HGCA

PROJECT REPORT No. 151

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

Part 1: The Wheat Growth Digest

Part 2: Methods for In-Field Crops Assessment

Part 3: Forecasting Crop Progress for Wheat

FEBRUARY 1998

Price £10.00

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ASSESSMENTS OF WHEAT GROWTH TO SUPPORT ITS PRODUCTION AND IMPROVEMENT

VOLUME I

Part 1: The Wheat Growth Digest
Part 2: Methods for In-Field Crop Assessment
Part 3: Forecasting Crop Progress for Wheat

Edited
by

R SYLVESTER-BRADLEY, R K SCOTT, R W CLARE
and S J DUFFIELD

University of Nottingham/ADAS Centre for Research in Agronomy,
ADAS Boxworth, Cambridge CB3 8NN

This is the first 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.

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ABSTRACT

Eighteen crops of the winter wheat variety Mercia were grown at six locations in 1992-3, 1993-4 and 1994-5, and their development and growth were recorded frequently. The husbandry of these crops aimed to avoid limitations of yield caused by low nitrogen supply, weeds, diseases, pests or lodging through prophylactic use of fertilisers and pesticides, hence attention was focused on effects of site and weather. Techniques of measurement were developed for accuracy and precision. These are presented in Volume II, *'How to Run a Reference Crop'* with sufficient detail for interested researchers or groups of cereal growers to assess soil and weather effects at locations representing their own crops. The resultant data have been summarised to provide comparators for many attributes of wheat performance, and the implications for husbandry decisions are outlined. These have been presented in different ways so that (a) through the section entitled '*The Dataset*', Volume III, crop scientists can study the variation between sites and seasons in the many interconnected facets of development and growth, and (b) through the section entitled '*The Wheat Growth Digest*', Volume I Part 1, practitioners can derive a summary of these same facets against which to compare observations of their own crops. The significance of deviations from the 'norms' is considered in terms of adjustments to husbandry.

Simplified techniques are described to enable wheat growers to assess the most important attributes of individual crops, in Volume I Part 2 '*Methods for In-field Crop Assessment*'. In the section entitled '*Forecasting Crop Progress for Wheat*', Volume I Part 3, 'look-up' tables are provided to allow the forward prediction of stages of development, green canopy size, crop dry weight, weight per grain, and grain yield. The rules on which these tables are based are presented, and their advantages and deficiencies are discussed.

The general conclusions to the Project include an assessment of the potential for the wheat industry of further exploiting this research, and an assessment of the feasibility of undertaking similar research on barley.

THE PROJECT GROUP

Co-ordinator

R. Sylvester-Bradley
ADAS Boxworth, Boxworth, Cambridge, Cambs, CB3 8NN

Authors

R.W. Clare
ADAS Rosemaund, Preston Wynne, Hereford, HR1 3PG

R.K. Scott
Department of Agriculture and Horticulture, Sutton Bonington Campus,
Loughborough, Leicester, LE12 5RD

A. Gay
ADAS Boxworth, Boxworth, Cambridge, Cambs, CB3 8NN

S. Duffield
CRSIO, Division of Entomology, Griffith, NSW 2680, Australia

R.M. Weightman
Dalgety Food Ingredients, Food Ingredients Development Centre, Station Rd.
Cambridge, CB1 2JN

E.J.M. Kirby,
Independent Consultant: The Studio, Blythburgh Rd., Westelton, Suffolk, IP7 3AS

G. Russell
University of Edinburgh, Institute of Ecology & Resource Management, West Mains
Road, Edinburgh EH9 3JG

J. Spink
ADAS Rosemaund, Preston Wynne, Hereford, HR1 3PG

A. Mills
ADAS Gleadthorpe, Meden Vale, Mansfield, Notts, NG20 9PF

M. J. Foulkes
Department of Agriculture and Horticulture, Sutton Bonington Campus,
Loughborough, Leicester, LE12 5RD

D.T. Stokes
Department of Agriculture and Horticulture, Sutton Bonington Campus,
Loughborough, Leicester, LE12 5RD

N. Crout
Department of Physiology and Environmental Science, Sutton Bonington Campus,
Loughborough, Leicester, LE12 5RD

A. Gillett
Department of Agriculture and Horticulture, Sutton Bonington Campus,
Loughborough, Leicester, LE12 5RD

S. Hoad
SAC, Crop Systems Department, Bush Estate, Penicuik, Midlothian EH26 0PH

P. S. Kettlewell
Crop and Environment Research Centre, Harper Adams Agricultural College,
Newport, Shropshire, TF10 8NB.

J.E. Macbeth
Crop and Environment Research Centre, Harper Adams Agricultural College,
Newport, Shropshire, TF10 8NB.

Additional Contributors

J.H. Orson
Morley Research Centre, Morley St. Botolph, Wymondham, Norfolk, NR18 9DB

A. Blair
ADAS Boxworth, Boxworth, Cambridge, Cambs, CB3 8NN

K. Raw
ADAS Boxworth, Boxworth, Cambridge, Cambs, CB3 8NN

L. Sharp
University of Edinburgh, Institute of Ecology & Resource Management, West Mains
Road, Edinburgh EH9 3JG

A. Wade
ADAS Rosemaund, Preston Wynne, Hereford, HR1 3PG

N. Armer
Department of Agriculture and Horticulture, Sutton Bonington Campus,
Loughborough, Leicester, LE12 5RD

S.C. Mitchell
Crop and Environment Research Centre, Harper Adams Agricultural College,
Newport, Shropshire, TF10 8NB.

J.L. Etheridge
Crop and Environment Research Centre, Harper Adams Agricultural College,
Newport, Shropshire, TF10 8NB.

G. Boulby
Crop and Environment Research Centre, Harper Adams Agricultural College,
Newport, Shropshire, TF10 8NB.

G. Breakwell
ADAS Rosemaund, Preston Wynne, Hereford, HR1 3PG

M. C. Alvey
ADAS Gleadthorpe, Meden Vale, Mansfield, Notts, NG20 9PF

D.W. Atkin
ADAS Gleadthorpe, Meden Vale, Mansfield, Notts, NG20 9PF

OBJECTIVES

The objectives, developed during the course of this project, were to formulate :

(i) a quantitative way of relating current performance of winter wheat crops, in terms of their development and growth, to performance in previous seasons, and hence to allow forward estimates of crop progress, leading eventually to explanations of both yield and quality for winter wheat.

(ii) accompanying explanations of how each estimate should be adjusted so that individual growers can modify the most pertinent forecast to suit their own particular circumstances.

(iii) guide-lines for the way that (a) the progress through stages of development, and (b) the estimates of growth, can be used to improve timeliness of husbandry decisions (such as use of fungicides, growth regulators and late N) and to optimise the selection of options (such as harvesting sequences, drying and storage priorities).

(iv) information to assist experimenters with H-GCA sponsored projects to interpret their results in the light of seasonal differences.

(v) a recommendation on whether there is potential for a similar system for barley.

These objectives are compatible, but not identical, with the objectives set out in the project proposal.

GENERAL INTRODUCTION

The research undertaken in this Project arose from HGCA Research Review No. 18 (Sylvester-Bradley & Scott, 1990). The Review demonstrated the extent to which cereal husbandry was dependent on accumulated experience, and proposed that there was considerable potential to revise and augment the basis of cereal husbandry, by harnessing the explanatory and predictive powers provided by knowledge of the way cereals develop and grow. The reconciliation of practical experience with physiological knowledge was seen to be weak. Husbandry decisions were not based on the way in which, for instance nitrogen or fungicides, are understood to increase yield.

Thus there was no satisfactory logic by which growers could objectively regulate the timings or rates of 'inputs' to their crop production systems. It was envisaged that improvements in the precision of decision-taking would arise through providing growers with 'a way of working things out', hence an 'ability to reason in the field'.

Such an ability to reason depends upon the adequacy of physiological explanations for practical observations, and this is a matter of degree; it can be measured. Every explanation is accompanied by an attendant certainty and, since growers seek close control over their crops, explanations only become acceptable when that certainty becomes relatively great. It was therefore a requirement of this work that the explanations devised and tested should be assessed for their certainty, and their value judged accordingly.

It is axiomatic that explanations allow rational predictions, and indeed a comparison of predictions is the only basis on which sound reasoning can proceed. In the case of crops, close predictions are difficult because they not only depend upon variable 'inputs', which are under the grower's control, but they are fundamentally affected by factors, including the weather, which are almost impossible to control or predict. Thus, there is bound to be some unavoidable uncertainty or 'risk' attached to any prediction. Growers are accustomed to working with risk, and generally accept this. Therefore the task of physiologists in general, and especially here, must be to maximise the explanatory power of their knowledge within the limits imposed by uncontrollable factors. In the case of cereal production, it appears that this task is far from complete. Certainly, at present, cereal growers have very little forward intelligence of the extent to which the current season's growth (and hence potential yield) exceeds or falls short of the norm; take for example the exceptionally high yields of 1984 which were not recognised until the combines were cutting the crop. Growers do not even have a means to estimate the extent to which each of their own crops differs from the current seasonal pattern of growth. Yet there is existing physiological knowledge which could be used to devise ways by which growers could be informed about progress of the current crop, in terms of both 'growth stages' (changes in plant form) and growth (changes in crop size). There are already schemes for estimating (and predicting) the progression of wheat crops through their early stages (from germination through ear initiation and stem extension as far as flag leaf emergence); there must be scope to extend these to include stages, at least through to flowering.

There are several further instances in which fore-knowledge of crop progress should aid decision making:

- With plant growth regulators, predictions of the future pattern of development and growth would improve timing and the probability of cost-effective yield responses.
- Similarly, prediction of the emergence of leaf 3, the flag leaf, and flowering could sometimes save one fungicide application.
- Estimates of the likely progress of grain filling might provide predictions of the last opportunity for cost-effective fungicide application.
- Similarly, these could improve decisions based on thresholds for control of aphids in the ear.
- The probability of obtaining grain of the required protein content could be improved by predictions based on the plants' nitrogen status between flag leaf emergence and watery ripe stages.
- Similarly, by monitoring the progress of grain filling and alpha-amylase activity pre-harvest, information on the likely quality of the grain could be obtained and used to plan harvest, sales of grain, drying and storage.

Thus, when this Project was proposed, the idea was to bridge between physiology and husbandry, and thereby to improve the basis for further crop improvement.

The research work was undertaken between 1991 and 1996 and comprised a combination of reviewing and experimentation. Working groups were convened (i) to review the decision making process for winter wheat and therefore to identify the way that husbandry practices might be affected by crop state, and (ii) to review and develop crop monitoring methods.

The experimental work was set up in the autumn of 1992 and ran until harvest 1995. Crops of the variety Mercia were grown to a common protocol at six locations and their development and growth were monitored weekly during the main period of growth.

The research was central to and closely interdependent with a programme of other HGCA- and MAFF-funded research projects. Whilst this Project was furthering the development of techniques to monitor and predict crop performance, the allied Projects were developing the evidence and rationales by which specific husbandry decisions can be improved, through being tailored to the state of the crop. The principal Projects in this programme, and their purposes, were as follows :

More recently, a Project (0023/1/95) has been initiated to integrate some of the findings from this work and to evaluate the benefits of the ensuing ‘interactive’ approach to crop management.

Project	*Purpose*
0037/1/91	How to choose varieties for specific growing conditions, according to crop characteristics.
0070/1/92	How to judge the timing and amount of fertiliser N according to the size of the crop's green canopy
0052/1/92	How to assess the risk of lodging and hence how to choose the best avoidance strategy
0050/1/93	How to judge the susceptibility of the crop to damage by foliar disease, hence whether to alter fungicide strategy.
0056/1/93	How to anticipate the likelihood of sprouting or low Hagberg falling numbers.

There have been many contributors from each of organisations collaborating in this project (ADAS, The University of Nottingham, Harper Adams Agricultural College and the University of Edinburgh) to the research and to this report. In addition, the research has also been conducted in collaboration with Dr E J M Kirby (under HGCA Project 0023/1/93). Responsibilities for specific aspects of the work are indicated by authorship of the sub-sections of the reports.

Two research students were employed under the Project. The detail of their work is described in their theses :

J E Macbeth. (1996) *The prediction of mature grain weight in winter wheat (Triticum aestivum, L.).* Harper Adams Agricultural College, Shropshire. 267 pp.

and

A Gillett. (1997) *Modelling the response of winter wheat to different environments: a parsimonious approach.* University of Nottingham. 219 pp.

Scientific papers reporting this research are being prepared.

This report is presented in five discrete sub-sections, each one with a different purpose and each one intended for use in a different context :

1. **The Dataset**

   – reports the data collected from the 18 wheat crops through 1992-5.

   This section is intended for crop scientists who seek extensive data against which to test and improve their understanding or 'models' of wheat growth. The data are plotted or tabulated so that their quality and extent is open for inspection. Subsequent to formal peer review (through publication in the scientific press) and with further funding, these data could be made generally available, ideally through the Internet.

2. **How to Run a Reference Crop.**

   – describes the techniques which were used to set up and collect data from the 18 wheat crops through 1992-5.

   This sub-section is intended for use, particularly by technicians allied to groups of cereal growers or researchers who want to track the development and growth of a crop which represents particular growing conditions.

3. **The Wheat Growth Digest.**

   – summarises and interrelates the results of monitoring the 18 crops in 1993-5.

   This sub-section is intended for use by growers and their advisors, as well as for researchers, so that they have a reference against which to compare their observations. A revised and augmented version of this section is to be published by the HGCA as '**The Wheat Growth Guide**'.

4. **Methods for In-Field Crop Assessment**

   – describes simplified measurement techniques which may be used by crop walkers and decision-takers in order to assess their crops on a common scale.

5. **Forecasting Crop Progress for Wheat**

   – describes the way in which some of the variation between the 18 crops monitored in 1993-5 can be related to the variation in the weather, and variation in soil attributes.

   This sub-section is intended for use mainly by consultants and technicians who are associated with cereal growers who want to predict the development, growth and yield of their crops.

GENERAL CONCLUSIONS

Any industry must manage its production process. The wheat industry is no exception. Survival and success depend upon control. Of course wheat is subject to uncontrollable forces, the weather interacting with the soil and with pests and pathogens. But these only heighten the need for frequent re-consideration; crop management, unrevised during growth, is virtually unknown.

The steps in any cycle of management are to :

i. set targets,
ii. assess progress,
iii. adjust inputs and
iv. monitor success.

The vital issue here is measurement. **No manager can mange without measuring.** The target, the progress, the inputs and the success all have to be **measured** if management is to be tight. Thus crop producers have to assess crop progress, and they must be able to relate progress to a final outcome. In the UK wheat industry there is much room for improvement here. Crop assessments often focus on the weeds, pests and diseases threatening the crop, rather than on the crop itself. Where crops themselves are being assessed, the assessments tend to be subjective and qualitative; the words used to describe crop state and crop progress are rarely well defined, and seldom are there attempts at measurement.

Cereal growers commonly receive intelligence and advice of current crop status and management options through consultants, the trade, trailing agencies and discussion groups. This is mainly based on casual observation and experience, rather than on any measure of the crop. It is clear that assessment of current crop status and any ensuing discussions and decisions could be assisted by clarification of the way that current growth should be judged, as well as the way that estimates of growth should colour husbandry decisions. This situation is unsatisfactory, not only for the immediate problems of crop management, but also for improving management. Without measurement, there is no basis for learning. Therefore, what we have come to develop here is both a series of measurements by which the grain production process can be monitored and targeted, and an understanding of the way that these measurements interrelate.

The grain production process

Yield formation is not a mystery. Like many production processes there are raw materials formed continuously by photosynthesis, whilst a production cycle, known through the series of ‘growth stages’, dictates the form that those raw materials must take.

Thus the crop can be regarded as a factory. By noting stages in the life-cycle and **assessing** the outcome of each stage, crop managers have a basis for managing the production process. Undoubtedly something of this sort already occurs; crop management has become increasingly vigilant and responsive, and less remote and preordained. However, if the industry is to learn and improve, it must look more at the crop itself, and adopt common scales on which to compare and communicate performance.

Crop potential

The simplest scale on which to assess the potential of wheat production in the UK is that of the energy provided for photosynthesis in sunlight (Fig. 1). The shortfall from potential from August through to April is largely a result of an absent or incomplete photosynthetic canopy, and the shortfall from May to July is largely due to a shortfall in photosynthetic efficiency. If wheat growers could manage their crops such that all the energy were intercepted, and if photosynthesis were to proceed with its normal efficiency, then total crop growth would be as large as 50 t/ha (Montieth 1977).

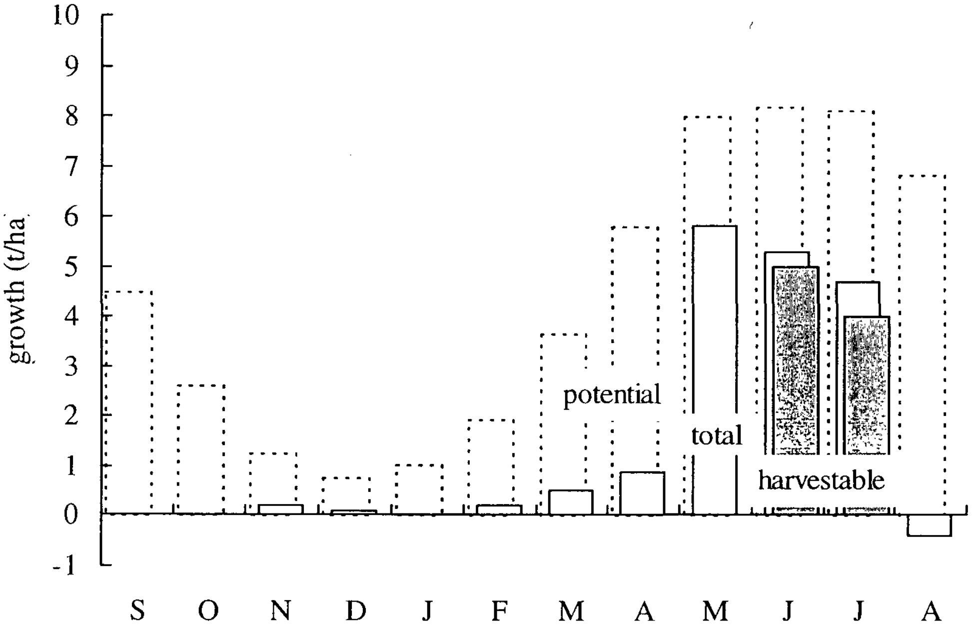

Figure 1 Potential crop growth assuming that all average annual incident radiation is converted to dry matter at 1.5 g MJ^{-1}, compared to the medians of total above-ground dry weight and grain dry weight achieved in the 18 crops of Mercia.

Plentiful rainfall in the UK means that only a minority of wheat crops encounter drought (Foulkes et al. 1994), and most soils are well supplied with nutrients (Archer, 1985). Thus conditions are highly conducive for wheat growth in the UK and there is no reason to believe that these conditions are close to being fully exploited by the industry. Wheat output per hectare continues to show significant improvements year on year, largely through the efforts of plant breeders (Silvey 1994) in increasing the proportion of total growth which can be harvested. There is every sign of ample scope for further improvement in exploiting our exceptional environment, and it is our contention that the 'interactive' approach to wheat agronomy, which has been developed during the life of this Project, provides a sound basis for such progress to be made.

