Sutton Bonington	9.15	10.60	9.93
Standard error			
Boxworth	0.05	0.04	0.09
Edinburgh	0.33	0.27	0.19
Gleadthorpe	0.12	0.13	0.07
Harper Adams	0.25	0.11	0.22
Rosemaund	0.06	0.22	0.44
Sutton Bonington	0.05	0.09	0.53

There was so much inconsistency between seasons across sites and between sites across seasons that there were no simple patterns in yield with either sites or seasons. However, as far as the sites are concerned, it is worth noting that Gleadthorpe had the smallest average yield and Sutton Bonington the largest. These two sites are both in central England and hence had similar weather. The main difference between them was probably in the moisture-holding capacity of their soils; yields at Gleadthorpe would be expected to be relatively good in moist seasons. This is supported by the smallest difference between the two sites being in 1993, the year with most summer rain.

As for the differences between seasons, 1993 gave the smallest average yield and 1994 the largest. These differences do not relate to summer rain; they appear to relate to the amounts of sunshine in these seasons, during the important grain filling months of June and July.

Thus to account for as much of the variation between individual sites and seasons as possible it will be necessary to deal with individual cases and take (at least) rainfall, soil water holding capacity, and summer sunshine into account, and to track their influences through the progress of each season.

Table 3.2. Grain yield for six sites in three seasons from quadrats harvested by hand at the time of combine harvest, calculated as the product of ear number per unit area (Table 3.5) and grain yield per shoot.

	1993	1994	1995
Grain yield tonnes per hectare at 100% dry matter			
Boxworth	7.87	8.87	6.92
Edinburgh	7.62	7.77	7.33
Gleadthorpe	8.59	7.88	5.74
Harper Adams	7.06	7.61	7.10
Rosemaund	7.82	8.65	7.46
Sutton Bonington	8.85	9.39	na
Standard error			
Boxworth	0.28	0.42	0.41
Edinburgh	0.74	0.15	0.66
Gleadthorpe	0.28	0.25	0.71
Harper Adams	0.77	1.12	0.39
Rosemaund	0.36	0.50	0.17
Sutton Bonington	0.16	0.11	na
Hand harvested less combine harvested grain yield tonnes per hectare at 100% dry matter			
Boxworth	0.55	0.92	0.26
Edinburgh	0.00	0.06	-0.30
Gleadthorpe	0.87	0.47	-0.55
Harper Adams	0.00	-0.80	-0.18
Rosemaund	-0.45	1.09	-0.71
Sutton Bonington	1.07	0.38	na

A difficulty in the explanation of variation in yield is in relating the combine-harvested grain yields to the grain yields from hand-harvested quadrats (Table 3.2). The combine yields clearly represent the yields that would have been obtained under commercial conditions, whilst the quadrat yields represent the final performance of these crops, measured using methods closely compatible with all the preceding measures of crop growth. The two measures were taken from alternate plots in one small block of land. Differences between plots can thus be expected to include some imprecision but no inaccuracy (bias). Standard errors for combine measurements (Table 3.1) were generally small compared to those from the quadrats (Table 3.2) because of their much larger area harvested. There were discrepancies between the two measures at most sites, mostly within the sum of their standard errors. However, in seven of the 18 cases this was not so, the worst discrepancy in this respect being at Sutton Bonington in 1993, where the quadrat yield was more than 1 tonnes per hectare greater than the combine yield.

Although considerable care was taken in the determination of yield in this study, it will be desirable to make further improvements in the precision and accuracy with which yield is determined in future studies. There are many possible sources of inaccuracy in the determination of yield (enumerated and discussed by Bloom 1985), and although differences were inconsistent here, the overall average quadrat yield exceeded the overall average combine yield by 0.16 tonnes per hectare, indicating that there may have been bias as well as imprecision. For the time being, further discussion will take the hand-harvested quadrat yields as the most appropriate estimate of crop performance, given that the hand method of measuring yield was the same as that used to measure growth.

Yield in relation to growth

Partitioning

Yield can be considered as a portion of total above-ground growth. Total crop dry matter at harvest was determined from the quadrats, but was also estimated from the combine plots by dividing the combine-harvested grain yield by the harvest index from grab samples. Both methods gave similar results on average but there were particularly large discrepancies at Rosemaund in 1993 and 1995 (combine exceeded quadrat by 2.4 tonnes per hectare in each case). The results shown in Table 3.3 are from the quadrats. They show generally less total growth in the dry year of 1995, generally large total growth at Sutton Bonington and small total growth at Edinburgh. Whilst the range in quadrat grain yield was 3.7 tonnes per hectare, the range in total dry matter was greater at 7.0 tonnes per hectare.

Table 3.3. Total above ground dry matter at harvest for six sites in three seasons determined from quadrat samples.

	1993	1994	1995
Total above ground dry matter tonnes per hectare			
Boxworth	18.7	19.9	15.3
Edinburgh	15.0	12.9	14.5
Gleadthorpe	16.6	16.1	13.9
Harper Adams	14.5	16.1	13.6
Rosemaund	15.7	17.2	16.8
Sutton Bonington	17.8	18.3	18.2
Standard error			
Boxworth	0.39	1.61	0.52
Edinburgh	0.15	0.22	1.36
Gleadthorpe	0.56	0.26	1.42
Harper Adams	1.17	0.44	0.50
Rosemaund	0.65	0.09	0.79
Sutton Bonington	0.37	0.44	0.70

Taking the ratio between grain and total dry matter, the harvest index, as an efficiency index relating yield with total growth (Table 3.4), there was a tendency ($0.1 < P < 0.05$)

for the crops with the highest total dry matter to have the lowest harvest index and vice versa. Thus, crops with large biomass did not necessarily have large yield. Although there were some discrepancies between the two attempts at estimating harvest index (Table 3.4), it is clear that the range in harvest index was large, from about 40% to 60%, and counter to the general premise that arose from work in the '70s and '80s showing greater stability in harvest index than in total dry weight (e.g. Gallagher & Biscoe, 1978a,b).