In particular, we have shown (in Volume I Part 3; '*Forecasting Crop Progress for Wheat*') that crop growth across a range of sites and seasons can be explained with satisfactory precision in terms of the size of the photosynthetic canopy and the availability of energy as sunlight. It has followed from this that crop growth can be managed through optimising the size of the photosynthetic canopy. We have shown, in a parallel Project (0050/1/92), that close control of the size of the green canopy can be achieved through nitrogen nutrition, and that this gives a superior outcome to a system which more crudely links nutrition with yield. We consider that reasoning about appropriate doses of fungicides must invoke a similar analysis, and further Projects (0051/1/92 & 0051/1/93) are in train to explore and develop this approach.

However, analysis of wheat production purely in terms of intercepted solar energy denies the evidence of interactions between development and growth that were envisaged and exposed through this Project. The Project has upheld that both total growth and grain formation cannot be adequately explained without regarding the life cycle as a series of distinct production phases in which a succession of different yield components are determined : shoots, culm leaves, fertile florets, stem sugars, and grains. Evidence of interactions is exemplified by the clear pause in dry matter accumulation shown by a majority of the monitored crops just before they flowered (The Dataset, Fig. 6). The only tenable explanation appears to be that photosynthesis was inhibited by a lack of adequate storage 'sink' in that phase; there was a full canopy and ample sunlight but no further growth was possible in the leaves, the stem or the ear.

It had been supposed that photosynthesis in the phase before flowering would mainly contribute to the store of stem sugars that would subsequently become available during grain filling. However, our measurements show that in many crops, these reserves were laid down during stem extension and ear formation, and that the capacity to store stem reserves became fully satisfied by the time the ears emerged.

Over and above this particular instance, there was generally more variation found than was expected in the efficiency of photosynthesis (Gillett 1997); it seems probable that we need to look more closely at the possibility of photosynthesis being controlled, perhaps intermittently, by 'sink' capacity throughout the crop's production cycle. If this is shown to hold, a way for significant improvements in wheat production should open up, either through plant breeding or through management, to enhance sink capacity. The most obvious instance in which sink controls growth is in the determination of grain number. Variation in grain number per ear was an important component of yield here and, in parallel work (under MAFF Project CE0515), we have shown that grain number depends upon photosynthesis, in this case influenced by shading during the phase from flag leaf emergence to ear emergence (GS39 to GS59). It appears that dull conditions during this phase significantly reduce both grain number and ultimate yield, despite similarly bright conditions later.

Thus despite the progress that has been possible by regarding wheat as a photosynthetic 'factory', it seems that further progress will be inhibited without better appreciation of way the crop stores photosynthate, in leaves, in stems and in grains. Although we have developed ways of calculating photosynthesis from solar radiation and canopy size, we have not yet developed ways of calculating storage capacity. We know the phases in which storage capacities are determined; what we now need is a quantitative measure of storage capacity in equivalent terms to assimilate supply and an explanation that links storage capacity with the crop's growing conditions.

Thus at present we have some capacity to predict growth, but prediction in detail is restricted by more than an inability to anticipate the weather; even with perfect knowledge of weather, it is not possible to reproduce an accurate profile of wheat growth. We do not take this as cause for despair. It merely means that, for the time being, improvements in wheat management must depend on **observation** as well as **calculation**. Thus a significant component of the work of this Project has been to develop the techniques and protocols necessary to provide sound observations of the crop: the concept of sound 'Crop Assessment' has become a central element of our 'interactive' approach to wheat management.

In developing Crop Assessments, it has become clear that some measurements which are of obvious importance in supporting decision-taking, for example the amount of stem sugars at flowering time, are not observable on the farm; the technique is too laborious and intricate. We therefore envisage that there is a need for two categories of Crop Assessment: those made *in-field* and those provided *remotely*.

For in-field measurements (see Volume I Part 2, *'Methods for In-Field Crop Assessment'*) it should be noted that although the methods are deceptively easy, there is a real danger of being misled by hidden inaccuracies. The work of the Project has involved much development of methods for conditions which relate to the real problems of agriculture: widely geographic separation and non-specialist staff. For example, we have had to encounter and overcome difficulties in the apparently simple task of counting leaves. Knowledge of leaf number is central to the optimum timing of fungicide applications and thus to the minimisation of fungicide doses, so any inaccuracy in counting leaves puts at jeopardy the effectiveness of fungicidal control. Yet we have found a need for considerable care in undertaking leaf counts. We therefore conclude that, to 'transfer' these 'technologies', there will be a need for some technical support.

For remote crop assessments we have developed the concept of Reference Crops. Every season shows particular attributes which distinguish it from most others. These attributes become apparent in a qualitative way as the season progresses, and they are often the subject of much discussion and debate: establishment delayed by dry seedbeds, tillering enhanced by a warm winter, nitrogen uptake delayed by a dry spring, growth slowed by a cold May, and the conundrum of a bright yet dry grain filling period. We have found, through organising the work on the six crops through each year of this Project, that we can now envisage a scheme of growing crops with 'standard' husbandry so as to measure these events with sufficient accuracy and immediacy that quantitative intelligence of seasonal conditions and their implications could be provided for the industry as each season unfolds. We envisage that, with suitable co-ordination, the industry could support such a system of remote intelligence at a very modest cost and with considerable benefit. We have therefore provided the necessary techniques as a separate report entitled Volume II *'How to Run a Reference Crop'*.

Having identified the measurements necessary to support Crop Assessment and the way in which these are best acquired, we have developed a comprehensive description of the wheat crop which interrelates the observations; the 18 crops which were monitored in this Project have given rise to Volume I Part 1, *'The Wheat Growth*

Digest' and *'The Wheat Growth Guide'*. The value of these two documents has been particularly evident to the scientists involved in the work. We have now acquired a full quantitative description of wheat growth, and find this invaluable in analysing any new observations or ideas. It enables detection of the unlikely and the impossible, and allows us to assess the likelihood of benefits from changing the crop's state in order to exploit particular conditions with which the crop is faced. In other words we have arrived at 'a way of working things out'. It is to be hoped that, through transfer activities, a capacity to 'reason in the field' will become more widely shared through the industry.

In forming this intelligence of wheat growth, it has become apparent that there would be particular benefits in improving our understanding of particular aspects of the crops behaviour. In addition to the uncertainties, already described, resulting from our inadequate understanding of sink determination, it seems likely that the industry would benefit from better explanations of the determination of :

- sink strength
- tiller survival
- the trigger for stem extension to start
- culm leaf number,
- the susceptibility of young florets to frost, and
- rooting development and activity.

These and other issues must be the basis by which the large shortfall in productivity of wheat can be gradually overcome and the full potential of the UK growing conditions can be exploited more completely. This goal is essential to all elements of the UK wheat industry, and we argue that the joint adoption of 'Crop Assessment', based on both in-field and 'remote' intelligence, would provide the necessary basis on which all the forces for development in the industry could share and integrate their efforts, rather than relying on serendipity.

It is evident from the scale of the shortfall, that crop improvement through crop assessment must be regarded as a long term goal. Just as the control of pests and diseases present frequent new challenges, so the path to improvement of the crop itself cannot be fully foreseen. For instance, through plant breeding there is an evolution of the crop which is just as significant as the genetic evolution of the pests, and pathogens, and the products used to control them. We can explain and predict components of the crop's growth with adequate precision to support short term or short distance reasoning, but there are bound to be further surprises as understanding improves.

The benefits from assessing crops quantitatively will come through working out how best to manipulate husbandry and genes to meet growth targets. A few suggestions of suitable targets and husbandry responses are offered in *The Wheat Growth Guide*. However, these reports are not husbandry or breeding manuals. Further support for husbandry decisions should accrue as growers and researchers come to integrate their observations and deduce how to meet the main concerns of management.

The possibilities and limitations of improving wheat production through physiological analyses have developed enormously in the five or six years taken to complete this Project. The prospect of providing a satisfactory way of calculating crop performance entirely from remote information was found impossible but, ways and means of adopting a functional approach to wheat management have been developed, and there is clearly scope for further progress. The prospect of taking the same approach for barley is evident. Already, a review is under way in relation to disease control (as part of Project 0034/1/96). Essentially, barley functions according to the same principles as wheat. If anything, the scope for functional analysis of barley seems more promising as barley is subject to a wider environmental range than wheat, with significant areas sown in spring as well as autumn, and with significant areas grown in the north and west, as well as the east and south.

To conclude, this Project introduces the large task of raising the awareness of a well peopled and geographically dispersed industry in the methods and concepts of quantitative Crop Assessment. 'Technology transfer' is the phrase now used to describe this process. We have purposely provided reports which far exceed in extent, depth and intended audience the normal requirements of a research project which has addressed one simple hypothesis. This is because we believe that the concepts developed here are crucial to improvement in the UK cereal industry. However, there will be a continuing need for effort to extend awareness, acceptance and adoption of these concepts before the full benefits can begin to be realised.

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Part 1

The Wheat Growth Digest

Edited

by

R. SYLVESTER-BRADLEY, R. K. SCOTT,
R. W. CLARE and S. J. DUFFIELD

CONTENTS

1. INTRODUCTION

It is natural that growers should seek to track crop progress to guide their husbandry. From first principles, there is much evidence that husbandry decisions should depend upon the state of the crop. Yet growers have lacked the help necessary to gauge the extent to which their crops are large or small, heavy or light, advanced or retarded, dense or sparse, lush or sparse, sturdy or weak, and there is little firm guidance on how decisions should then be changed. This document is intended to help in satisfying this need. It provides a set of reference criteria against which winter wheat, growing in the United Kingdom, may be compared.

Full exploitation of the information provided here will also depend upon a clear rationale for the way in which husbandry should best be tailored to crop state, for example, to work out whether a larger than normal crop needs a smaller or a larger than normal amount of fertiliser. It is intended that comprehensive guidance along these lines will be the outcome of a number of allied research projects. Full explanations are beyond the scope of this report. However, pointers to the implications for husbandry are given in each section.

There are many attributes that may be assessed in the field during growth. Those selected here relate to both the form of the plant, as it develops through leaf production, stem extension, and flowering to grain formation and harvest, and to the size of the plant, as it grows in stem number, height, canopy area, dry weight, and nutrient content. Publications already exist which describe crop development. The emphasis here is more on growth, since this is more significant in terms of controlling crop husbandry, and is the more difficult to quantify.

Wheat growth and yield depend on the weather. Differences between sites and seasons often outweigh every other influence on crop performance. The reference criteria reported here arise from crops of the wheat variety Mercia, grown to a standard protocol. There are 18 crops in the set; these were located at six sites in the UK over the three seasons 1992-3, 1993-4 & 1994-5 (see Fig 1.1).

The main objective of the project was to focus attention on the influence of location, and particularly the influence of season on crop performance; it was not the intention to assess the effects of husbandry on crop performance. A standard husbandry system (protocol) was used to provide internally comparable, but not truly representative, husbandry. The chosen variety Mercia was introduced in 1986 and has been recommended ever since on account of its suitability for breadmaking. Mercia is relatively early to mature, has no serious weaknesses in resistance to disease or lodging, and has high grain quality. It is not a semi-dwarf variety, and does not have the rye chromosome translocation that is associated with higher yielding varieties introduced more recently. Findings from the 18 Mercia crops certainly illustrate patterns of development and growth that apply to all wheat crops. However, there are differences of detail between varieties; these are the subject of other contemporary HGCA Project Reports.

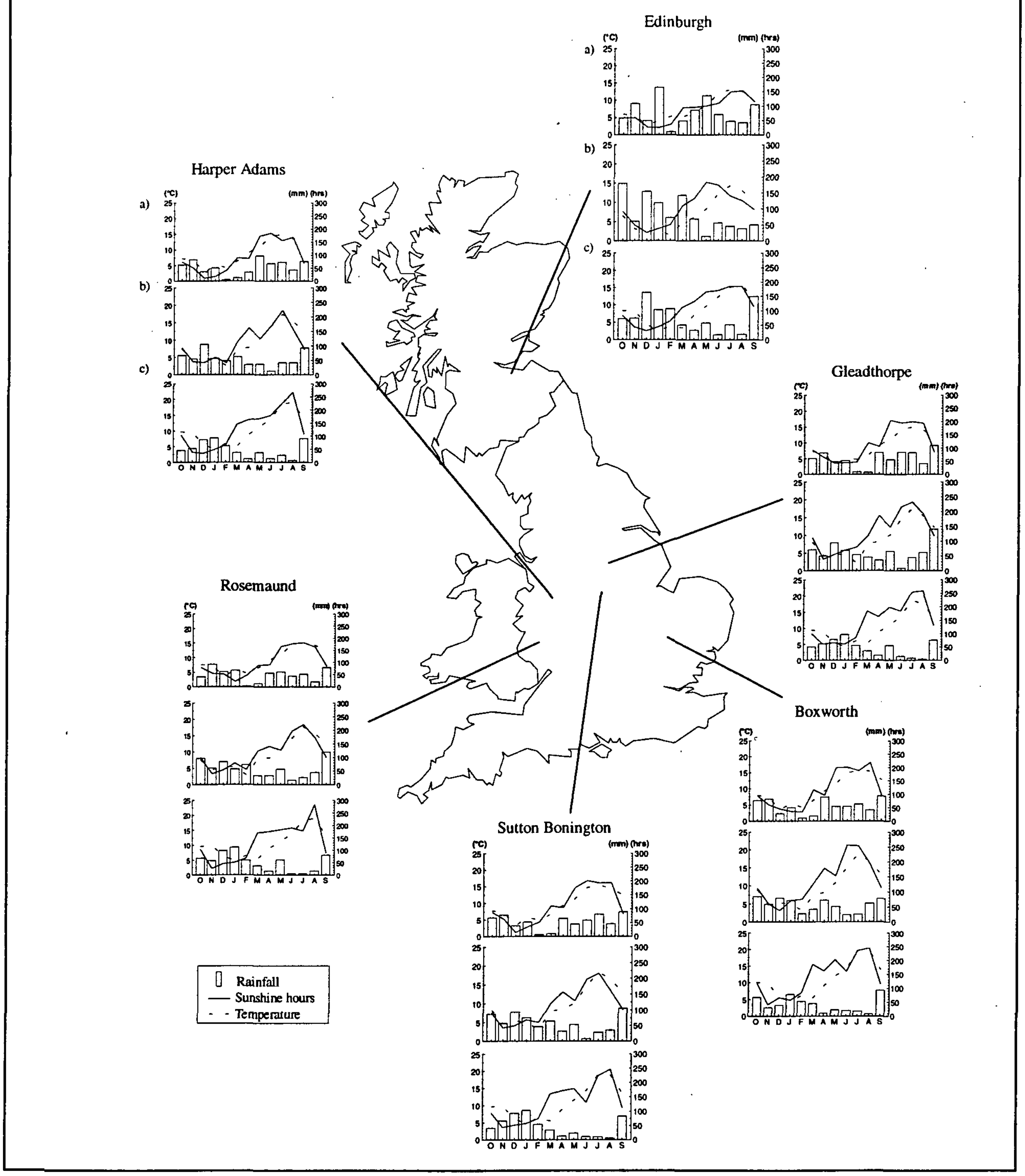


Figure 1*:* *Weather conditions recorded at the six reference sites in a) 1993 b) 1994 and c) 1995*

The husbandry 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 (see Section 3, 'Crop Establishment') and, even in the relatively dry summers of 1994 and 1995 (see histograms Figure 1), no crop was irrigated.

The crop attributes were measured by methods developed for research purposes, giving maximum accuracy and precision. Generally the data on crop growth are as good as any others known to the authors. Growers must recognise that, unless they invest considerable effort, their own assessments are likely to be less precise. There is some inherent 'operator error' when assessments are made by different personnel at different sites; this component of variability is included within the variation reported here.

The weather

Most of the variation between the 18 crops must be attributable directly or indirectly to differences in the weather. The weather for each case is summarised on the map. In relation to long-term averages 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. The winter was colder than normal. Over-winter rain was sufficient to rewet the soil and to cause drainage. The spring was dry and warm, but summer rainfall was similar to the long term average, so that growth was not expected to be restricted by moisture supply except on the lightest soils.

1993-4: The autumn of 1993 was sufficiently wet for drilling to be delayed and establishment to be inhibited at most sites. At Edinburgh rainfall from September to March was about 50% more than the long term average; total rainfall over-winter at the other sites was more typical. 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.

1994-5: The autumn of 1994 was wet in some places but not sufficient to prevent good crop establishment. As in 1994, the spring of 1995 was bright in March and April. However, the summer was even drier than in 1994, with sub-average rainfall through from April to August. The summer was also very warm and bright; August was particularly sunny.

The sites were located near to research establishments to enable careful management as well as to represent the variation generally seen across the UK wheat acreage. There were no sites in the south, where conditions would be warmer and cause faster crop development, or in the north of England where conditions would be intermediate between those in England and Scotland. The principal difference amongst the sites in this data set was between the sites in Scotland and those in England. Conditions in Scotland were generally wetter and cooler than in England, with 200 mm more rainfall throughout the season and temperatures about 2°C cooler. Generally, the differences in weather between seasons were as great as the differences between sites.

Soils and husbandry

Other than weather, the differences between sites were mainly due to soil type. These are summarised in the Table 1.1.

Table 1.1 Site conditions

Section1

	1992/3					
Site	Boxworth	Edinburgh	Gleadthorpe	Harper Adams	Rosemaund	Sutton Bonington
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 (0-90cm) (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
Pests	OB Midge	Aphids	None	None	None	None
Diseases	None	None	None	Take-all	None	None
Weeds	None	None	None	None	None	None
Lodging	None	None	None	None	None	None

Section 2

	1993/94					
Site	Boxworth	Edinburgh	Gleadthorpe	Harper Adams	Rosemaund	Sutton Bonington
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 (0-90cm) (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	OB Midge	None	None	None	None	None
Diseases	None	None	None	None	None	None
Weeds	None	None	None	None	None	None
Lodging	None	None	None	None	None	None

Section 3

			1994/5			
Site	Boxworth	Edinburgh	Gleadthorpe	Harper Adams	Rosemaund	Sutton Bonington
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 (0-90cm) (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	Aphids	None	None	None	None	None
Diseases	None	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(0), K < 120 mg/l (0), Mg < 20 mg/l; Pests, Diseases and Lodging causing a yield loss of > 5%

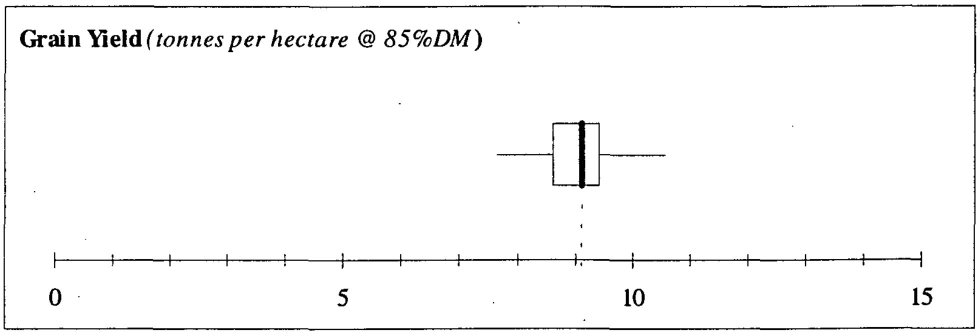
There was a wide range of soil types from clay to sand. No soil was shallow, although shallow soils over chalk or limestone do represent a significant proportion of the UK wheat acreage. Organic matter contents were generally typical for each of the soil types. Only at Harper Adams in 1992-3 was the soil organic matter content particularly high; and grass had not been grown recently at any site.