Table 3.4. Harvest index for grain from six sites in three seasons from grab samples taken from the combine-harvested plots.

	1993	1994	1995
Harvest index %			
Boxworth	37.0	43.8	42.0
Edinburgh	50.8	58.9	52.8
Gleadthorpe	51.1	50.1	42.5
Harper Adams	48.3	51.6	46.7*
Rosemaund	46.2	45.7	42.7
Sutton Bonington	48.2	49.6	47.8
Standard error			
Boxworth	0.7	0.8	1.8
Edinburgh	0.7	0.6	0.8
Gleadthorpe	0.5	0.4	0.6
Harper Adams	1.1	0.7	0.8
Rosemaund	1.2	0.3	1.5
Sutton Bonington	0.4	0.6	1.2
Difference in harvest index (quadrat less grab)			
Boxworth	5.2	0.7	3.1
Edinburgh	0.0	1.4	-2.1
Gleadthorpe	0.8	-1.1	-1.2
Harper Adams	0.3	-4.3	na
Rosemaund	3.8	4.6	1.7
Sutton Bonington	1.5	1.9	na

* *'Grab' sample data are not available, so data are from the 'quadrat' sample taken at the same time.*

If the apparent independence of grain dry weight and total dry weight found here can be shown to hold more widely, for instance with other contemporary varieties, it would seem that we may have to identify another approach, if we are to improve understanding of variation in grain yield. It is therefore worth seeking other ways to understand variation in grain yield.

Components of grain yield

Grain yield can be considered as the product of ears per square metre, grains per ear and weight per grain. There was larger variation in number of ears per metre^2 (Table 3.5) than in either grains per ear (Table 3.6) or weight per grain (Table 3.7); ears per metre^2 was the only one of these three components to be significantly related to grain yield (r^2

0.25, P 0.04). All individual components varied more than grain yield, indicating considerable inter-component compensation. However, ears per metre^2 is largely set before grains per ear, which is determined before weight per grain. Since ear number was the only component to be related to yield, it can be concluded that compensation was incomplete, and that there is value in pursuing this approach further, when seeking to understand variation in yield.

Table 3.5. Ears per square metre from six sites in three seasons. Data are from hand-harvested quadrats.

	1993	1994	1995
Ears per m^2			
Boxworth	696	665	425
Edinburgh	534	494	596
Gleadthorpe	594	674	523
Harper Adams	515	568	464
Rosemaund	606	602	569
Sutton Bonington	596	649	633
Standard error			
Boxworth	19	25	14
Edinburgh	81	40	56
Gleadthorpe	45	10	49
Harper Adams	48	14	10
Rosemaund	23	49	28
Sutton Bonington	20	28	46

Table 3.6. Grains per ear from the six sites in three seasons, calculated from hand-harvested quadrats.

	1993	1994	1995
Grains per ear			
Boxworth	26.4	34.5	40.7
Edinburgh	35.5	36.0	28.2
Gleadthorpe	35.2	32.0	33.4
Harper Adams	37.0	28.9	34.5*
Rosemaund	32.7	32.5	39.6
Sutton Bonington	35.5	36.4	na
Standard error			
Boxworth	0.77	0.86	3.23
Edinburgh	1.77	1.60	0.09
Gleadthorpe	1.38	1.23	0.79
Harper Adams	1.16	1.12	0.92
Rosemaund	1.03	0.76	2.28
Sutton Bonington	0.52	0.87	na

* *Concurrent quadrat data not available. Data taken from quadrat sample in preceding week.*

Compared to other varieties Mercia shows relatively numerous ears but few grains per ear and light grains (Final Report on HGCA Project 0037/1/91). There were fewer ears per square metre in 1995 than in the previous two seasons, perhaps due to the dry spring and some inhibition of nitrogen uptake during tiller survival period. Harper Adams had the fewest ears compared to the other sites. However, these effects were not statistically significant and the variation in ear number was wide, from 425 to 696 m^{-2}.

At most sites, grains per ear was determined independently on hand-sampled plots (Table 3.6) and combine-harvested plots (from grab samples). On average the quadrat samples gave one more grain per ear than the grab samples. There is no obvious reason for this since, after sampling, the methods of measurement were the same. In two cases (at Harper Adams and Rosemaund in 1994) there were differences of about 10 grains per ear, so these estimates must be considered very uncertain.

There were about two more grains per ear in 1995 than in the two previous seasons, presumably to compensate for the fewer ears. The range in grains per ear was from 26 to 41, but there were no consistent site effects.

Table 3.7. Weight per grain from six sites in three seasons; data are from a sub-sample taken from the hand-harvested quadrat and threshed in a small scale thresher.

	1993	1994	1995
Weight per grain mg at 100% dry matter			
Boxworth	43.0	38.7	40.2
Edinburgh	41.7	44.0	43.6
Gleadthorpe	41.6	36.5	32.7
Harper Adams	37.0	46.3	37.0*
Rosemaund	39.4	44.4	33.6
Sutton Bonington	41.6	39.7	na
Standard error			
Boxworth	0.23	1.25	1.60
Edinburgh	0.80	3.46	1.37
Gleadthorpe	1.43	0.37	1.74
Harper Adams	1.11	0.90	3.20*
Rosemaund	0.51	2.24	2.75
Sutton Bonington	0.40	0.57	na

* *Concurrent quadrat data not available. Data taken from quadrat sample in preceding week.*

Weight per grain was also determined on the same samples as grains per ear, and there were similar discrepancies, the greatest being at Boxworth in 1993 where the grab exceeded the quadrat determination by 6 mg. However, the average grains per ear was the same from both samples.

Weight per grain was less in 1995 than in either previous year, presumably associated with the prolonged drought in that year. The range in weight per grain was from 33 to 46 mg, with Gleadthorpe showing the lightest grains in the two dry years, 1994 and

1995, and Edinburgh showing the heaviest grains. There was no obvious or significant relationship between weight per grain and grain yield.

Grain quality

Grain protein concentration

Grain protein ranged from 8.5 to 11.8%. There were only small differences between years, with the greatest protein concentration in 1993. According to the usual criterion for breadmaking flour, (minimum protein concentration 11%, NIAB Cereals variety handbook 1997) only 5 of the crops had a high enough protein content to qualify as breadmaking wheat. The protein concentration did not appear to have a strong relationship to the total amount of nitrogen taken up by the crop, nor did it appear to be associated with more nitrogen being transferred from straw to ears. The only site where protein concentrations were acceptable in more than one year was Rosemaund. Edinburgh was the site with the lowest protein concentration, and Boxworth also failed to have acceptable protein concentrations. The largest number of acceptable protein concentrations occurred in 1993.

Table 3.8 Protein concentration of combine harvested grain from six sites in three seasons.

	1993	1994	1995
Grain protein at 14% moisture content			
Boxworth	10.9	9.5	10.1
Edinburgh	8.5	9.9	9.8
Gleadthorpe	10.6	10.0	11.8
Harper Adams	11.6	9.2	10.2
Rosemaund	11.1	11.6	10.4
Sutton Bonington	11.8	10.6	9.3
Standard error			
Boxworth	0.10	0.29	0.36
Edinburgh	0.36	0.02	0.14
Gleadthorpe	0.08	0.14	0.22
Harper Adams	0.12	0.17	0.15
Rosemaund	0.08	0.13	0.03
Sutton Bonington	0.07	0.29	0.36

Specific weight

In contrast to the situation with protein concentration specific weight of the grain was generally above the minimum value required. Specific weights were least in 1995, but only two sites, Edinburgh in 1993 and Gleadthorpe in 1994 produced grain of specific weight so low that it could result in price reductions.

Table 3.9. Specific weight of combine harvested grain of the crops from three seasons at six sites.

	1993	1994	1995
Grain specific weight at 15% moisture content kg/hl			
Boxworth	83.2	80.6	80.3
Edinburgh	74.4	77.5	82.6
Gleadthorpe	79.9	79.4	74.9
Harper Adams	77.4	78.0	78.2
Rosemaund	82.4	78.1	77.8
Sutton Bonington	79.5	80.8	79.0
Standard error			
Boxworth	0.10	0.16	0.24
Edinburgh	0.56	0.29	0.19
Gleadthorpe	0.44	0.03	0.61
Harper Adams	1.14	0.69	0.37
Rosemaund	0.37	1.64	0.33
Sutton Bonington	0.32	0.39	0.27

Table 3.10. Hagberg falling number of combine harvested grain of the crops from three seasons at six sites.

	1993	1994	1995
Hagberg falling number s			
Boxworth	318	406	320
Edinburgh	125	272	322
Gleadthorpe	340	426	332
Harper Adams	425	323	284
Rosemaund	402	419	315
Sutton Bonington	387	327	323
Standard error			
Boxworth	7.5	6.7	3.3
Edinburgh	6.7	9.2	3.1
Gleadthorpe	4.9	4.1	5.4
Harper Adams	7.7	10.4	6.4
Rosemaund	7.0	17.5	9.9
Sutton Bonington	3.7	6.9	11.6

Hagberg falling number

Generally HFNs were well above 250 s, the minimum for breadmaking in the UK, as would be expected in this variety, and there were a few crops with values above 400. The low HFN at Edinburgh in 1993 and 1994 is probably related to the relatively long, slow grain filling and drying phases at this site, since by the time of harvest some of the more advanced grains may have commenced germination, with the accompanying large effect on HFN.

5. DISCUSSION

The dataset presented here allows an assessment of the importance of site and season in governing wheat development, growth and performance in the UK. It appears that the way that 'performance' arose was more variable than performance itself. The coefficient of variation for the 18 yields was only 8.5%. This may be a feature of the particular variety employed, since Mercia has been shown, of recently recommended varieties, to be the one least responsive to 'site potential' (NIAB 1995). Mercia is also lower yielding than all the present recommended varieties, so it is unlikely to have expressed the full potential of the growing conditions here. Although it is important to use a variety with perennial commercial interest in studies such as this, it may be necessary to identify candidates which accentuate the environmental effects on yield as well as growth.

However, concurrent with this Project, a parallel Project (HGCA Code 0050/1/92) entitled 'An integrated approach to nitrogen nutrition' also measured growth and yield at a range of sites throughout England and Scotland using the variety Mercia. In this case there were a similar number of sites: 4 in 1993, 6 in 1994 and 8 in 1995, but the husbandry conditions were purposely varied in terms of sowing date and residual nitrogen. The median grain yield was similar at 9.0 tonnes per hectare but they were more variable, ranging from 5.3 to 10.7 tonnes per hectare, with a coefficient of variation of 15%. It is therefore likely that the consistent husbandry in the dataset here was important in reducing yield variability.

The structure of the dataset generated by this study is such that there is more scope to interpret seasonal effects than site effects. There are six sites for each season whereas there are only three seasons for every site, and the crops monitored at each site were normally in different fields, and therefore with somewhat different soils each season.