No soil was sufficiently acid, or low in phosphate or potash, for growth effects to be expected, and there were no serious cultural problems except an 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 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.

Variation in crop performance

The variation in many crop attributes was considerable. The main reference, which has been derived from the 18 crops, and which is described in each of the following sections is the **median** (the value which divides all the observations into two halves, when they are arranged in ascending order). The diagrams show the median as a bold central line, but also, each is accompanied by 'whiskers' indicating the maximum and minimum, and by a box indicating the lower and upper quartiles (the values which divide all the observations into four quarters when they are arranged in ascending order).

For example, the 18 values of grain yield are represented as follows,



Grain Yield *(tonnes per hectare @ 85%DM)*

n= 18

with a minimum of 7.7, a median of 9.1, and a maximum of 10.6 t/ha. Emphasis in the text is on the median. Variation around the median arises for many reasons, some being clear and some being unexplained. The variations are discussed only where this will assist with further comparisons.

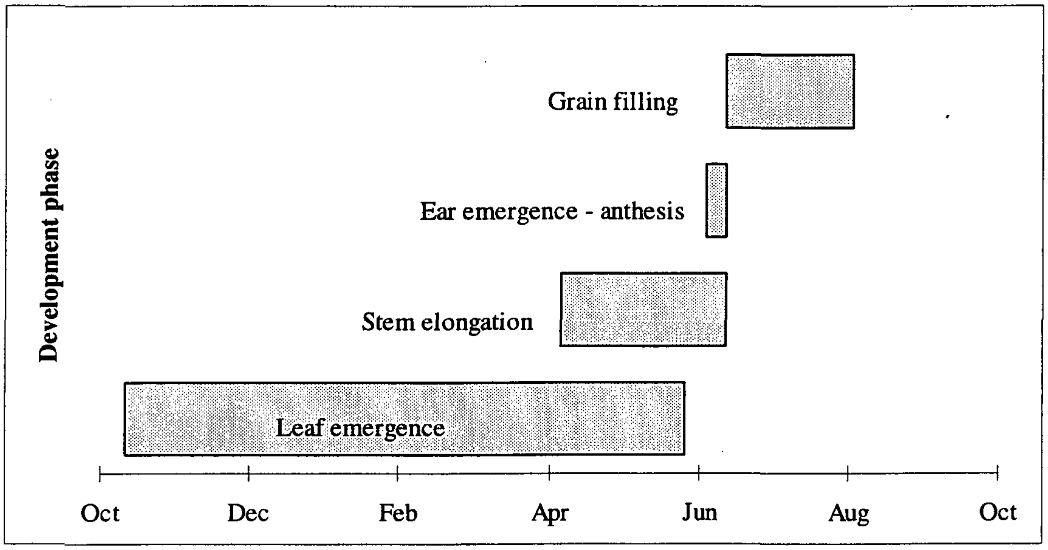
In relation to yields in contemporary experiments, the level of crop performance in this set of crops was representative. Comparisons available from adjacent or contemporary experiments show that performance of these 18 crops might have been greater with more recently introduced varieties, and with irrigation. Any alterations to other aspects of husbandry are unlikely to have improved performance significantly.

2. PLANT DEVELOPMENT

by E. J .M. Kirby

Development describes the changes in plant form and complexity that occur between the seedling to the mature plant at harvest. Developmental stages can be described and identified in various ways, including changes in the shoot apex as it develops into an embryo ear. For crop management, the stage of development is usually defined by the external form of the plant, and it is usually referred to as the 'growth stage' (GS).

Dates of Development Phases of Winter Wheat Crop



It is convenient to divide the life cycle into phases which refer to the principal changes which occur during a particular period of development, e.g. the elongation of the stem (as in the figure above). The phases occur sequentially through the life of a plant, but overlap as, for example, leaf emergence continues after stem elongation starts. More details of growth stages are given in Volume I Part 2: *"Methods for In-Field Crop Assessment"*.

Phase of development	Principal Growth Stages
Leaf emergence	PGS 1
Stem elongation and booting	PGS 3, PGS 4
Ear emergence and anthesis	PGS 5, PGS 6
Grain filling	PGS 6, PGS 7, PGS 8, PGS 9
Ripening	PGS 8, PGS 9

- Warm seasons always lead to faster development and growth stages occur early.
- Cold weather in autumn may lead to more effective vernalisation which accelerates development.
- Cooler conditions at high altitude and latitude tend to delay development.
- The only husbandry decisions to have a significant effect on the progress of development are the choice of variety and the date of sowing. Varieties differ in the extent to which they respond to vernalisation, daylength and temperature. Growth stages occur later in late sown crops, but occur closer together.
- Later stages of wheat development respond to daylength such that most crops reach maturity within a month of each other, even if their sowings differ by six months.
- Differences in the pattern of daylength and temperature between different latitudes, for example between southern Europe and Scotland, require that varieties with different responses must be chosen in order to ensure that maturity occurs in weather suitable for harvest.

Leaf emergence

- Leaf emergence lasts from seedling emergence until the flag leaf is fully emerged.
- Leaves appear at regular intervals, when temperature is taken into account (see Section 4 '*Leaf Emergence*').
- Leaf growth stages (PGS 1) refer to leaves on the main shoot (not tillers).
- Mainstem leaves are difficult to count after the winter because of weather damage.
- Emergence of the third leaf on the main shoot (GS 13) marks the beginning of tillering (see Section 5, '*Tillering*') and the absence of emerging tillers at this stage may indicate a management problem (soil fertility or soil conditions).
- Emergence of the last three or four leaves are important stages for crop management because these leaves are responsible for photosynthesis during grain filling. Emergence of the flag leaf is included in principal growth stage 3 (GS 37, GS 39).
- The median date for emergence of the flag leaf (GS 39) was 21 May.
- GS 39 marks the end of leaf emergence. Maximum green area generally occurs soon after this stage.

Stem elongation

- Stem elongation (GS 30) begins when the internodes below the embryo ear start to grow in length and the nodes become obvious.
- The beginning of stem elongation is defined as 'Ear at 1 cm'. It has previously been defined as 'pseudo stem erect'. The median date for this stage was 15th April.
- Stem elongation stages within principal growth stage 3 are defined according to elongation of successive internodes. The extension of each internode causes its upper node to become 'detectable' (e.g. GS 32 = two detectable nodes).

- The median date for GS 31 was on 23 April, only eight days after that of GS 30.
- The median date for the second node stage was the beginning of May.
- The second node stage normally coincides with emergence of the third or fourth leaf from last, depending on whether there are going to be five or six extended internodes.
- Stem elongation continues until about the time of flowering and after the ear has first emerged.

Ear development

- Swelling of the ear within the sheath defines 'booting' (principal growth stage 4).
- 'Booting' stages may overlap with emergence of the flag leaf.
- Ear emergence begins when the tip of the ear is raised above the base of the flag leaf blade. This is caused by extension of the last internode, the peduncle.
- Booting and ear emergence coincide with rapid expansion and development of the ear. In the Mercia crops they occurred during late May and early June.
- After ear emergence the number of shoots usually remains constant until the crop is harvested.
- Complete emergence of the ear occurred only shortly before the beginning of flowering.

Anthesis (flowering)

- At anthesis all the fertile shoots have ears.
- At anthesis the pollen is released, the eggs are fertilised and grain growth starts.
- Cold weather can delay anthesis by a few days.
- The median date of anthesis was in mid June.
- Inclement conditions at this stage may reduce the number of florets fertilised and therefore final number of grains.

Grain filling and ripening

- The growth stages during this phase are characterised by the texture and hardness of the grain.
- From the median date of flowering to the median date of hard dough (GS 87, normally taken as the end of grain filling) was approximately six weeks.
- Grain filling is best measured in terms of dry mass (see Section 11, '*Grain Filling*').
- Grain ripening is best characterised by the moisture content of the grain (see Section 12, '*Grain Ripening*').

Implications of Growth Stages for husbandry decisions

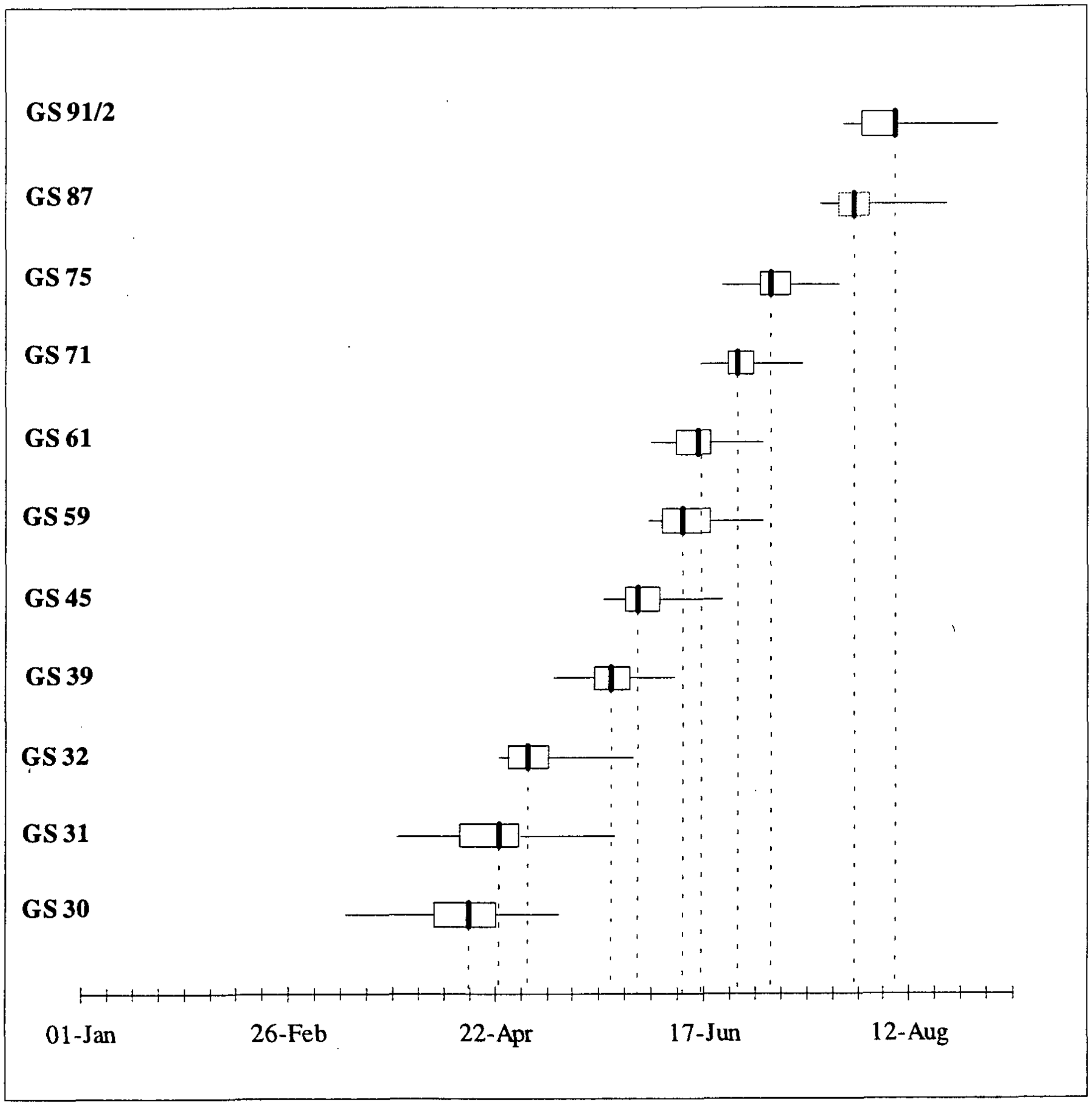
Growth stages are commonly used to specify the timing of husbandry practices, particularly applications of agrochemicals. A summary of the way that husbandry practices are timed is given below :

Growth stage	Husbandry application
GS 30 'Ear at 1 cm'	growth regulator to shorten lower internodes
GS 31 First node detectable	the main dressing of fertiliser nitrogen
GS 32 2nd node detectable	fungicide to control eyespot and *Septoria* on the third from last leaf
GS 37 Flag leaf just visible - GS 45 Boots swollen	growth regulators to shorten upper internodes
GS 39 Flag leaf ligule just visible	fungicide to control diseases on all yield-forming leaves
	soil-applied N to improve protein % of crops for bread-making
GS 59 Ear fully emerged	fungicide to keep the ear disease free
GS 61 Beginning of anthesis	aphid control according to level of infestation
GS 71 Grain watery ripe	
GS 75 Medium milk	Urea N as a spray to increase grain protein of crops intended for breadmaking
GS 87 Hard dough (<30% moisture content)	pre-harvest glyphosate to kill perennial weeds

- Whilst the timing of most husbandry practices is not critical, in the sense that crop damage will be caused, the efficacy of most applications tends to be maximised by timing them according to growth stage rather than calendar date, since they are often intended to affect the growth of a particular organ, and need to comply with label recommendations which specify growth stages.

- *For example,*
  - chlormequat is intended to inhibit extension of the lower-most internodes of the stem, hence it needs to be applied just before they are due to extend, and
  - fungicides applied at flag leaf emergence are intended to prevent damage, particularly to that leaf, hence need to be applied as soon as possible after it has emerged, so as to minimise the chance of infection.

Dates of important growth stages

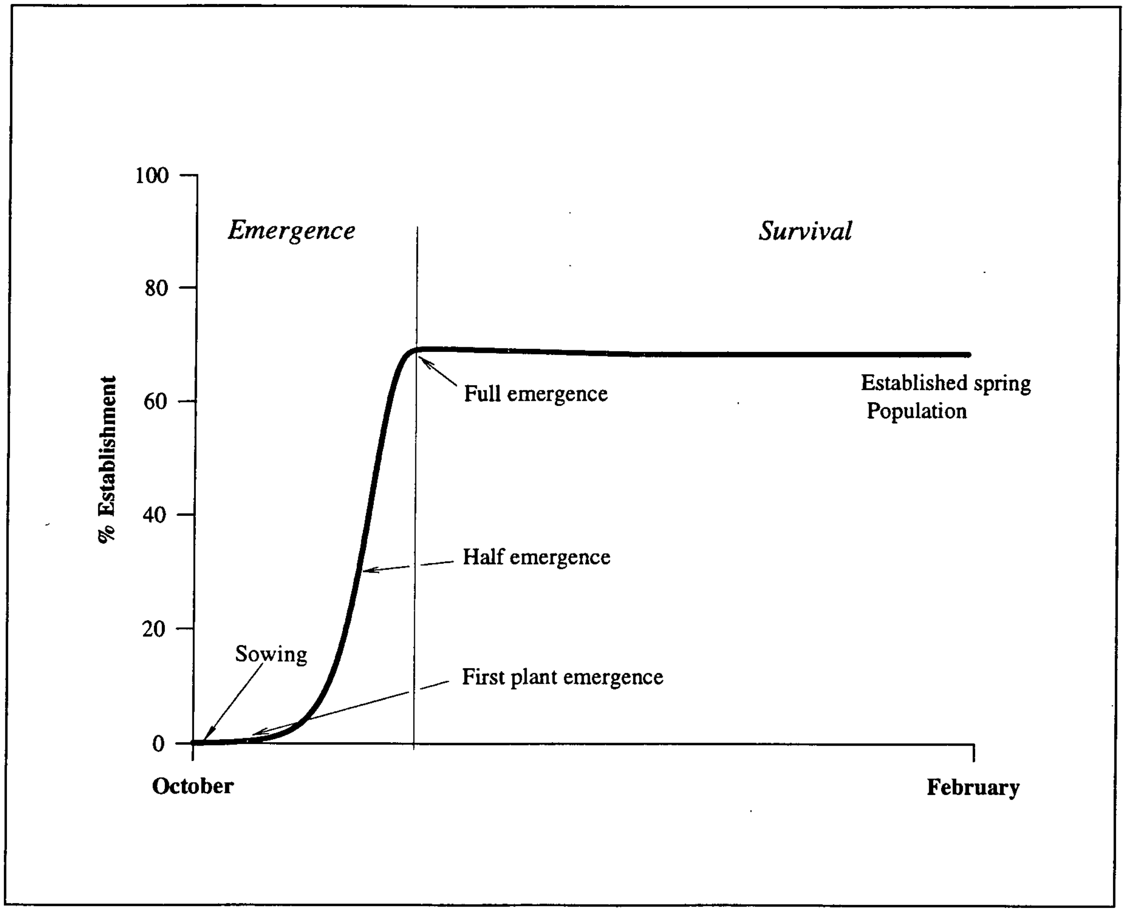


3. CROP ESTABLISHMENT

by A. Mills

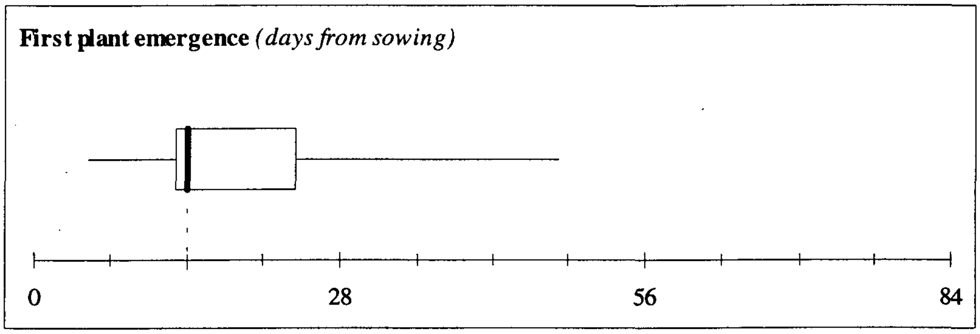
Crop establishment describes the number of plants which are present per unit area of crop (plants /m^2). It may also be expressed as a proportion of seeds sown e.g. a 60% re-establishment means that 60% of the seeds sown produced viable plants at the time of counting.

It is best assessed in the spring prior to the beginning of tillering. Establishment reflects both the proportion of seeds which emerge as seedlings and their subsequent survival over-winter.

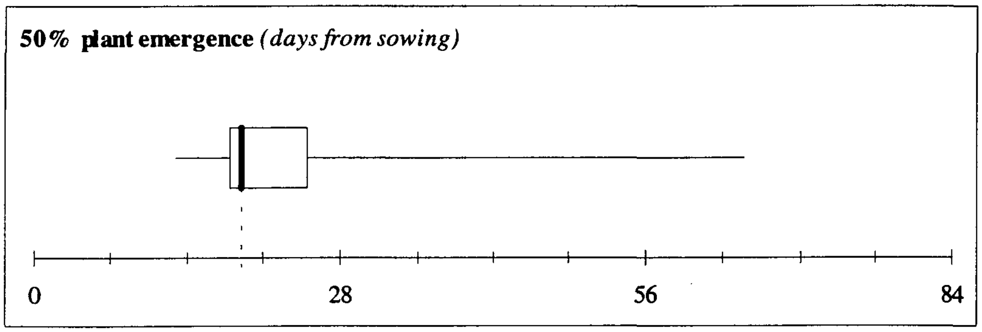


Emergence

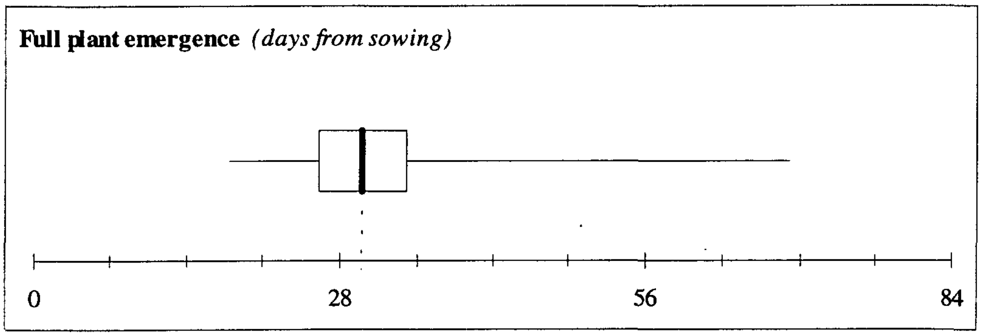
Soil moisture and warmth are required to induce germination (GS 03). At germination, the radicle (GS 05), which forms the primary seminal root, and then the coleoptile, emerge from the caryopsis (GS 07). After the coleoptile has penetrated the soil surface, (seedling emergence), the first leaf extends (GS 09) and eventually grows through the coleoptile tip (GS 10).


First plant emergence *(days from sowing)*

n=9


50% plant emergence *(days from sowing)*

n=7

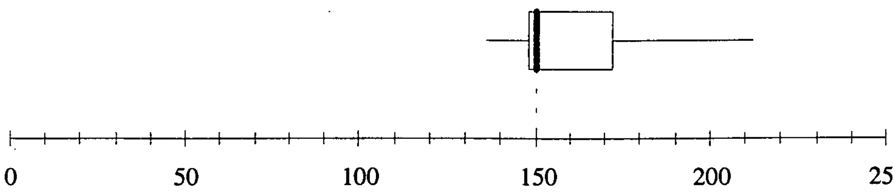

Full plant emergence *(days from sowing)*

n=7

- The first plants took about 2 weeks to emerge, although there was a wide range from less than a week up to seven weeks after sowing in Edinburgh in 1993-4.
- The duration of emergence was quite short, occurring over a period of about 16 days.

- Much of the variation in the time from sowing to emergence is caused by differences in the temperature between the sites and seasons.

Thermal time to emergence *(expressed as °C above zero between sowing and 50% plant emergence)*



n=7

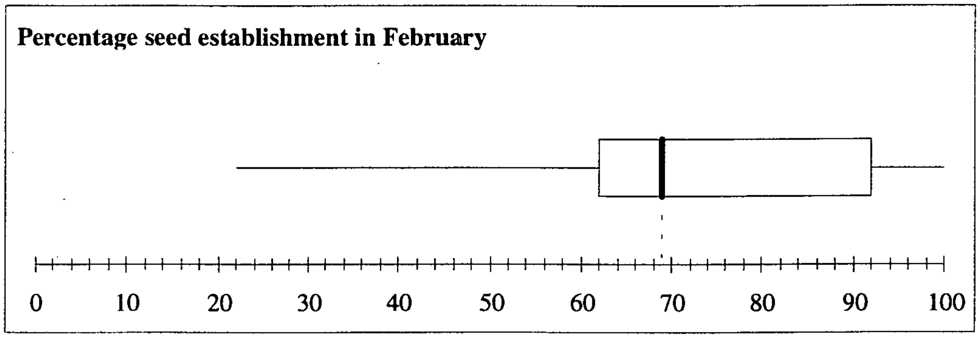
- For the seven sites where records were kept, the median period from sowing to 50% plant emergence was 150 °C days. The variation between sites was much less than the variation in number of days to emergence.
- The time taken for some plants to emerge is extended beyond 200°C and it is likely that the seedlings have inadequate soil or moisture availability.
- Emergence is also affected by the:-
    - sowing depth
    - germination capacity (vigour, quality and size) of the seed
    - quality of the seed bed
    - disease and pest damage
- Delayed drilling normally results in extended and a lower percentage emergence, which is often counteracted by increasing the seed rate.
- Increased seed rate can on its own, be associated with decreased percent emergence. Hence, increased seed rate does not *completely* compensate for expected poor emergence.

Over-winter survival

- Plant damage or loss may occur due to :
    - sharp frost following a period of mild weather. Frost damage is accentuated in crops, for example of early developing varieties, which are at more advanced stages of development.
    - poorly prepared and unconsolidated seed beds.
    - 'Frost heave'.

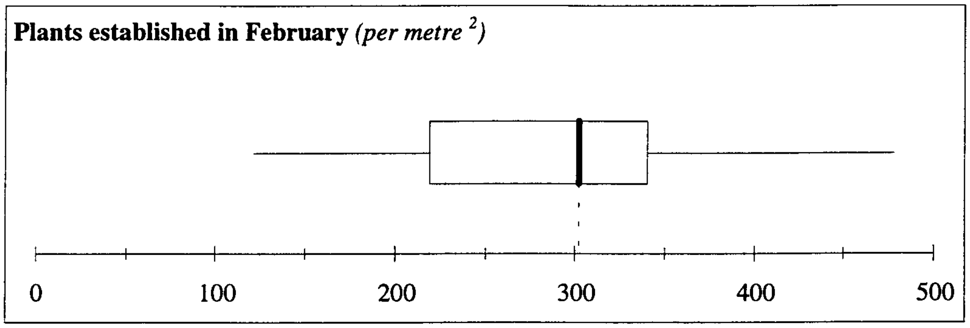
  - impeded drainage of the top soil, leading to poor rooting and standing surface water (waterlogging).
  - wind, disease or trace element stress.

- Plant loss may also result from pest damage such as slugs, wheat bulb fly, frit fly and wireworms.



n=14

- By February a median establishment of around 70% was achieved.
- The minimum establishment was recorded at Harper Adams in 1993/4 where soil conditions were very wet.



n=14

- The median number of plants surviving through to the spring was greater than the target of 275 per m^2.
- Despite attempts to establish a consistent number of plants there was considerable variation in the 'final' number of plants. (The maximum of 478 per m^2 arose through a divergence from the sowing protocol).
- Very little plant death is expected after the spring.

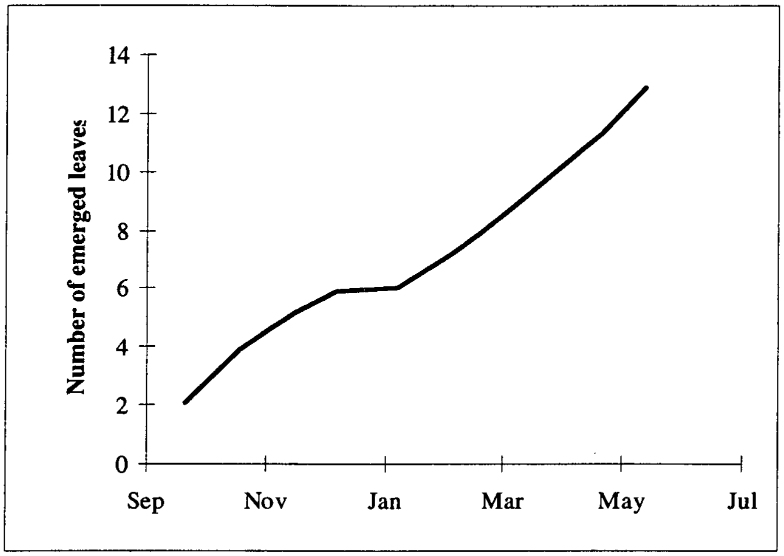
Husbandry Implications

- Seed rate should be based on seeds per metre^2 and can be adjusted for expected establishment in the autumn, and for overwinter losses to aim for a specific target population in the spring.
- Variation in tillering tends to compensate for variation in establishment, depending on the tillering capacity of the variety. It may be possible to counteract the effects of poor establishment by using fertiliser N to encourage tillering.
- Poor establishment does not have serious implications for yield unless it has affected the crop to such an extent that significant areas have very few (less than 50 per m^2) or no plants.
- High numbers of plants (due to good establishment and high seed water) reduce the formation of roots. The resultant poor root anchorage increases the risk of lodging and cause a greater need for growth regulator applications.
- Dense plant stands tend to be more competitive with weeds and hence have a decreased need for herbicides.

4. LEAF EMERGENCE

by E.J.M. Kirby

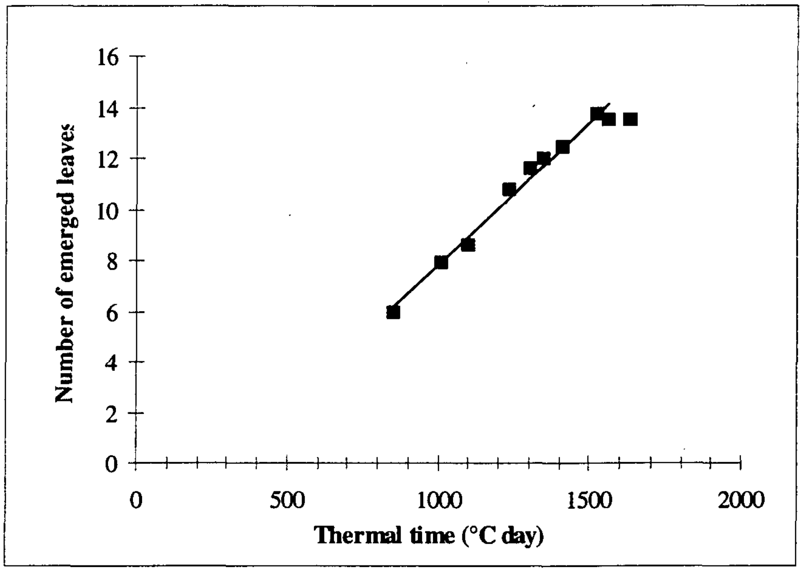
Leaf emergence on the main shoot starts as the seedling emerges from the soil and continues until the flag or final leaf emerges (see the figure below). Each leaf emerges from within the cylinder formed by the leaf below. As it grows, more of the leaf blade (lamina) is exposed until the ligule (junction between blade and sheath) is clear of the sheath of the leaf below and its lamina is fully exposed. The number of emerged leaves is used as an index of crop development (see Section 2, '*Plant Development*' and Part II, *"In -field Crop Assessment"*) e.g. GS 13 describes a plant with three fully emerged leaves).



- Tillering is related to leaf emergence. The first tiller is usually visible when the main shoot has three emerged leaves.
- Tiller production then continues in step with leaf emergence until the maximum number of tillers is achieved at about the beginning of stem extension.

Rate of leaf emergence

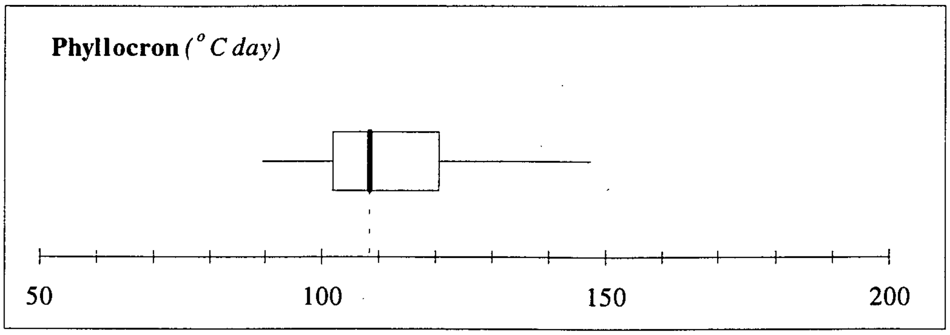
- Leaf emergence may be very slow over the winter (see the figure above) as temperature rises in the spring.
- The rate of leaf emergence depends mainly on temperature.
- Because of its dependence on temperature, the rate of leaf emergence is usually analysed and expressed in terms of thermal time.



The points are observations and the dashed line is the fitted regression.

- Rate of leaf emergence varies significantly between varieties.
- The average rate for Mercia is relatively high at about 0.009 leaves per °C day.
- Late sown crops usually compensate by greater rates of leaf emergence.
- Leaf emergence rate is affected by soil compaction and severe nutrient deficiency.
- Leaf emergence rate is not much affected by other environmental factors such as plant population.

The time between emergence of two successive leaves is called the phyllocron. In crops like wheat where leaves are growing over variable temperatures during several seasons, the phyllocron will vary with temperature. This can be taken into account by measuring thermal time above 0°C (for a description of thermal time see Volume I Part 3 *"Forecasting crop progress for wheat")*. The average length of phyllocron for Mercia sown in October is about 112°C days. Phyllocron is shorter for later sowings.



n=16

- The median phyllochron would indicate that, at an average temperature of 5°C, the period for a leaf to emerge would be about 22 days (108°days/5°C).
- The last two leaves (the flag leaf and the penultimate leaf) usually emerge when the temperature is about 12°C. Thus the median duration of emergence would be nine days (108°days/12°C).

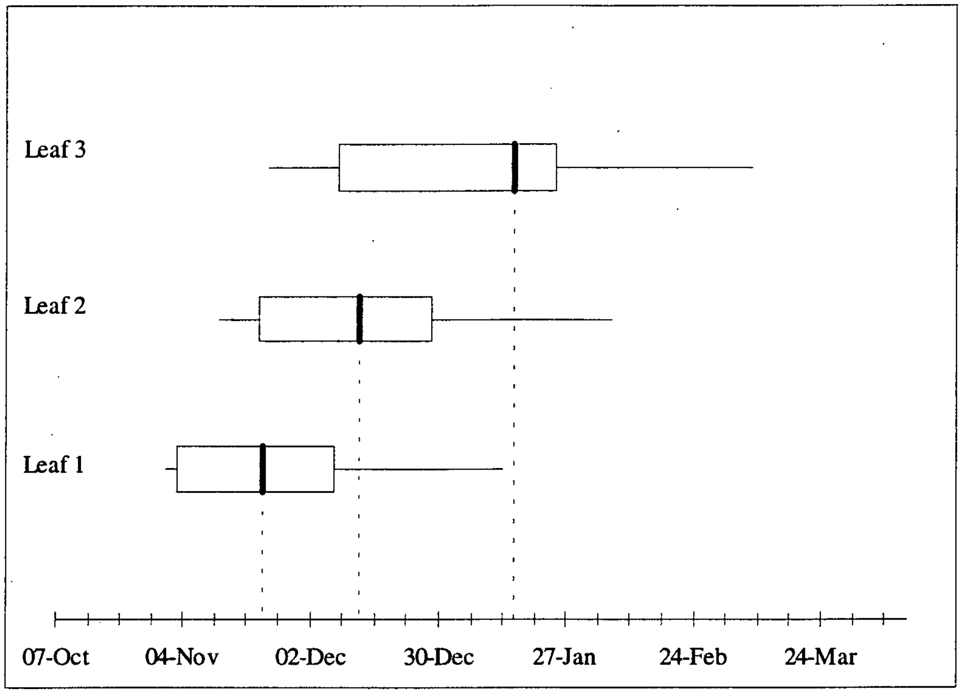
Leaf numbering systems

If leaves are counted from the first or basal leaf, the flag leaf number will be from 9 to 14. In practice, because the lower leaves die over the winter, it is difficult to use this system and it is usual to number the final leaves from the flag leaf downwards. Thus the flag leaf is leaf 1 or F and the penultimate leaf is leaf 2 or F-1, and so on. The latter system is used to identify leaves in fungicide scheduling systems designed to protect the canopy from disease during the stem extension and ear emergence phases of the life cycle.

Emergence of leaves in the autumn.

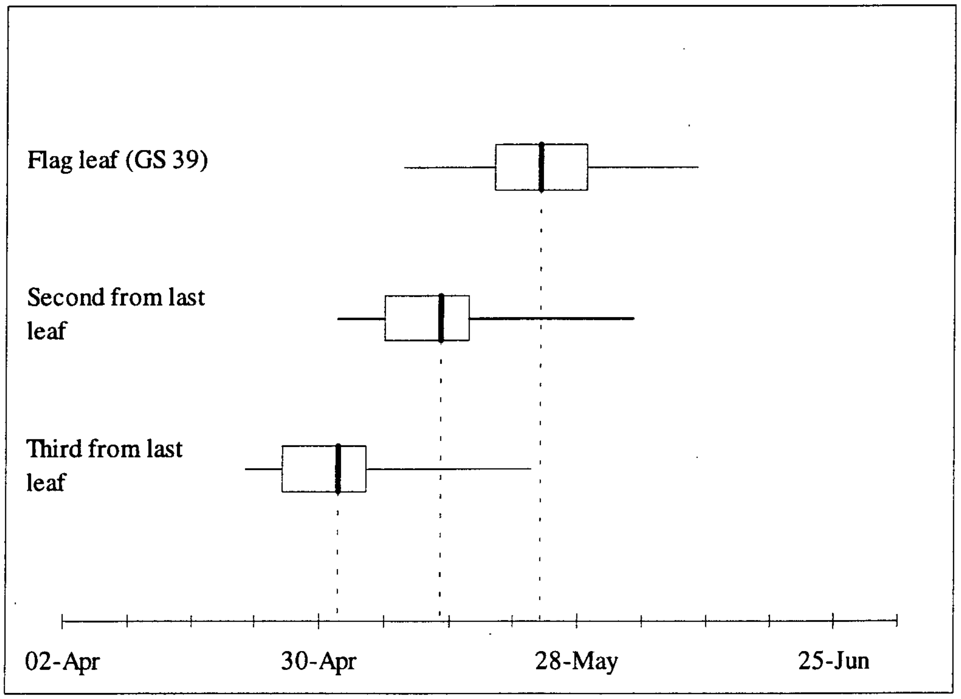
- The timely emergence of the first leaf on the shoot (leaf 1, numbering from the basal leaf upwards, GS 10) depends on weather or soil factors (See Section 3,*'Crop Establishment'*).
- Based on the phyllochron observed in one phase of development, leaf emergence at other stages can be predicted. For example, leaf emergence in the Mercia crops was not recorded until spring, but the predicted dates when the other leaves emerged have been calculated as in the following diagram :

Predicted dates of emergence for leaves 1 to 3



n = 18

Observed dates of culm leaf ligule emergence

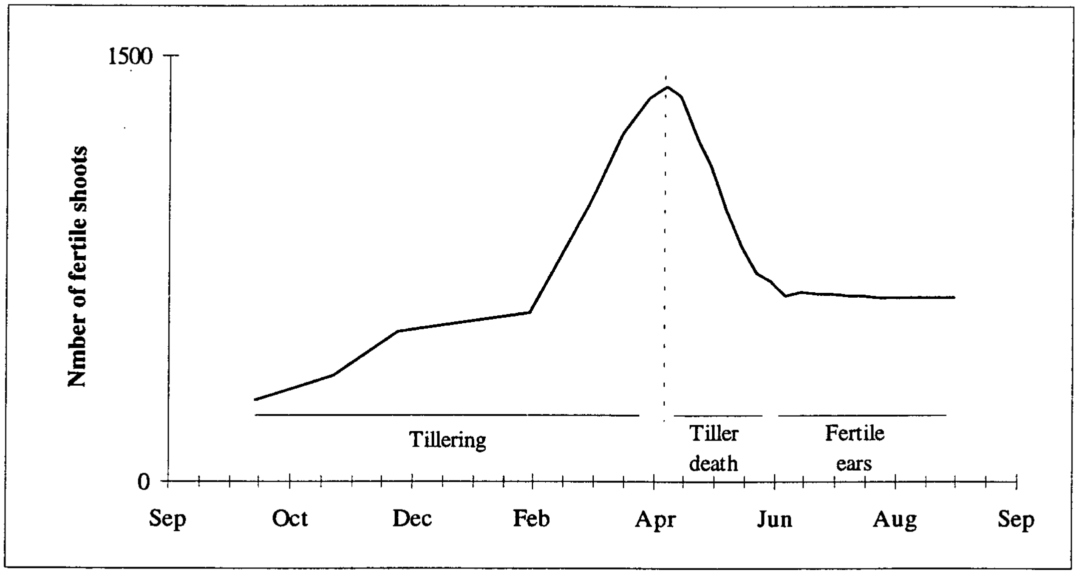


n = 18

5. TILLERING

by E. J. M. Kirby

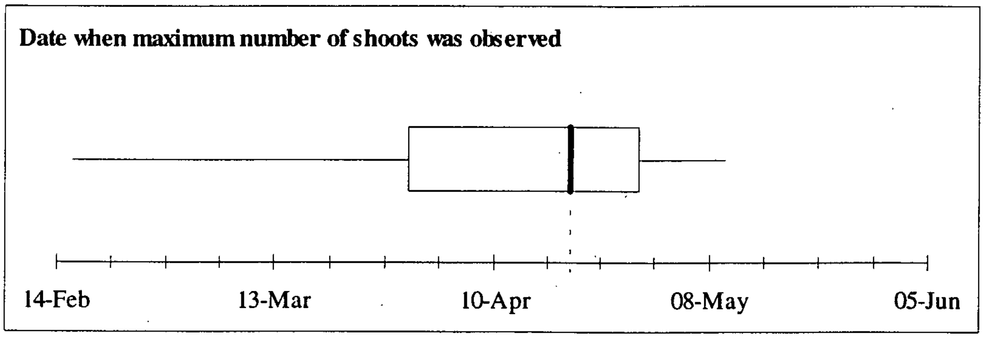
Tillering is the increase in shoot number by the production of branches or tillers in the leaf axils.