It is to be hoped that, if the flow of information can be dramatically speeded up, exercises such as this would be appropriate for providing intelligence to the industry about the progress of development and growth as each season unfolds (see the Introduction to *Volume II 'How to Run a Reference Crop'*). It is therefore of interest the extent to which the seasonal differences identified here related to the general performance of the crop in each of these seasons as far as we know it from national statistics. Figure 8 shows a comparison of the mean yields for the three seasons with the national yields as reported by MAFF. There are insufficient data for a statistical assessment but, as far as can be seen, there is no indication of a useful relationship.

There are clearly many issues that need to be addressed here if crop monitoring is to be taken as indicative of much wider crop progress. Not only the respresentativeness of the variety, as discussed above, but the respresentativeness of the sites in terms of geographic distribution, soil type and rotational position and the choice of husbandry in terms of sowing dates, seed rates and subsequent use of fertilisers and agrochemicals. Probably it will be best to maintain a rigid protocol and assume that the interactions between these factors will be less important than the factors themselves. Given a sufficient number of sites and a sufficient period of years it is almost certain that the predictive power of such an exercise will become evident. This can be seen from looking at the relationship between the yields from just one farm, Boxworth, through the 10 years of the 1980's and the national yields (Figure 8).

Looking now at development and growth, it has been difficult to show clear season or site effects. Evidently it will be important to interpret the progress in any season according to the characteristics of each site; only limited value would be gained from assuming that seasonal effects could be taken into account in decision making without consideration of the way that these might be modified for each particular field.

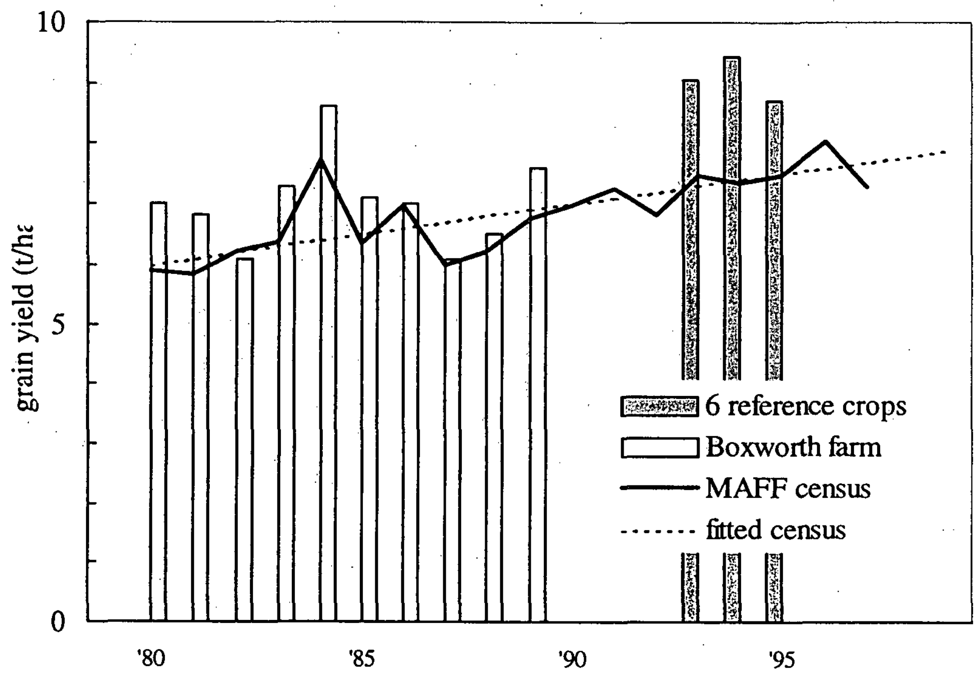

Figure 8. *Grain yields determined from the MAFF census, from the average of all fields at ADAS Boxworth and from the six 'reference crops' in the dataset described here.*

The prospect of operating a perennial reference cropping exercise is attractive since, as the number of monitored seasons increases, site and regional patterns in development, growth and performance will become more and more evident. In just the three years monitored here it is only possible to identify a particular contrast between the Scottish site and the English sites. Edinburgh clearly showed less growth and slower development through the winter and early summer. For the most part, the canopies were remarkably small yet, due to their persistence, the production of grain was not compromised. Grain filling continued into August in Scotland whereas it had always finished by the end of July in England.

It is not possible to attribute the differences in Scotland to particular effects, since there are several coincident differences in the growing conditions: the soil usually has more organic matter (though not according to Table 1.2), it is colder, has longer days and more rainfall. These differences indicate that the pattern of nitrogen nutrition is likely to have been different; the later harvest and cooler conditions after harvest will generally have resulted in less mineralisation of organic N in the autumn, the greater rainfall will have caused more leaching potential over winter (though perhaps no more actual N loss), and the slower growth and depletion of topsoil moisture will have resulted in more mineralisation of N during summer. It is also likely that the greater summer rainfall would provide increased availability of fertiliser N.

There are not such extreme differences between the English sites. Geographically it would probably be necessary to introduce sites in southern counties and in Yorkshire and Northumberland in order to sense regional effects with any confidence. It may also be necessary to discriminate between central and northern Scotland. As far as soil type is concerned, the main effect appeared to be the greater evidence of drought in 1994 and 1995 on the loamy sand soils at Gleadthorpe. Clearly from our work under Project 0037/1/91 at Gleadthorpe there were responses to irrigation in both these years, and in 1996. It will be important to have a sub-set of sites where it is possible to detect the importance of drought in each season, so that these can be extrapolated across the wide range of soils on which wheat is grown.

As far as the husbandry of these crops is concerned, there is a need for persistent vigilance. Despite intentions of achieving crops unaffected by pests, weeds or diseases it did not prove possible to avoid poor establishment in the autumn of 1993, and over-compensation for poor establishment (so that plant numbers were unsatisfactorily high) in other years. On the light soils, despite precautions, there was significant take-all and manganese deficiency in one crop.