The phase of tiller production is normally distinct from the phase of tiller death. Tiller death normally ceases well before maturity. Occasionally, the resumption of tiller production ('secondary tillering') is stimulated by moist conditions during ripening, or rain following particularly dry conditions.

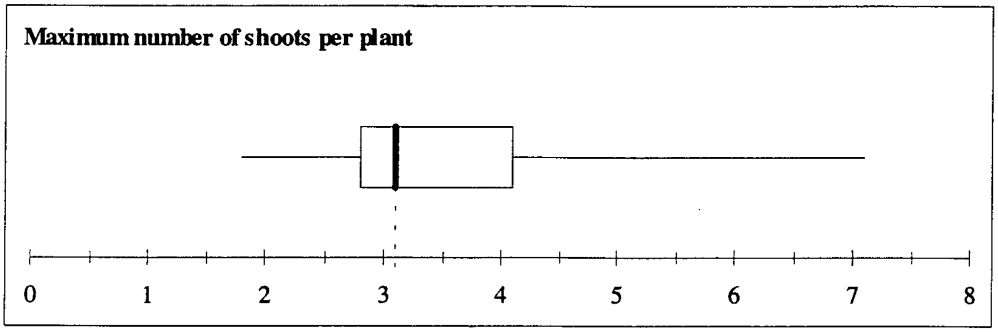
Tiller production

- With early sowing (September) the main tillering phase tends to be in the autumn, whereas with late sowing (late October) tillering is mostly delayed until spring.
- Tillering starts when three leaves are visible on the main shoot and continues until about March or April when the maximum number of shoots is present.



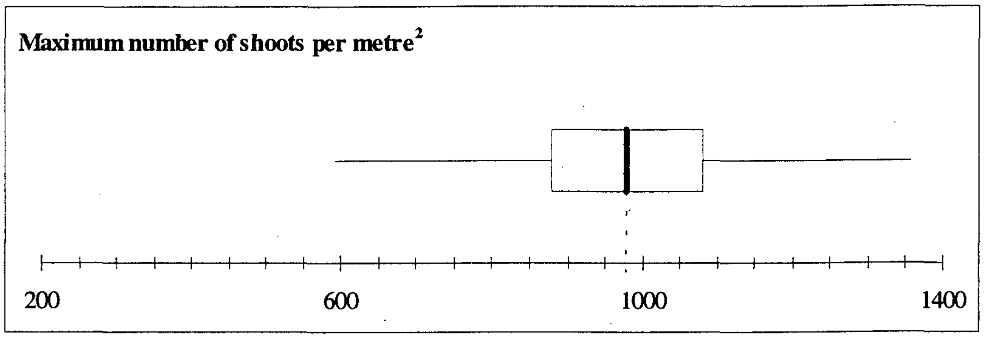
n=18

- The maximum number of shoots was most often observed in April; the median date was 20 April.
- The maximum number of shoots occurs earlier in warm seasons.
- Shoot production tends to last longer where there are fewer plants (per metre^2).
- There tend to be more shoots per plant (i.e. main shoot plus tillers) where there are fewer plants, because there is less inter-plant competition.



n=15

- The median maximum number of shoots per plant was about three.
- Shoot production tends to last longer where there are fewer plants (per metre^2) because there are more shoots per plant.
- Low soil fertility and poor soil conditions reduce shoot production.
- Early sowing increases the maximum number of shoots.

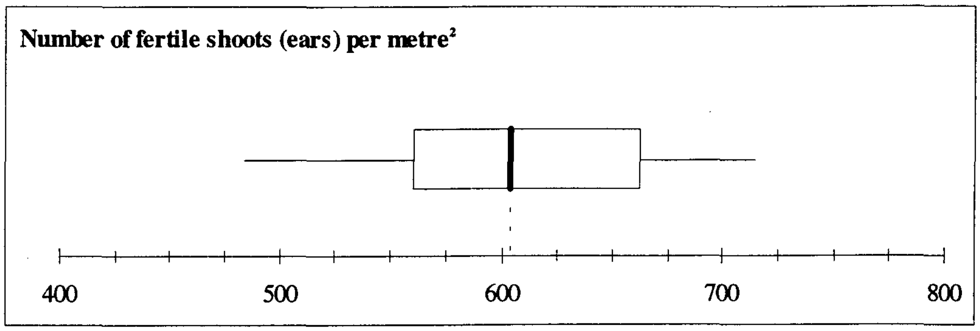


n=18

- In the Mercia crops there was a median of about 1000 shoots (per metre^2) at the end of shoot production.
- Varieties differ in their tillering potential. Mercia has moderate tiller production in relation to contemporary varieties.
- Although higher plant populations cause fewer shoots per plant, maximum shoot number (per metre^2) increases with plant population.

Tiller survival

- Almost always, more tillers are produced than survive to form ears.
- The phase of tiller death coincides with the growth of the stem.
- The smaller, later formed tillers tend to die first.
- Tiller death is best explained by there being inadequate resources for growth of all live shoots.
- Shoot number normally stabilises between ear emergence and anthesis stages.
- All surviving shoots at anthesis have ears and will normally bear grain.
- After anthesis the number of fertile, ear-bearing shoots remains constant until harvest.
- Variation in fertile shoot number, or ear number, commonly accounts for a large proportion of variation in canopy size, total dry weight and grain yield.



n = 18

- The Mercia crops had a median number of fertile shoots of 604/m^2.
- The median fertile shoot number per plant was about 2¼, i.e. most plants had one fertile tiller per main shoot.
- Varieties differ in their shoot survival. Mercia shows relatively high tiller survival compared to other contemporary varieties.
- Ear number is highly susceptible to variation in growing conditions, especially nitrogen supply, during spring and early summer.
- The number of ears at harvest can be confidently predicted by counts made at anthesis.

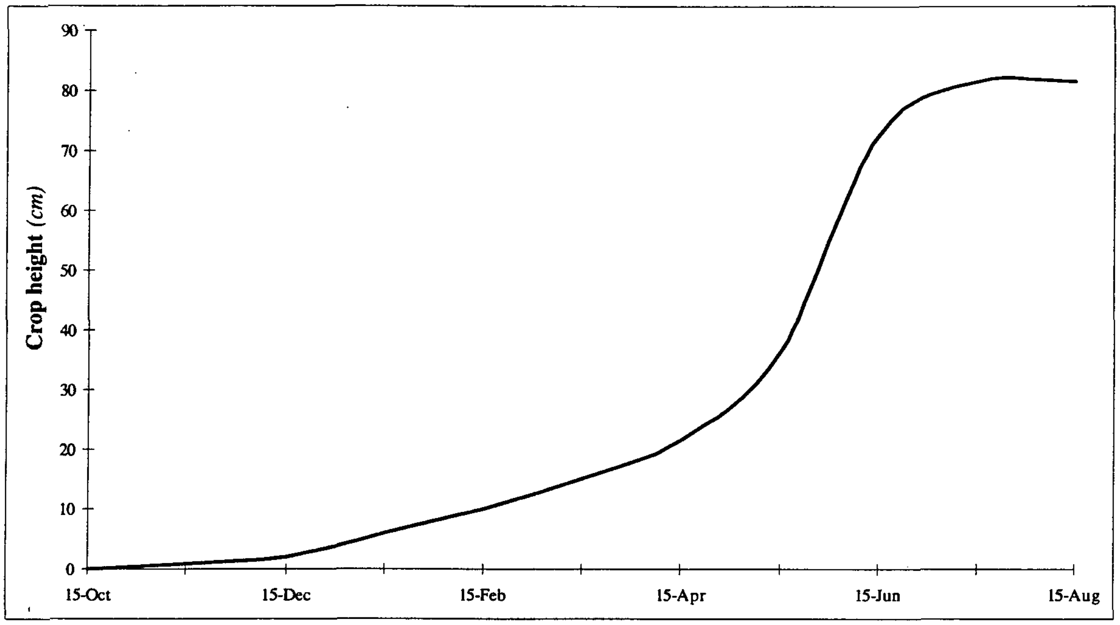
Husbandry implications

- Since there is little further tillering after the beginning of stem extension, the maximum number of shoots can indicate an upper limit to the eventual performance of the crop.
  - Shoot numbers of less than 450 (per metre^2) are seldom associated with high yields.
- High or low shoot numbers early in the spring can be manipulated by altering the amount and timing of the first spring nitrogen application.
- High shoot numbers, especially if associated with high plant numbers, are indicative of high lodging risk, which can be countered by application of plant growth regulators.
- High numbers of surviving fertile shoots tend to be associated with low harvest indices (see Section 15 '*Grain Yield*') and relatively high straw yields.

6. CROP HEIGHT

by J Spink

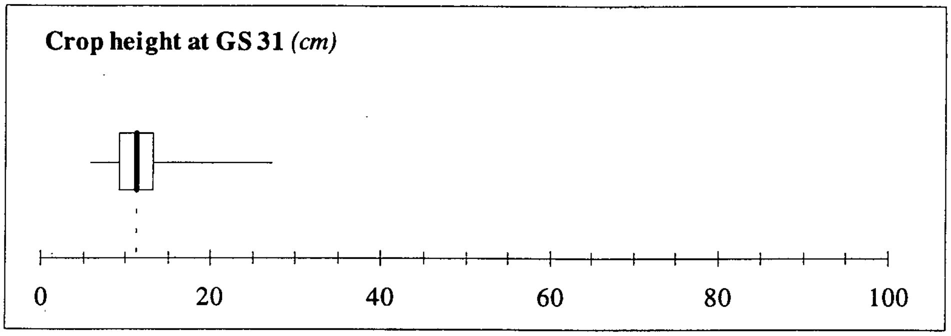
Crop height was measured to the ligule of the last fully emerged leaf until after ear emergence. Height was then measured to the collar of the ear. Ear length contributes about 10 cm to crop height.



Early in the crop's life there is a little growth in height through extension of leaf sheaths, but crop height largely increases as a result of extension of the internodes beneath the final four or five leaves, and the peduncle beneath the ear. Thus the stem or culm consists of five or six extended internodes. The pattern of internode extension is for the internode to begin when the previous internode is half complete. Final crop height is reached at about the time of flowering.

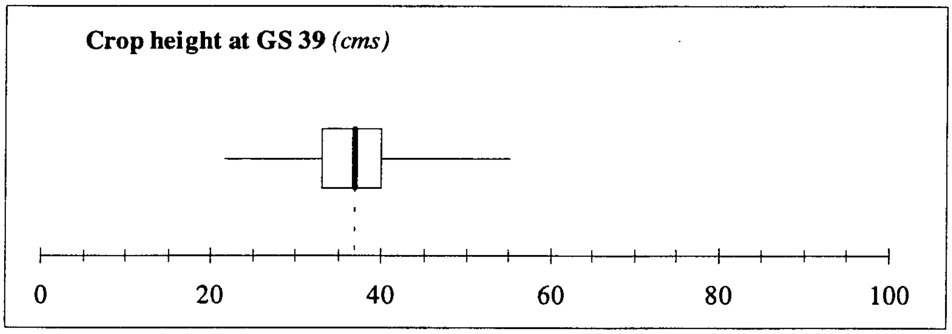
- Crop height is affected by variety, sowing date, nitrogen use, plant growth regulator (PGR) use, and plant and shoot number per metre^2, as well as site and season.
- There has been a trend for final crop height to decrease over recent decades through the introduction of improved varieties containing the *rht* genes.
- Mercia is not a semi-dwarf (*rht*-containing) variety; it is about middle of the range in terms of crop height of those varieties listed in the Recommended List (1995; shortness of straw = 6).
- All the reference crops received full PGR applications of Chlormequat at GS 30-31 followed by Terpal at GS 37-39, and therefore represent minimum expression of crop height, given recommended rates of nitrogen.

- Stem extension nominally begins at GS 30 when the shoot apex is 1 cm or more above the base of the plant but when the first internode is less than 1 cm. However the stem will appear to have started extending slightly prior to this.


Crop height at GS 31 *(cm)*

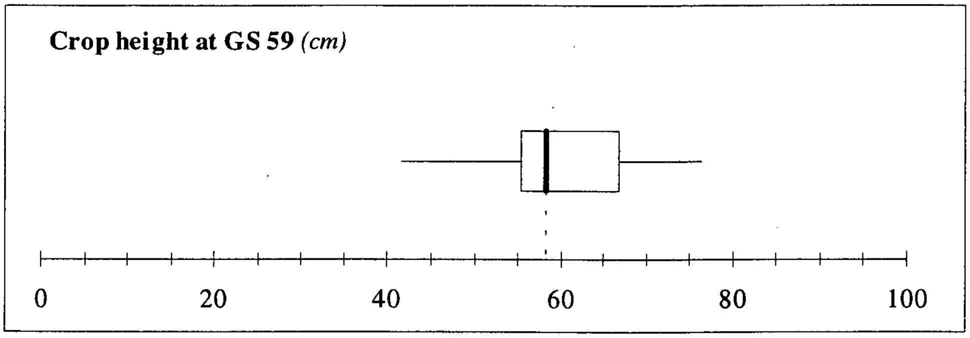
n = 11

- By GS 31 the median crop height was 11.2 cm, most of which consisted of leaf sheaths (or the 'pseudostem').
- Crops which have been sown early, are in high nitrogen residue sites or have not received (or only recently received) a PGR would be expected to be at the higher end of the range of crop height.
- Warm winter or early spring growing conditions would tend to increase crop height early in the season.


Crop height at GS 39 *(cms)*

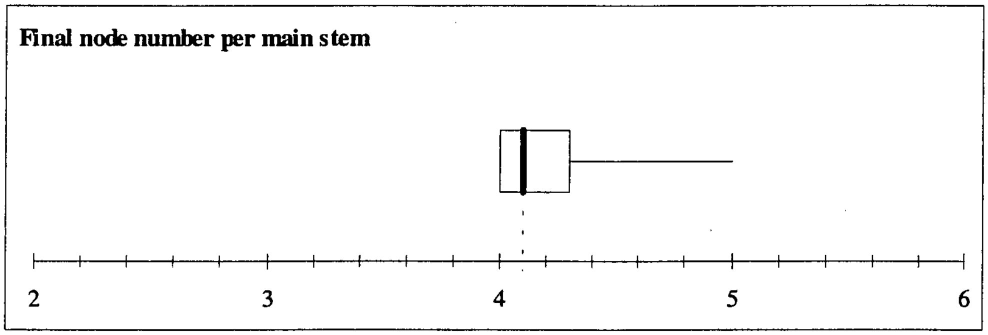
n = 14

- By GS 39 the median crop height was 36.9 cm, or about 60 % of the final median crop height.
- Tall varieties, high residual nitrogen and omission of PGR applications will tend to increase crop height at this stage.
  - Height of crops on low nitrogen residue sites that have had large applications of nitrogen may be catching up with crops grown with a high residue.
  - Early PGR applications have their main effect on the lowest two internodes and shorten the crop by about 10 cm.



n = 17

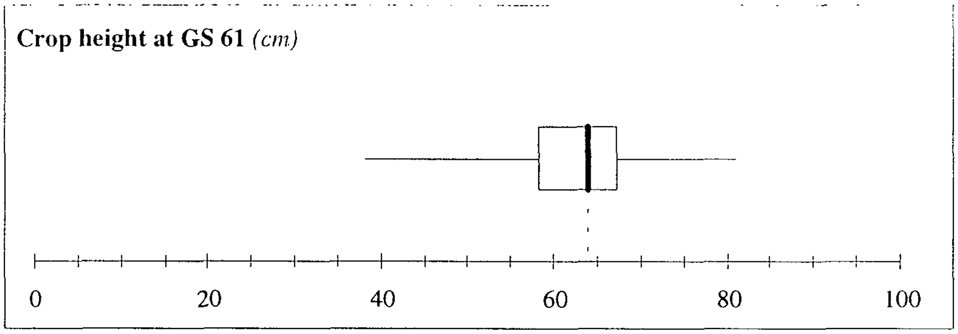
- From GS 39 to GS 59 the median crop height had increased by 22 cm to 59 cm, due to continued extension of flag leaf sheath.
- Peduncle extension had not affected height by this stage because, only when the crop has reached GS 59 does the collar of the ear become visible above the flag leaf ligule.
- The small minimum value of only 41.6 cm was at Edinburgh in 1994 and was due to low temperatures and low incident radiation through the season. No other height was less than 49.7 cm at this stage.
- Further increases in crop height from this stage are due purely to extension of the peduncle. The peduncle often accounts for approximately one third of the final height of the crop.
- The main effect of applied nitrogen is in extending the penultimate internode and peduncle.
- Further stem extension accounted for only an extra 8 cm of crop height in Mercia with a full PGR program.
- The height increase from GS 59 could be expected to be larger, perhaps as much as 20 cm, with other varieties or crops without a late application of Terpal.



n = 17

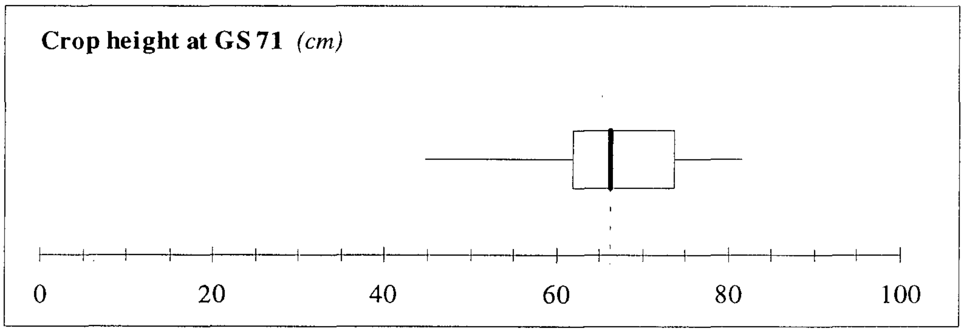
- Median final node number was 4.1.
- On no occasion was the number of nodes less than 4 and only on 3 occasions was it as much as 5.