The nitrogen of these crops was made according to conventional practice, whereas it has been shown concurrent with this project (under Project 0050/1/92) that it is possible to reduce variability in nitrogen nutrition by using soil mineral N analysis to estimate soil nitrogen supply. It may also be useful to attempt to moderate fertiliser applications, according to the principals of Canopy Management (Sylvester-Bradley *et al.* 1998) so that canopy size is less variable across the sites.

The variation in growth, both in terms of canopy size (GAI) and total dry matter in the dataset was much larger than the variation in grain yield. One of the important features this revealed was that just producing a large total dry weight did not necessarily lead to very high yields, as grain growth appeared to vary independently of total dry weight; harvest index varied by as much as total dry weight. The approach to explaining this independence of grain yield from total growth developed during the project is explained in '*The Wheat Growth Guide*' (Sylvester-Bradley *et al.* 1997). It seems best to consider that the crop is accumulating a source of redistributable reserves before flowering, and that at the same time it is determining the number of grains that will be available to fill. Grain yield then depends on whether there is sufficient storage capacity and whether photosynthesis during grain filling and the accumulated stem reserves will be successful in filling this capacity.

If wheat crops in the UK are to be managed according to the progress of the crop it will be necessary to provide intelligence, not so much about total accumulation of dry matter, but about (a) the accumulation of stem reserves, (b) the determination of grain number and (c) the potential for complete and prolonged light interception by the crop's canopy during grain filling. Canopy size will be very variable from field to field but can be assessed on the farm. On the other hand, stem reserves and potential grains per ear will be difficult to determine on the farm but could be estimated from weather data and intelligence from reference crops. During May and June, when these components are being determined, light interception can be considered complete for almost all crops, so the radiation levels (which directly drive photosynthesis) and temperatures (which determine the duration of growth phases) can be treated as the main controlling variables.

The provision of such remote intelligence may seem problematical, since it can take so long to collect, collate and interpret crop measurements from disparate geographical sites. However, during the course of this project the collaborators attempted to test such a system; crops were sampled on Mondays during the main growing season, principal crop data including dry weights and weather data were provided to the coordinator on the Wednesday, and the collated and interpreted data were returned to the collaborators by the Friday. The mechanisms of the data transfer and interpretation are largely open to increased automation. It therefore seems feasible that crop intelligence could be provided to the industry within the timescale of decision making.

The precision of the data collected was generally good. However, the effort needed to check the data has far exceeded anything that was originally envisaged, and there are aspects of the data collection which could be improved further. For example, there are indications of a pause in growth in crops for which there was a prolonged period between ear emergence and flowering (Figure 6). The frequency of sampling was not sufficient to be confident of the duration of this effect. Destructive sampling dictates that spatial variation, from quadrat position to quadrat position, will always underly temporal changes; it would be useful to develop non-destructive techniques for monitoring the carbon fixation of crops over such important periods. Similarly, it may prove possible to use spectral reflectance techniques or leaf extension sensors (auxanometers) to monitor the canopy expansion and senescence of green canopies in a more continuous and therefore reliable way than with the destructive sampling methods that were employed here.

Undoubtedly the collection of data was very laborious in these studies. It will be necessary to examine whether it was necessary to collect such comprehensive measurements. The comprehensiveness of the measurements has been useful so far in terms of quality control; several separate measurements have been taken of the same attribute (see for example the discussion of bias and imprecision in relation to yield) so that cross checking and replacement of missing data has been possible. If the reliability of these simple but deceptively difficult measurements can be improved it may prove possible to reduce the need for these double checks. Also, some measurements, for instance of the numbers of dead and dying shoots (not reported here), will not be important for the purposes of tracking crop progress.

It is important not to overlook the quality control effort that has been required to provide these data. The prospect of coordinating a large number of collaborators for whom the methods are novel yet misleadingly simple is challenging; the challenge must be grasped. Exploitation of the crop knowledge depends on good quality crop observations and assessments. All the experience gained in this project highlights a strong requirement for training and effort to simplify and automate as far as is possible. As an example, ear number is commonly calculated indirectly, by dividing weight per ear into combine harvested grain yield. This, and similar indirect methods, clearly have the potential to mislead, through compounding of errors and biases.

There is considerable further scope in the data reported here to extract further explanations and understanding of the more detailed facets of crop growth, for instance through the data on dead shoots. Further examples are that the nitrogen uptake data can be interpreted in terms of its supposed direct effect on canopy expansion, the importance of dry matter in providing for canopy expansion can be examined, and the degree to which soluble stem reserves contributed to grain filling can be assessed.

Through projects conducted concurrently with this Project it has become evident that there will be a need to introduce new measurements in order to properly assess crop progress. For instance the depth of the rooting crown and the dimensions of the rooting cone are important in countering lodging (Berry *et al.* 1998) and the alpha amylase content and germination capacity of the grain during grain filling indicates the potential for sprouting (Kettlewell *et al.* 1998).

The measurements taken here only began in spring. The work to develop Canopy Management has shown the importance of determining a potential number of shoots over winter which can be manipulated to form and adequate canopy. It would be important in future to take some simple measures of plant establishment in the autumn and development of shoots over winter if this aspect of crop progress is to be revealed.

The methods for monitoring development in this study were those in use by the industry. However, the study has placed focus on particular stages which are not well defined by the decimal code (Tottman 1987). There is a need to define stages which clearly identify the appearance of the last four leaves; at present only flag leaf emergence is identified. Also, stages which clearly identify the development of the ear in the 'boot', replacing the stages of 'booting'; perhaps meiosis could be identified by proving synchrony with ear extension (Snape & Worland, personal communication). Also stages which discriminate the events during filling of the grain; the project has indicated that grain moisture content would be better than the present descriptions of endosperm texture.

Turning to the assessments of growth made here, there has been a certain shift in approach during the research, from attempting to explain growth simply in terms of energy capture and dry matter accumulation, to an appreciation of the need for a more sophisticated and therefore challenging analysis, involving estimation of sink capacity as well as energy capture. The challenge will be to integrate and prioritize the processes identified through this more complex approach so that an industry which is seeking to control its costs and its outputs can do so with as simple and therefore time-efficient judgments as possible. For most growers it must be recognised that the state of understanding reached here is prohibitively complex as a basis for decision taking.

A more straightforward description of the analysis developed through this and parallel projects is presented in '*The Wheat Growth Guide*'. An example of the data necessary for this is shown in Figure 9. In summary, it has been shown that there are four phases of canopy life, slow expansion over winter, fast expansion in May, followed by slow and then rapid senescence. Leaf weight is are very small in relation to total crop weight; the leaves at the time of ear emergence contribute 85% of the crops green surfaces but only 15% of its dry weight. Nitrogen and moisture are seen as being far more important than dry matter in providing for and controlling the expansion of the canopy. The stability of the Canopy Nitrogen Requirement (CNR; Sylvester-Bradley *et al.* 1997) throughout the phases of expansion and senescence and the greater variability of specific leaf area (SLA) are indicative of this conclusion.

The Dataset

Understanding of the importance of photosynthesis and the way that photosynthesis is controlled has come through a parallel MAFF-funded project at ADAS Terrington where mobile shades have been used to test the effects of dull conditions during the phases of the crop's life shown in Figure 1. This has re-emphasised how dry matter accumulation relates strongly with radiation receipts but that there are modifications to the conversion coefficient between energy and crop dry weight, ε. This variability was not appreciated at the start of this project it is better appreciated now, but it still needs better explanation (Gillett 1997). However, it has been shown that a reduced sink size, for instance due to shading during determination of grains per ear, can result in subsequent reduced growth and reduced ε. The accumulation of stem reserves which are subsequently redistributed during grain filling appears to occur earlier than had been originally supposed; in good growing conditions water soluble sugars can reach near maximal amounts concurrent with stem extension. Thus sugar deposition in the stem and expansion of the ear can occur concurrently, between flag leaf emergence and ear emergence. The period just before flowering can be considered as an opportunity to replenish stem reserves but an opportunity that may not be required if growing conditions have been satisfactory beforehand. However, it should be noted that the variety Mercia, as used here, and the variety Slepjner, as used in the shading study, both have limited capacity to store soluble stem reserves. Varieties with larger capacities may need longer periods for stem storage.

The stability of rates of dry matter accumulation by the crop has been noted for a long time and has led to the concept of a 'grand phase' of growth (Monteith & Scott 1980); this stability is evident in the data presented here and the difficulty in reconciling the concepts of a constant ε with constant growth in an environment of varying but generally increasing radiation levels must be faced. Clearly there are short term perturbations in growth rates from week to week but the general stability of growth implies a degree of predetermination, perhaps through feed-forward effects of growing conditions in one phase through sink determination for the succeeding phase. It is interesting that, although total dry weight did not relate well to grain yield, there was a weak but positive and statistically significant association between growth rate and grain yield (Figure10).

The apparent importance of 'sink' in governing growth and yield raises a requirement for better quantification and explanation of sink determination and sink capacity. At present the literature does not appear to offer any useful yardstick for sink capacity; the most favoured option developed during this work appears to be in considering sink in terms of organ volume. Since organs grow first by cell division and cell expansion, there is an initial phase of volume growth which is only followed by weight growth. As shown by the work of Macbeth (1996) on grain filling within this project, it is possible to regard this sequence as first a creation of capacity and second a fulfillment (or otherwise) of that space. Volume growth tends to be associated most with temperature and nitrogen supply, whereas weight growth has been more closely associated with light interception. The two are inevitably inter-linked but the disassociation of temperature and light that can be a feature of British weather may be a component of the variation in crop growth which has been so difficult to account for over the years. It will be useful to attempt measurements of organ volume to test this idea. Assuming that air is a small component of tissue volume, fresh weight data, which are available from this and many other projects, could be used to test these ideas.