- Node number is only altered by extremes in terms of sowing date or seasonal weather.
- Varieties with particularly fast or slow rates of development may have more or less nodes respectively than the norm.

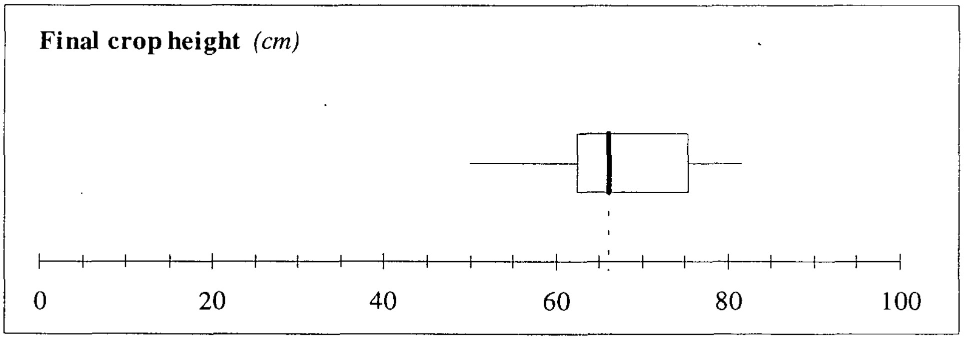


n=14

- By GS 61 the median crop height of 64 cm was within 2 cm of the final median crop height.
- Stem elongation continued to increase slightly between mid anthesis and early grain fill.



n=14



n=14

- By GS 71 crops had achieved their final height, the median being 66 cm.
- The maximum crop height was relatively short at 81 cm probably due to the two growth regulator applications. The tallest crops were associated with fertile conditions e.g. (Boxworth 1994).
- Edinburgh produced relatively short crops.

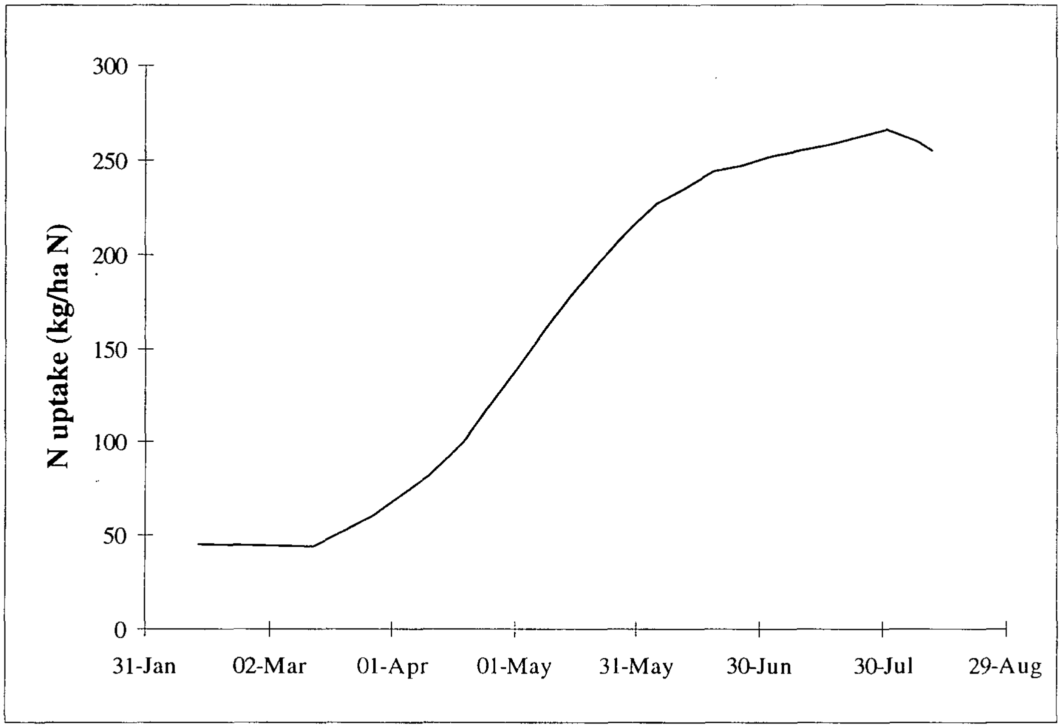
Husbandry implications

- Crop height is an important determinant of the lodging risk of wheat. Increased crop height will increase the force exerted by the aerial parts of the plant on the stem base and root system.
- PGR applications are the main method of controlling crop height.
- However, most products e.g. those containing chlormequat, must be applied before height has been expressed even if split applications have been made. It is therefore necessary to judge likely height from crop conditions in spring, particularly the shoot density and leafiness (indicating soil fertility).
- GS 45 is effectively the latest crop growth stage at which decisions about PGR program can be made.
- To some extent, it is therefore possible to use observations of crop height in deciding on final PGR applications.

7. NITROGEN UPTAKE

by D.T. Stokes

N uptake is shown by changes in the amount of N in the above-ground crop over time. It is measured as the product of crop dry weight and the N concentration of the dried material, determined by chemical analysis.

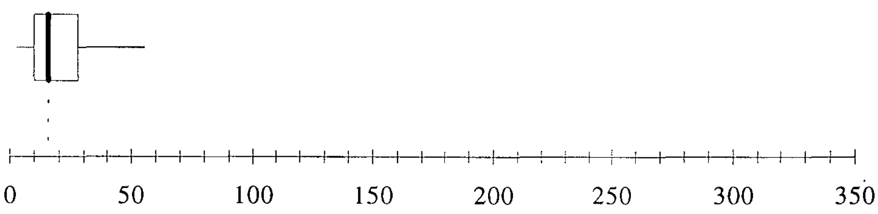


- Crop N is acquired from fertiliser N, via the topsoil, and from native soil N which is distributed throughout the rooted zone (one metre depth or more).
- About 40 kg/ha N may be contributed by the atmosphere, either in rain, as dust or as N-containing gases, e.g. ammonia.
- Soils in arable rotations supply enough N for wheat to produce roughly half its potential yield of grain.
- Fertiliser N has a major influence on N uptake. Most N is applied in March and April just prior to the rapid uptake phase.
- N uptake has a major influence on expansion of the crop's green canopy, primarily through increasing shoot numbers.
- Where they are used, animal manures can contribute significant N amounts for crop uptake.

The pattern of N uptake

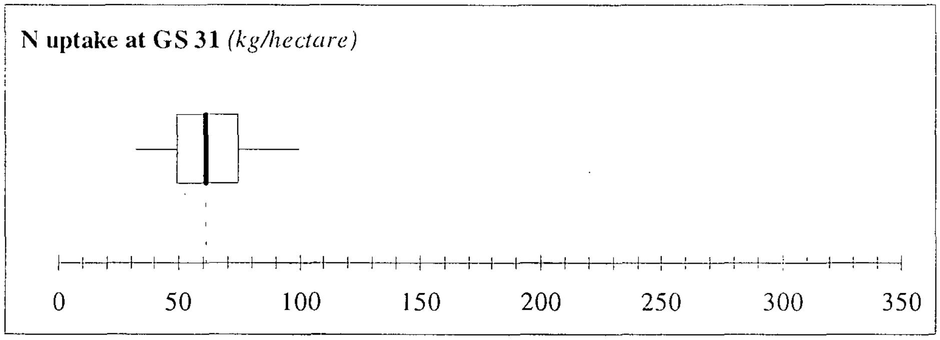
- Uptake is usually small over winter when the potential for crop growth is small.
- Uptake of N from autumn to spring is known to be increased by :
  - large amounts of unrecovered fertiliser from the last crop
  - presence of N-rich crop or animal residues, such as animal manures, legume roots or leafy vegetable waste
  - absence of low-N crop residues, such as cereal straw
  - thorough soil disturbance increasing mineralisation of soil organic matter, e.g. deep ploughing rather than shallow cultivation
  - early sowing
  - warm weather
  - unimpeded rooting

N uptake in mid March *(kg/hectare)*



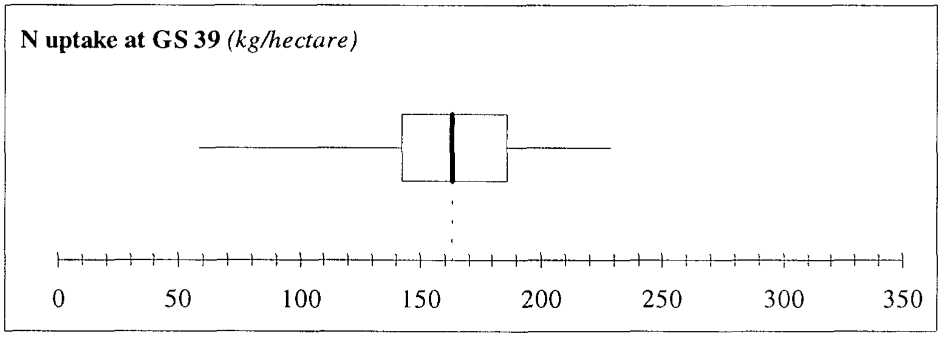
n=18

- By mid March, the median uptake of N was 16 kg/ha, and the maximum was 56 kg/ha N.
- Up to 5 kg/ha of this N originates from the seed, but most is acquired from the soil.
- Roots are still extending at this stage and the topsoil is often becoming depleted of N, so fertiliser N may be required to provide for subsequent uptake.
- The effect of N uptake at this stage is to promote tillering.



n=18

- From March to the start of stem extension median uptake had increased by about 45 kg/ha N. However, amounts were variable.
- The largest fertiliser applications are made at this stage.
- N uptake after GS 31 primarily helps to improve shoot survival.
- Most N is taken up over the next four to six weeks.
- Uptake of N through the summer is known to be increased by :
    - organic soils
    - warm, moist conditions in the topsoil
    - plentiful supplies of fertiliser N
    - adequate shoot numbers
    - absence of root disease e.g. take-all
    - absence of growth restrictions e.g. from unsatisfactory P, K or pH levels
    - adequate water supply at depth, for N uptake during late season

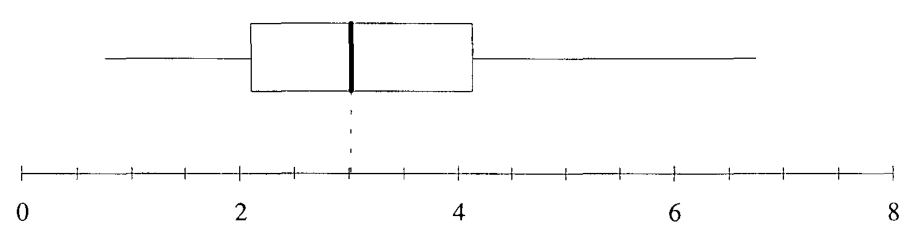


n=18

- From first node stage to flag leaf emergence, median N uptake had increased by 100 kg/ha, and the total in the crop was 163 kg/ha.

- Most of this N was used in the formation of the 'yield-forming' leaves.
- Formation of these leaves also depended upon redistribution of N from dying shoots.
- Rapid N uptake ceased when the flag leaf and ear had appeared and the plant had reached its maximum size.

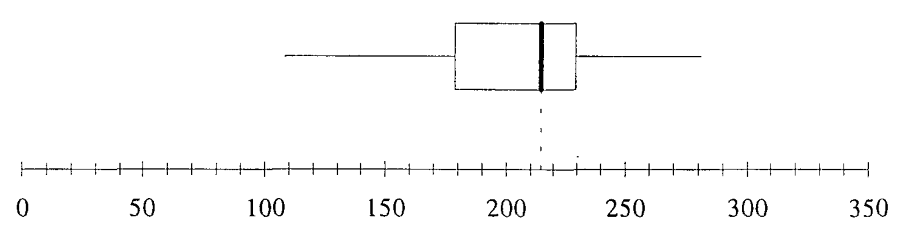
Rate of N uptake between GS 31 and GS 39 *(kg/hectare/day)*



n=17

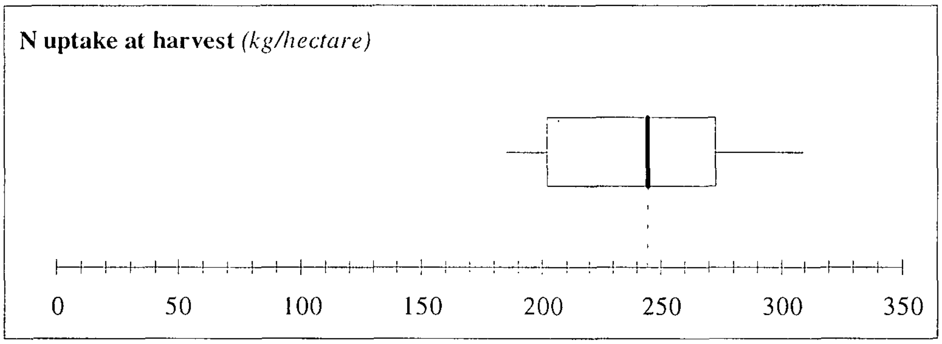
- During the phase between GS 31 and maximum canopy size, the median rate of N uptake was about 3.5 kg/ha/day. At this rate, crops can take up about 140 kg/ha during the main phase of canopy expansion.

N uptake at GS 61 *(kg/hectare)*



n=18

- By the start of flowering median N uptake had increased by a further 50 kg/ha, but there was only a further 30 kg/ha N uptake during grain filling and ripening.
- During grain filling there is a massive redistribution of N within the crop as the proteins in the leaves are degraded and their 'N' is transferred to form grain protein (see Section 15, '*Grain Protein Formation*')
- N can be taken up during grain filling provided that soil water is available. This late N appears to originate from the previous year's crop and is often taken from below 60 cm in the soil.



n=18

- At final harvest, the median total uptake was 244 kg/ha N. About three quarters of this N was in the grain; the rest was in chaff and straw.
- Occasionally there was a small decrease in crop N before harvest. This was probably due to loss of dead leaves.

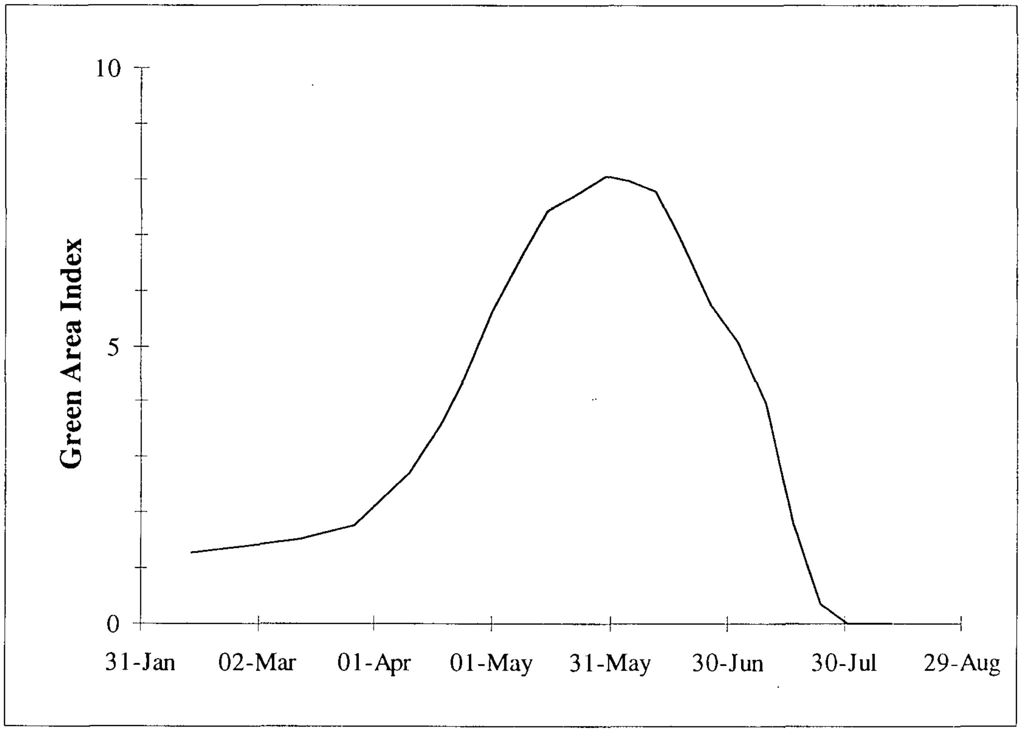
Husbandry implications

- Slow N uptake is associated with slow expansion of the leaf canopy and N remaining in the soil is vulnerable to loss.
- Where N uptake is expected to be slowed over-winter by poor soil supplies, e.g. after minimum cultivation, on a soil of low organic matter, and where large amounts of straw remain, use of autumn-N may be justified.
- Late sowing and cold temperatures reduce canopy expansion. N uptake is likely to be reduced and soil N not taken up may be more vulnerable to over-winter leaching. Early sowing may better utilise soil N especially where animal manures have been applied and soil N is in the form of nitrate.
- Warm conditions over winter and during early spring will increase canopy expansion and the demand for N. Where soil N is low during early spring, warm temperatures are likely to increase the risk of crops becoming deficient and yellow.
- Take-all restricts or curtails root activity prematurely, thus final N uptake may be inadequate. Emphasis on early N applications may avoid this effect where significant take all is anticipated.
- Large crop offtake may indicate efficient removal of most of the soil N. Crops about to become deficient will become pale.
- Large uptake of N in early spring without any yellowing may indicate large supply of soil N and the possibility of reducing fertiliser N amounts. Soil and crop N can be assessed in February or March and can be used to confirm that fertiliser N applications can be reduced.
- Rapid N uptake indicates increased susceptibility to foliar pathogens, and a greater need for precise fungicide use.

8. CANOPY EXPANSION

by D. T. Stokes

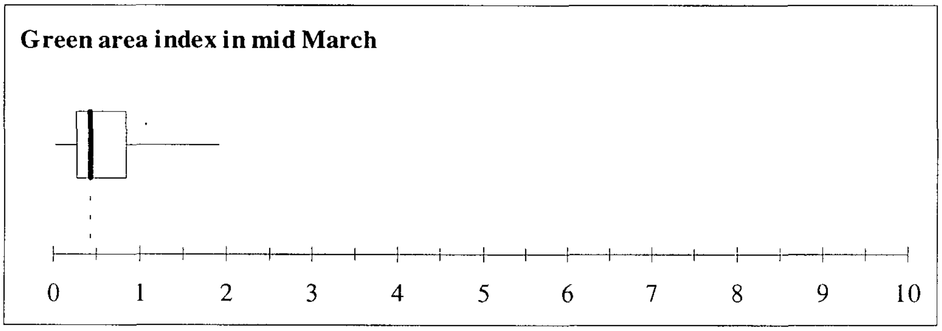
The crop canopy is comprised of all its green surfaces, leaves, sheaths, stems and ears. These are responsible for capture and conversion of the energy in sunlight, through photosynthesis, into the carbohydrate necessary for crop growth and yield formation.



- Most of the green area of wheat is comprised of leaf blades. The number of leaves depends on the number of shoots surviving and the number of leaves per shoot (see Section 4, '*Leaf Emergence*' and Section 5, '*Tillering*').
- Canopy size is measured as the Green Area Index (GAI), which is the ratio between the total area of all green tissues, one side only, and the area of ground they occupy.
- There is a relationship between canopy size and the proportion of sunlight intercepted. Each successive unit of canopy size results in diminishing increments in light energy intercepted up to a point where full light capture is achieved.

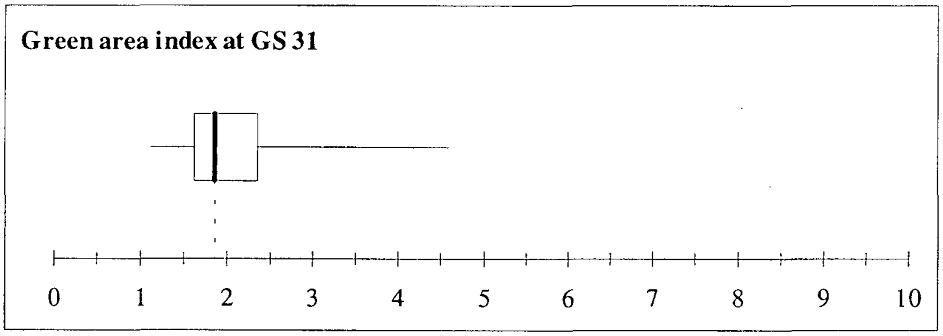
The pattern of canopy expansion

- The typical pattern of canopy size for winter wheat shows phases of (i) slow expansion, (ii) rapid expansion, and (iii) rapid contraction.
- During early autumn and over-winter, the crop canopy is composed mainly of leaves and is quite small.
- Canopy size can be influenced by :
  - early sowing
  - high seed-rate
  - percentage establishment
  - freely tillering varieties
  - plentiful supply of soil N
  - application of large amounts of fertiliser N
  - efficient recovery of fertiliser N
  - freedom from water shortage
  - P and K deficiencies and low pH
  - control of foliar disease


Green area index in mid March

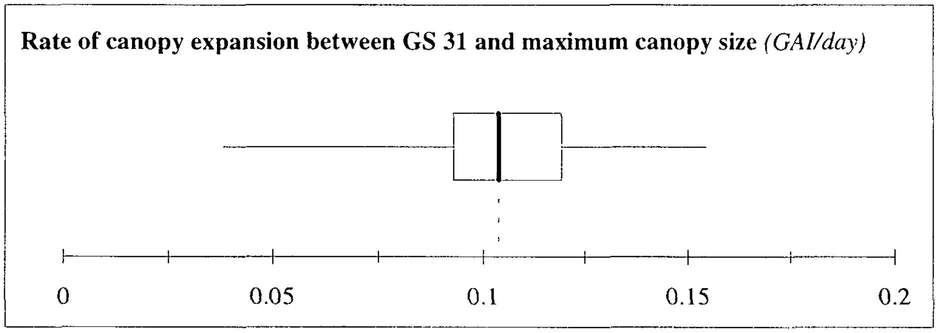
n=18

- By mid March, the median GAI was 0.4, but GAI was very variable: from 0.01 at Edinburgh in 1993 to 1.9 at Boxworth.


Green area index at GS 31

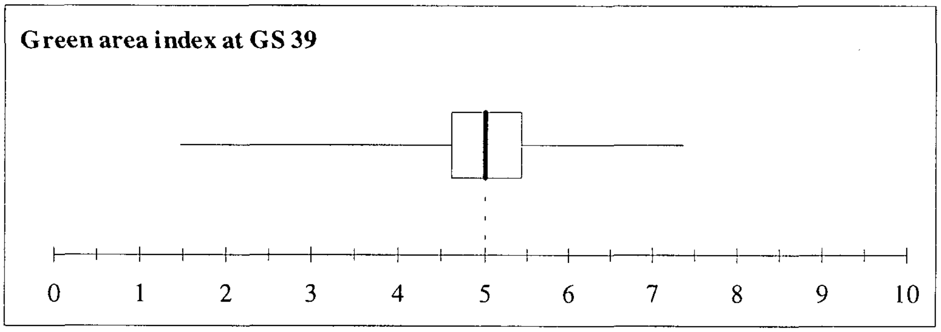
n=18

- At the start of stem extension the median GAI was 1.9.
- After this stage the rate of canopy expansion is at a maximum as temperatures increase, the stem's contribution to GAI becomes significant, and the largest leaves emerge.



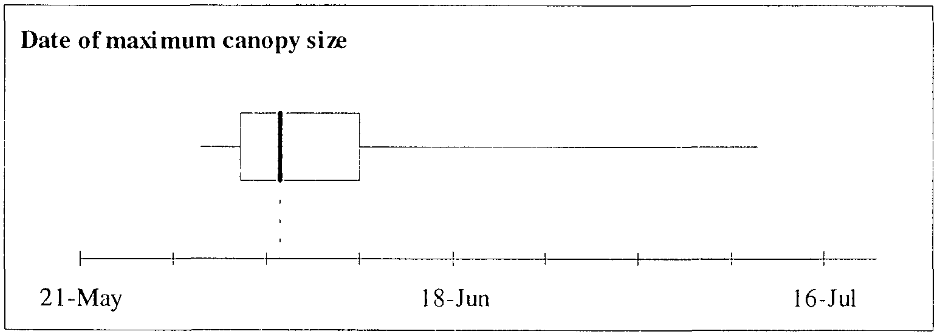
n=18

- The median rate of canopy expansion was 0.1 GAI per day. Crops expanding at this rate could increase their GAI by 3 units during May provided the potential for expansion does not become restricted.



n=18

- At flag leaf emergence (GS 39) the median GAI was 5.9, but there was a five fold variation in GAI.
- Small canopies result from inadequate plant or shoot survival, or N deficiency.
- Maximum canopy size is normally reached shortly after ear emergence because ears contribute to GAI. However, in N-starved crops the lower leaves have already started dying by this stage and maximum size occurs earlier.
- At flag leaf emergence, leaf blades still comprised about 85% of the GAI.



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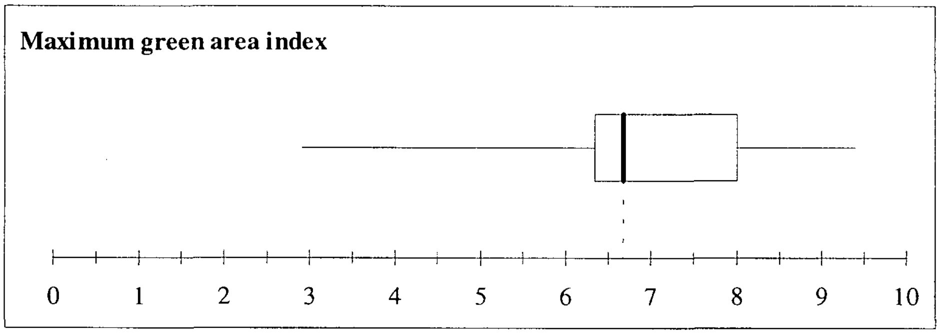
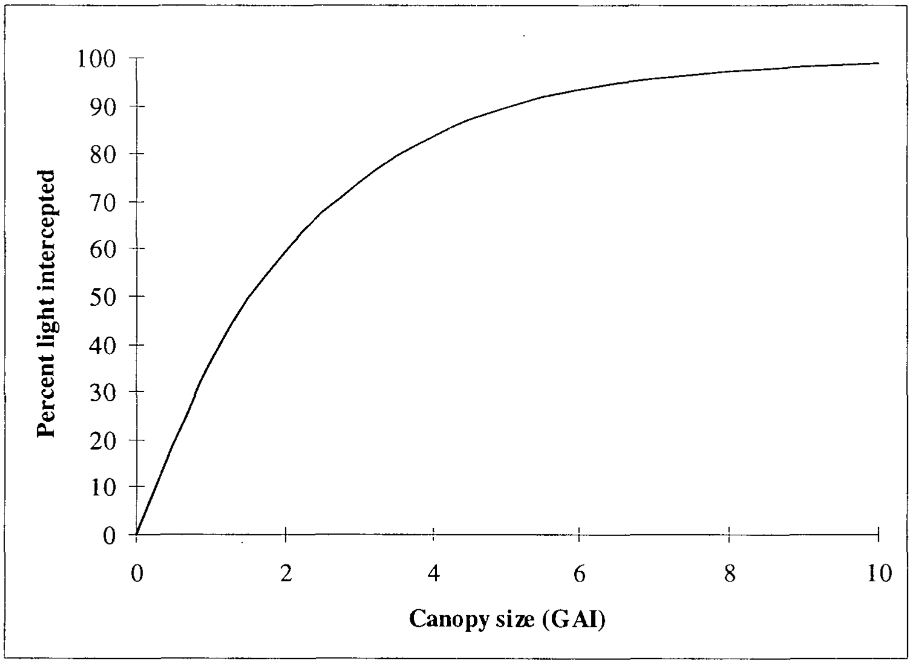


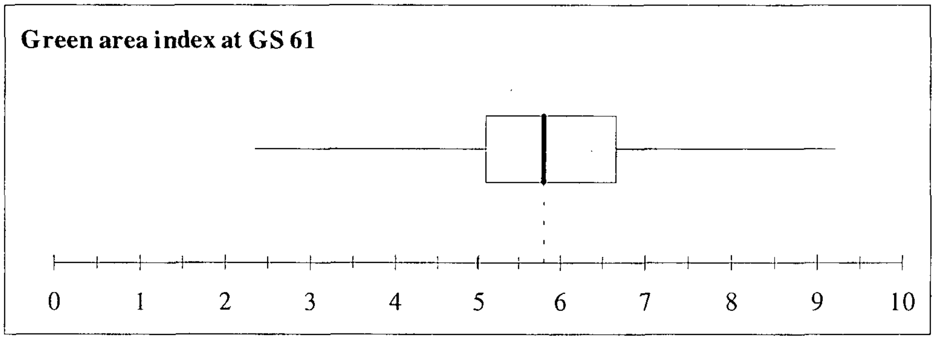
n=18

- The median date when canopies reached maximum size was 5 June, i.e. between flag leaf emergence and anthesis.
- At its maximum, median canopy size was 6.6.
- The benefit in terms of light capture of canopies expanding from 2 to 3 GAI is about 15%, whereas an increase from 6 to 7 GAI results in a benefit of 3%. (see the figure below).

Light intercepted by increased canopy size



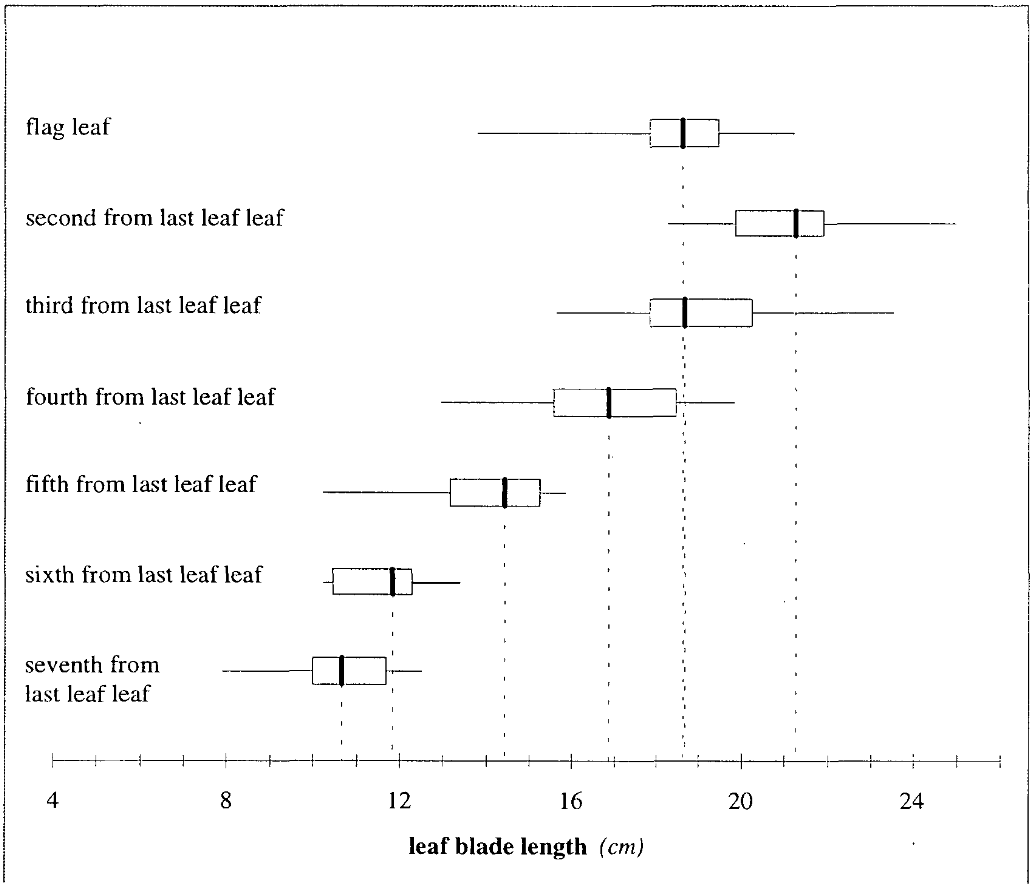
- By anthesis some canopy senescence had occurred, mainly through death of the lowest leaves. Canopy size was less variable across sites and years at this stage; the crops from the middle interquartile range had a GAI between 5.0 and 6.7.



n=18

- At this stage leaf blades comprised about 80% and stem and sheath comprised about 20% of the green canopy area.

- The last five leaves form the majority of the leaf component of the canopy. Median leaf lengths were progressively longer for the later emerged leaves except for the flag which was about 2 cm shorter. This pattern differs between varieties.



n=18

- From June onwards the canopy senesces, and is often completely dead by the end of July, bringing crop growth to an end (see discussion of growing periods in Section 13, '*Crop Growth*').

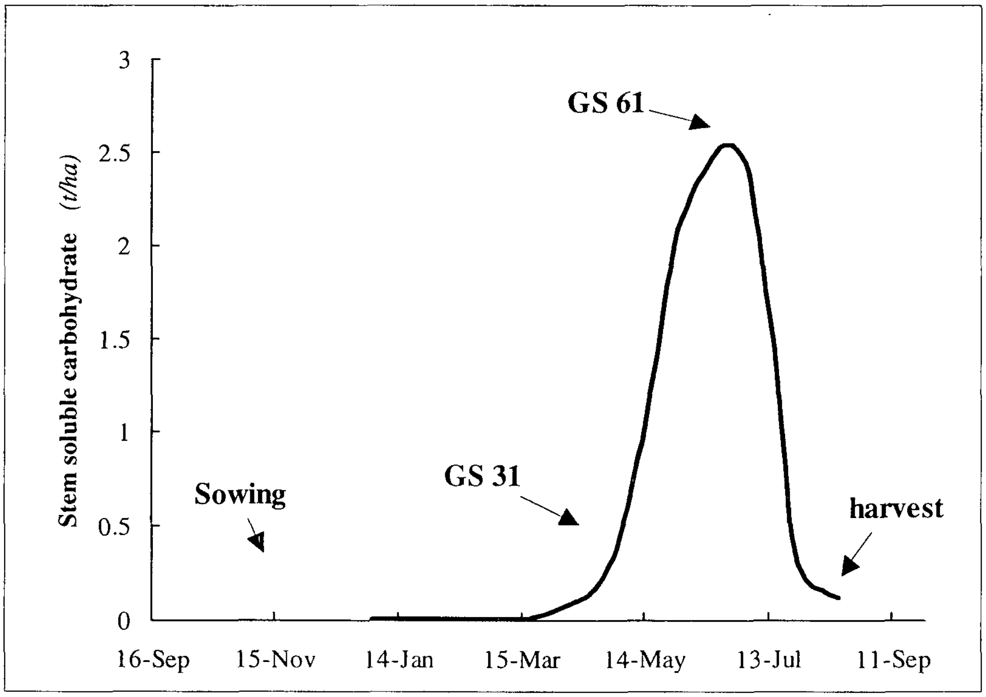
Implications for husbandry decisions

- Canopy size determines the proportion of sunlight intercepted, and therefore growth rate.
- There appears to be an optimum canopy size for growth.
- If the canopy is too small, less than GAI 4, some sunlight will be wasted.
- If the canopy is too large, GAI 8 or more, it will probably have cost more to produce and protect than is necessary to intercept all the available sunlight.
- Large canopies are more competitive with weeds, but reduce spray penetration.
- Early sowing in autumn will increase canopy size but also increases the risk of green area loss overwinter.
- Large canopies in early spring indicate a large supply of soil N which may allow for reduced use of early fertiliser N.
- If canopy expansion is on target in April for a moderate GAI, say 6, and soil N is still plentiful, fertiliser N may be reduced.
- The rate of canopy expansion can be used to predict the maximum canopy size.
- Large potential canopy size may indicate a reduced requirement for fertiliser N.
- Crops with large potential maximum canopy sizes will be at greater risk from foliar disease and lodging.
- If maximum canopy size is large, say GAI 8, late N is likely to have less impact on protein percentage because crop N is likely to be sufficient for grain protein formation.

9. STEM CARBOHYDRATE STORAGE

by M. J. Foulkes

- Some dry matter for grain-filling comes through redistribution of materials accumulated in the stem. In addition to structural materials the stem contains soluble carbohydrates which are readily remobilised.
  - Soluble carbohydrate stored in stems is measured as the product of i) dry weight of stems, with their attached leaf sheaths and ii) their percentage of water-soluble carbohydrate determined by chemical analysis.
- Soluble carbohydrates in stems increase rapidly during stem extension and ear emergence, but then decrease during grain filling.
- Soluble carbohydrate stored in stems can be used to support grain filling, if the green canopy senesces prematurely, for example, due to water stress or foliar diseases.

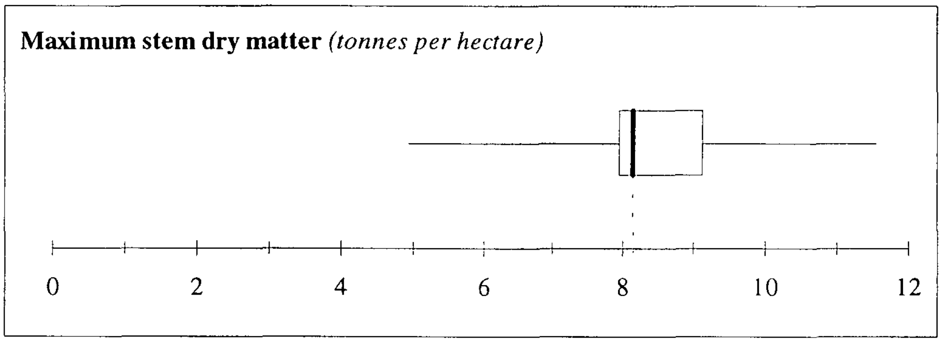


During stem extension, leaf, stem and ear are in competition for assimilate to form structural tissues (mainly lignin, cellulose and hemi-cellulose), but during the later stages of stem extension, from GS 37 onwards, this demand for assimilate decreases rapidly, and proportionately more assimilate is available to form soluble (storage) carbohydrate in the upper internodes.