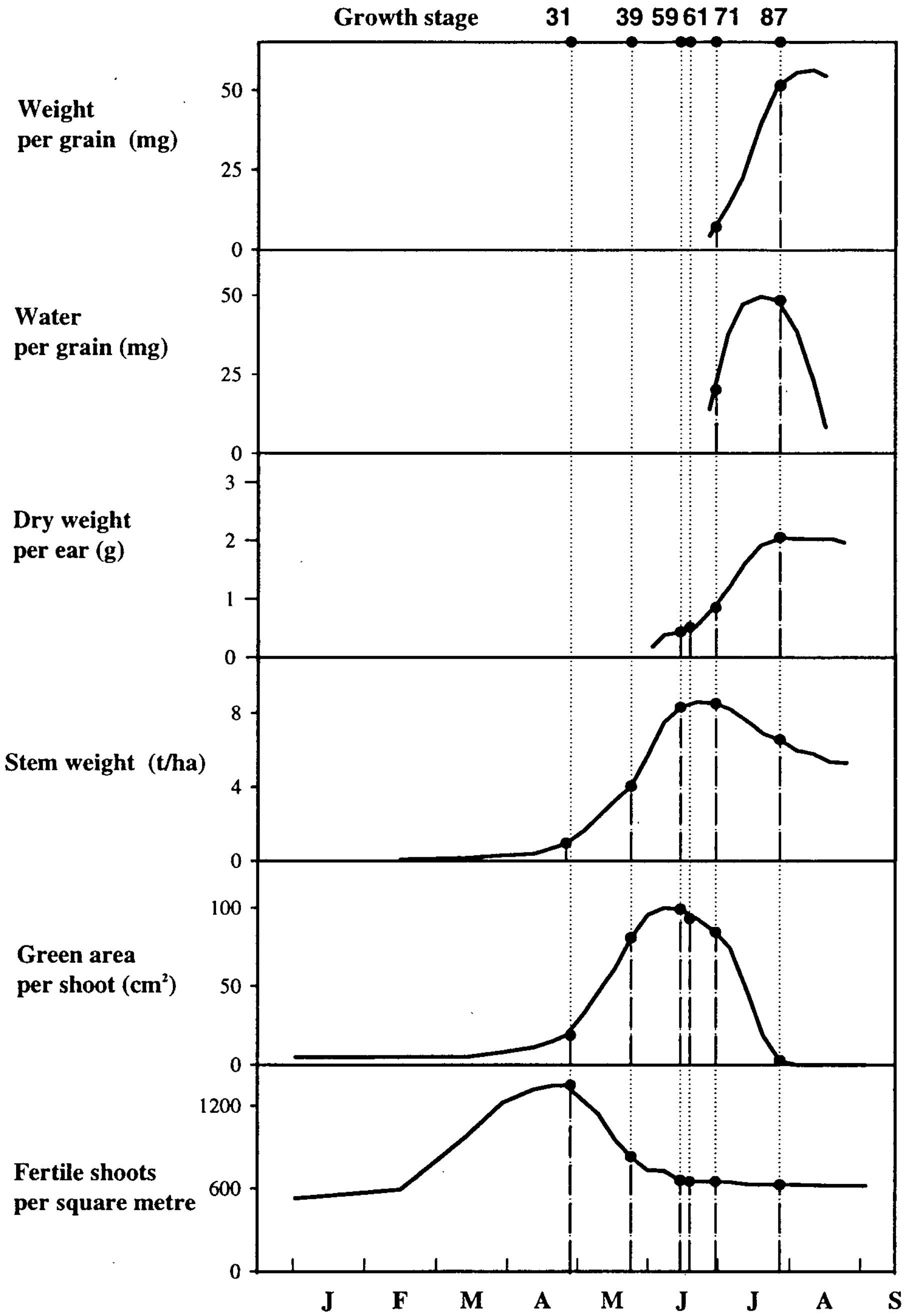

Figure 9. Example dataset from one site in one year showing growth stages and phases considered to be important in determination of final crop performance.

The loss in total dry weight before harvest is certainly a real feature of growth that has not been noted previously. It deserves more research, but this is difficult as it is haphazard and involves small changes in large, hence variable weights. The evidence is that the weight loss is mainly from straw, rather than grain. It may therefore not have any major commercial significance.

The uncertain understanding of growth exemplified by this discussion indicates the degree of difficulty that there is in anticipating grain yield. It cannot be considered realistic, at the present state of understanding, to predict yield with any certainty, before the grain has mostly filled. This issue is discussed more fully in Volume I Part 3: '*Forecasting crop progress for wheat*'. However, there is a period whilst the crop is ripening when at present there is very little appreciation of the likely weights of grain with which the industry will shortly have to cope. There seems a possibility therefore of sampling crops and predicting their grain yield from the ear weight and ear number. The end of grain filling appears to coincide with a grain moisture content of 45%, so simple sampling weighing, drying and re-weighing should be sufficient to make reasonable and useful predictions of grain yield.

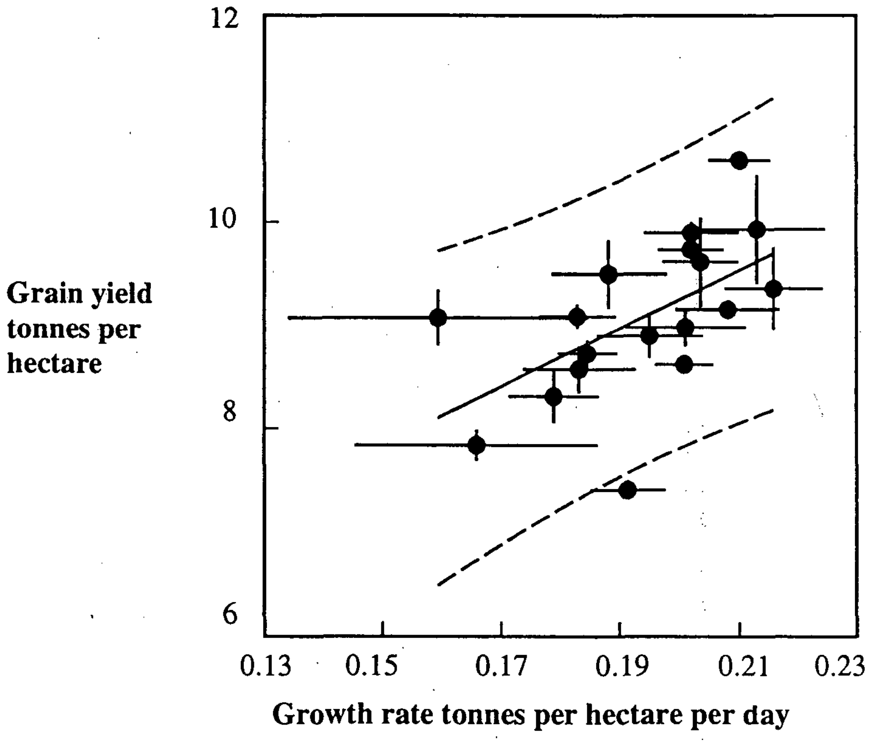

Figure 10. Relationship between grain yield and growth rate during the grand growth phase (when the GAI exceeded 3) for the six sites in three seasons. Vertical and horizontal bars are standard errors of Grain yield and Growth rate respectively, the dashed lines indicate 95% confidence limits of estimates of yield from values of growth rate.

The conclusion of the project in relation to predicting growth and yield is that, for the foreseeable future, predictions with useful precision can only be made for short periods, and they will regularly have to be revised according to crop observations. Gradually, just as with the progress that has been made with the forecasting weather in recent years, it should become possible to achieve greater and greater understanding, therefore more and more certain predictions over longer and longer intervals. It is to be hoped that the wheat industry in the UK will develop the considerable resolution necessary to seek this goal.

6..REFERENCES

Berry, P.M. Sylvester-Bradley, R., Scott, R.K., Clare, R.W., Spink, J.H. and Baker, C.J. (1998). Factors affecting lodging. *Management through understanding, research into practice* Proceedings of the sixth HGCA R & D conference on cereals and oilseeds. Home-Grown Cereals Authority: London 11.1-11.11

Barraclough, P.B. and Leigh, R.A. (1984) The growth and activity of winter wheat roots in the field; the effect of sowing date and soil type on root growth of high yielding crops Journal of Agricultural Science, Cambridge **103** 59-74

Bloom, T.M., (1985) Bias in the measurement of crop performance. *Aspects of Applied Biology* **10**, Field trials methods and data handling 241-258

Brocklehurst, P.A., Moss, R.P. & Williams, W. (1978) Effects of irradiance and water supply on grain development in wheat. *Annals of Applied Biology* **64**, 375-384.

Church, D.M. & Austin, R.B. (1983) Variability of wheat yields in England & Wales. *Journal of Agricultural Science* **100**, 201-204.

Fischer, R.A. (1985) Number of kernels in wheat crops and the influence of solar radiation and temperature. *Journal of Agricultural Science* **105**, 447-461.

Gallagher, J.N. and Biscoe, P.V. (1978a) Assimilate partitioning and high yields in cereals. *Opportunities for Chemical Growth regulation.* BPGRG Monograph No. 1, 113-24

Gallagher, J.N. and Biscoe, P.V. (1978b) A physiological analysis of cereal yield. II Partitioning of dry matter. *Agricultural Progress.* **53** 51-70

Gillett, A.G. (1997) Modelling the response of winter wheat to different environments: a parsimonious approach. PhD Thesis, University of Nottingham

Gregory, D. J., McGowan, M., Biscoe, P.B., Hunter, B. (1978) Water relations of winter wheat, 1, Growth of the root system *Journal of Agricultural Science, Cambridge* **91** 91-102

Hay, K.M. & Walker, A.J. (1989) *An introduction to the physiology of crop yield.* Co-publishers: Longman Scientific and John Wiley & Sons, New York, 292 pp.

Herzog, H. (1986) Source and sink during the reproductive period of wheat. *Journal of Agronomy and Crop Science, Supplement No.* **8**. 104 pp.

Kettlewell, P., Lunn, G., Major, B., Scott, R.K., Froment, M., and Naylor, R. (1998) Sprouting and Hagberg Falling Number *Management through understanding, research into practice* Proceedings of the sixth HGCA R & D conference on cereals and oilseeds. Home-Grown Cereals Authority: London 12.1-12.7

Kirby E.J.M.(1992) Identification and prediction of stages of wheat development for management decisions. Project report No. 90. Home Grown Cereals Authority, London, 39pp.

Kirby E.J.M. and Weightman, R.M. (1997) Discrepancies between observed and predicted growth stage in wheat *Journal of Agricultural Science, Cambridge* **129**, 379-384

Macbeth, J.E. (1996) *The prediction of mature grain weight in winter wheat* (Triticum aestivum, *L*). PhD Thesis, Harper Adams Agricultural College, Shropshire.

Monteith, J.L. & Scott, R.K. (1982). Weather and yield variation in crops. *Food, Nutrition and Climate. Eds. K. Blaxter and L. Fowden. pp. 127-153. Applied Science Publishers, London.*

NIAB. (1995). *Cereals Variety Handbook.* National Institute of Agricultural Botany, Cambridge.

Ross G.J.S. (1987) A maximum likelihood program. Numerical algorithms group, Oxford.

Sylvester-Bradley, R. Scott, R.K. & Wright, C.E. (1990) *Physiology in the production and improvement of cereals.* Research Review No. 18. Home-Grown Cereals Authority, London, 156 pp.

Sylvester-Bradley, R., Watson, N.A., Dewes, M.E., Clare, R.W., and Scott, R.K. Dodgson, G. (1997) *The Wheat Growth Guide to improve husbandry decisions.* Home-Grown Cereals Authority, London.

Sylvester-Bradley, R., Stokes, D.T., Scott, R.K., Clare, R.W., 1998 Canopy management in winter wheat. (1998) *Management through understanding, research into practice* Proceedings of the sixth HGCA R & D conference on cereals and oilseeds. Home-Grown Cereals Authority: London 5.1- 5.10.

Thorne, G.N. and Wood, D.W. (1988) Contributions of shoot categories to growth and yield of winter wheat. *Journal of Agricultural Science* **111**, 285-294.

Tottman, D.R. (1987) The Decimal Code for the Growth Stages of Cereals with Illustrations. *Annals of Applied Biology* **110**, 441-454.

Weightman, R.M., Kirby, E.J.M., Sylvester-Bradley, R., Scott, R.K., Clare, R.W. and Gillett, A. (1997) Prediction of leaf and internode development in wheat *Journal of Agricultural Science Cambridge*, **129**(4)