- The accumulation of carbohydrate reserves starts near the end of each internode's extension, i.e. when the internode above it is elongating rapidly.
- Almost all of the soluble carbohydrate accumulating in the topmost internode, the peduncle, does so after flowering (GS 61).
- There is a good relationship between accumulation of soluble carbohydrate in the stem and duration of the period between flag leaf emergence and the onset of rapid grain growth.

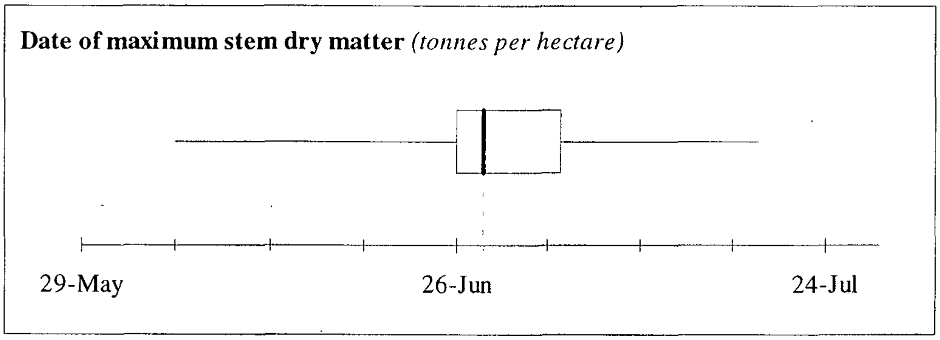
Accumulation of stem reserves

- There is significant genotypic variation in stem and leaf sheath weight. Mercia is about middle of the range for current varieties.
- Most field-to-field variation in stem and leaf sheath weight is explained by environmental rather than genotypic effects.



n=18

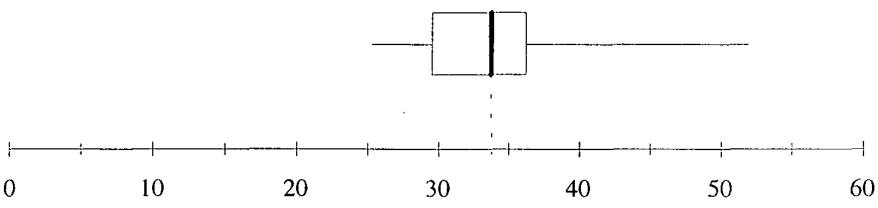
- The median maximum amount of stem dry matter for the Mercia crops was 8.2 tonnes per hectare; the range was 4.9 - 11.7 tonnes per hectare.
- Smallest amounts of stem dry matter tend to occur with poor establishment, late sowing date, low N residues from previous crops, take-all infection of roots in second wheats, when dull, warm conditions prevail during April and May, or on shallow or sandy soil types prone to pre-anthesis drought.



n=18

- The median date of maximum stem weight was 28 June, nine days after GS 61.

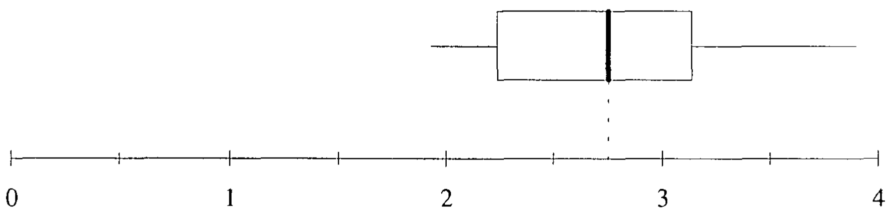
Maximum water soluble carbohydrate of stem plus leaf sheath *(%)*



n=18

- The median maximum concentration of soluble carbohydrate in stem dry matter was 34%. There was a range across the eighteen crops from 25 to 52%.
- The effects of environment and variety on percentage of soluble carbohydrate are of similar extent.
- Mercia is towards the lower end of the varietal range for percentage of soluble stem carbohydrate.
- High radiation receipt from GS 37 - GS 72 normally contributes to percentage of soluble carbohydrate above the norm, and conversely dull conditions during this period lead to values lower than the norm.
- The dry weight of stems and leaf sheaths and their concentration of soluble carbohydrates combine to give the weight of soluble carbohydrate.
- The maxima were reached on the same dates as maximum stem dry weight.

Maximum soluble carbohydrate in stems *(tonnes per hectare)*



n=18

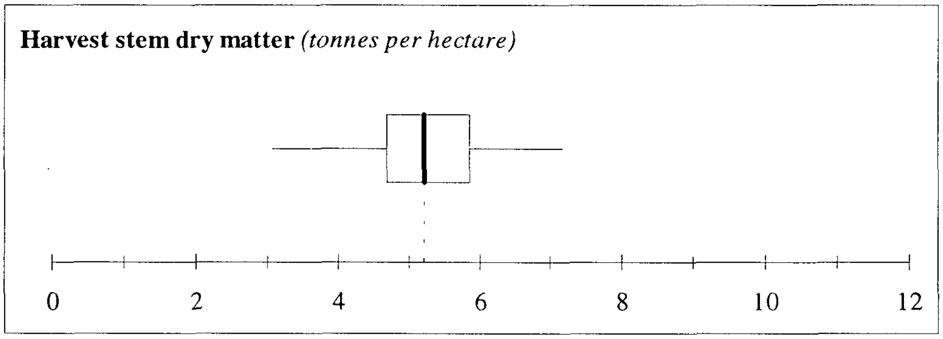
- The median maximum amount of soluble carbohydrate was 2.8 tonnes per hectare; the range was 1.9 - 3.9 tonnes per hectare.

- The variation in soluble stem carbohydrate explained by environmental effects is greater than that explained by variety effects, although significant differences do exist between current varieties.
- For current varieties, Mercia is towards the lower end of the genotypic range.
- The amount of soluble carbohydrate tends to be greatest where large stem dry weights have been caused by good growing conditions; (early sowing, high residual soil N, low take-all infection and absence of early drought).

Utilisation of stem reserves

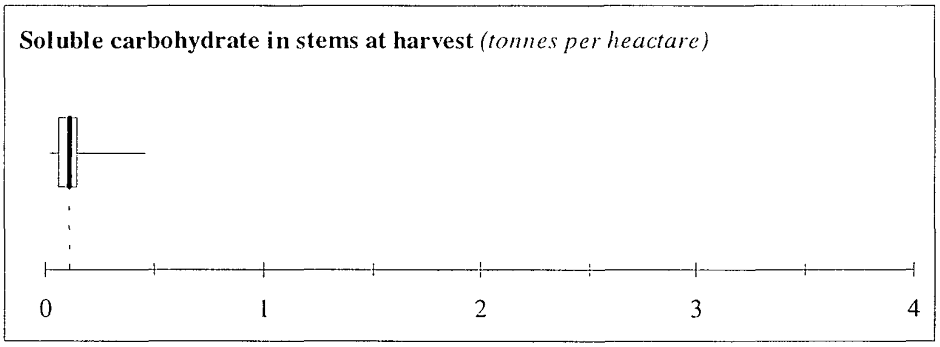
- The mobilization of soluble carbohydrate stored in stems for use in grain filling generally starts at about the mid-to-late grain fill stage.
- Depletion of reserves is reflected in changes in dry weight and carbohydrate concentration of stem tissues after anthesis.

Harvest stem dry matter (tonnes per hectare)



n=18

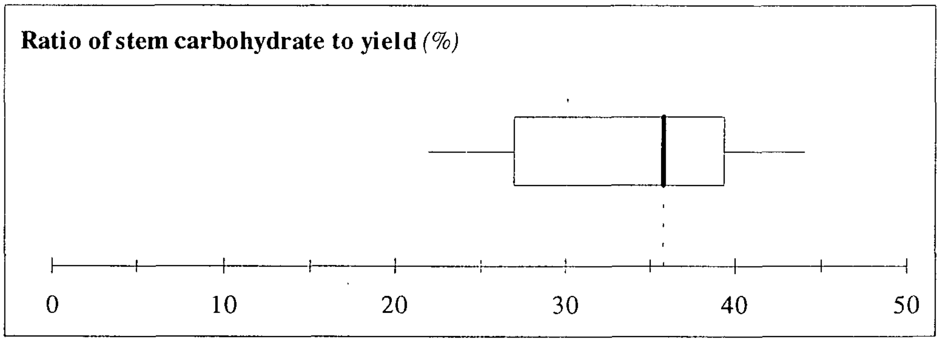
- Median stem dry weight decreased by about 3.0 tonnes per hectare from the maximal amount present after anthesis, to a median of 5.2 tonnes per hectare at harvest. The range in stem dry weight at harvest was 3 - 7 tonnes per hectare.
- Much of the decrease in stem weight could be attributed to remobilisation and translation of soluble materials since the concentrations of soluble carbohydrates became very small by harvest.



Soluble carbohydrate in stems at harvest *(tonnes per heactare)*

n=18

- Percentage soluble carbohydrate in the stems had decreased from a median content of 34% shortly after flowering, to a median content of 3% at harvest. The range at harvest was from 0.7-6.7%.
- Variation in percentage stem soluble carbohydrate at harvest is small and is not significantly affected by either environment or variety.
- Median dry weight of soluble stem carbohydrate at harvest was also small at 0.14 tonnes per hectare and was little affected by site or season, the range being from 0.04 to 0.46 tonnes per hectare.
- Effectively all the soluble carbohydrate accumulated is lost by harvest in both stressed and unstressed post-anthesis conditions.
- It is assumed that unstressed plants lose proportionately more soluble reserves by unproductive respiration, although reserves may still contribute significantly to grain filling.
- Evidence from the parallel HGCA project no. 0037/1/91 *'The exploitation of varieties for UK cereal production'* suggests that varieties with highest yield potential tend to be those which accumulate greatest amounts of stem soluble carbohydrate.
- The amount of soluble carbohydrate remobilised during grain filling is strongly correlated with the maximum amount accumulated. The variation in the amount of stem reserves used in grain fill will therefore relate to those factors influencing the maximum amount accumulated.
- The relationship between the amount of soluble carbohydrate accumulated and grain yield can give an indication of the potential contribution of soluble carbohydrate to grain yield.



Ratio of stem carbohydrate to yield *(%)*

n=18

- The median potential contribution of soluble carbohydrate to grain yield was 36% with a range of 22 to 44%.
- A proportion of the potential contribution of soluble carbohydrate will be lost in respiratory processes, due to maintenance respiration and energy costs incurred in the transport of soluble carbohydrates to the grain.
- It is also probable that respiratory losses vary inversely with demand for assimilate by the grain.
- The percentage contribution of soluble carbohydrate to grain yield will be greatest for crops having highest amounts of soluble carbohydrate, grown in conditions where canopy survival is lower than the norm.

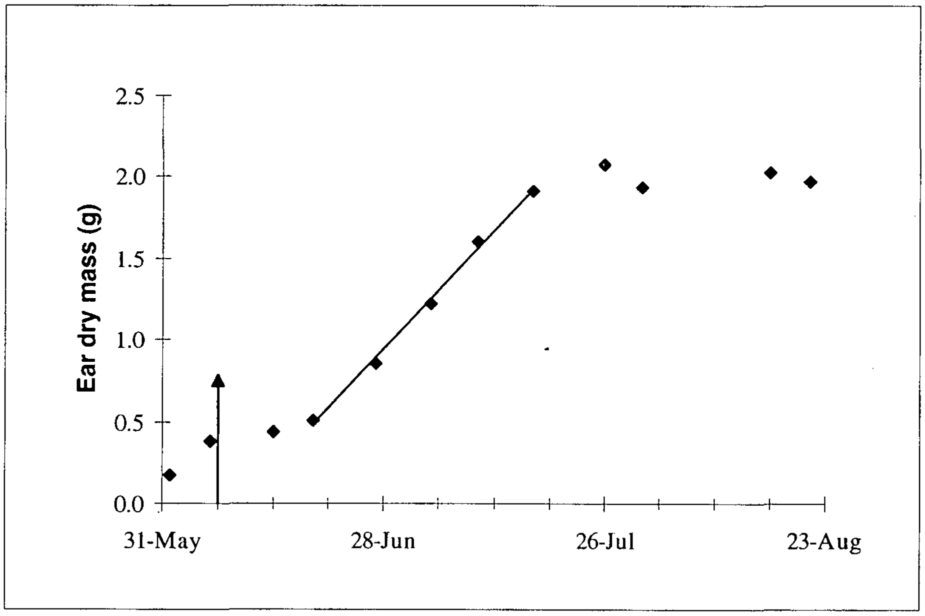
Husbandry implications

- The contribution of stem soluble carbohydrate reserves to grain yield is relatively important in stressed environments, particularly where the canopy senesces prematurely.
- For crops with stem reserves below the norm, the economic benefit from applying fungicide at GS 55-56 is increased. This is particularly so when:
  - weather is favourable for disease development and disease levels are above thresholds
  - growing susceptible varieties for the quality market
  - canopy is smaller than the norm, and
  - ear capacity is larger than the norm
- For crops with stem reserves below the norm, the benefit from applying a fungicide at GS71 is increased, especially with:
  - potential ear size larger than the norm
  - canopy size smaller than the norm
  - varieties susceptible to ear blight and intended for the quality market
  - high disease pressure and poor growing conditions
- For bread wheats with stem reserves below the norm, the economic benefit from applying an insecticide post ear-emergence is increased. This is particularly so:
  - where the canopy is smaller than the norm, and senescence is predicted to be more rapid than the norm
  - with high temperatures and high soil moisture deficits
  - with high levels of foliar disease
  - with low N status, and
  - with a larger potential ear size than normal or a later than predicted end to grain filling

10. EAR FORMATION

by E. J. M. Kirby

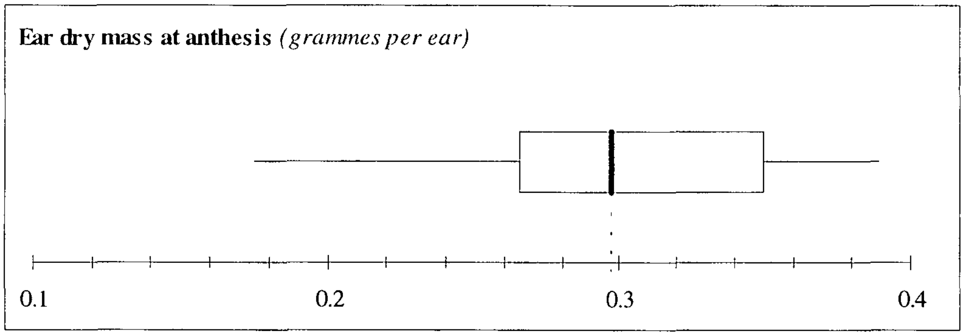
- Growth in ear dry weight lasts from early in the life cycle of the plant, before stem elongation starts, until harvest. In the early stages the ear is minute, as it develops within the emerging leaves.
- The ear is first seen at ear emergence when it weighs about 0.1g. At this stage it is composed mainly of the rachis (central stalk of the ear) and glumes, lemmas and paleas (the parts which enclose the grains in the mature ear).
- The rachis and glumes, etc. form the chaff at harvest when the grains are threshed. At flowering, the carpels (which become the grains after fertilisation) are only a very small fraction of the total dry mass of the ear.



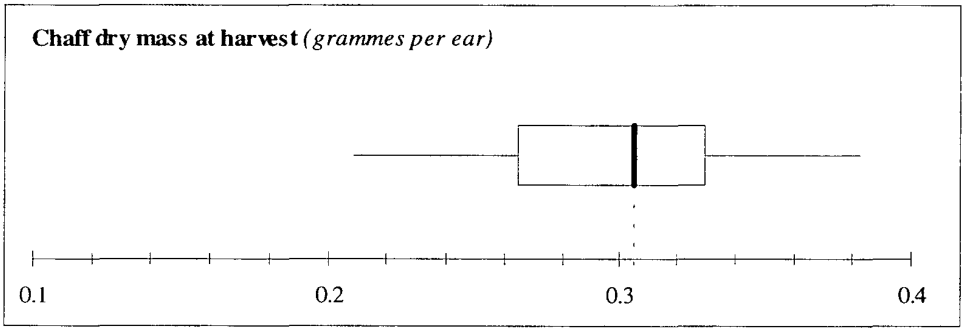
Crop ear dry mass from ear emergence to maturity. The dashed line is the fitted regression to estimate 'ear growth' rate. The arrow marks anthesis.

- The increase in dry mass of the ear is slow at first, then increases and remains more or less constant for a time and finally declines to zero. Often there is a slowing down of growth for a few days after anthesis.

- At anthesis the rachis, glumes, lemmas and paleas are more or less fully grown and weigh approximately the same as the chaff dry mass at harvest.
- The glumes, lemmas and paleas are photosynthetic organs and they contribute significantly to ear growth.



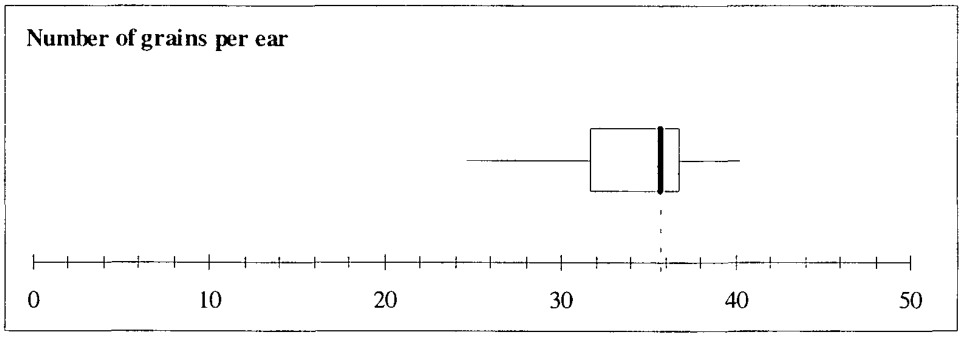
n=11



n=10

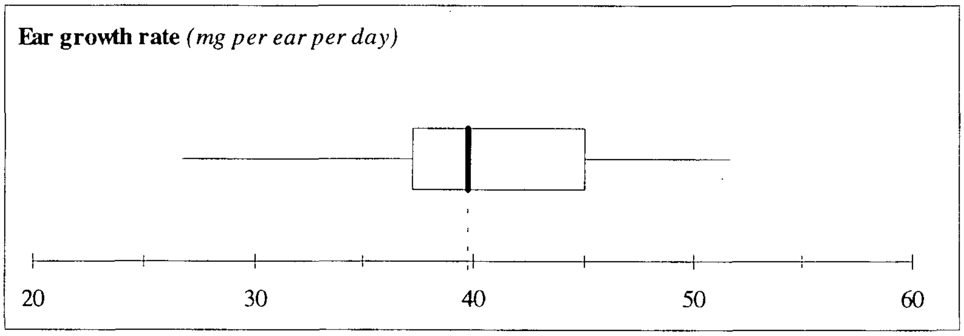
- At anthesis the median dry mass per ear was about 0.3g, similar to the final dry weight of chaff per ear.
- After anthesis, ear growth is due almost entirely to growth of the fertilised grains (see Section 10, '*Ear Formation*').
- The number of grains depends on the number of potential grain sites (carpels) at anthesis and the number which are fertilised and survive.
- The number of carpels depends on growth conditions when the spikelets and florets are forming (double ridge stage to anthesis).
- The weather during the period around ear emergence is particularly critical.
- Late frosts, around the time of ear emergence, may kill developing carpels and reduce the number of grains per ear.

- Inclement weather at anthesis, such as heavy rain, may interfere with pollination and reduce the number of grains per ear.



n = 10

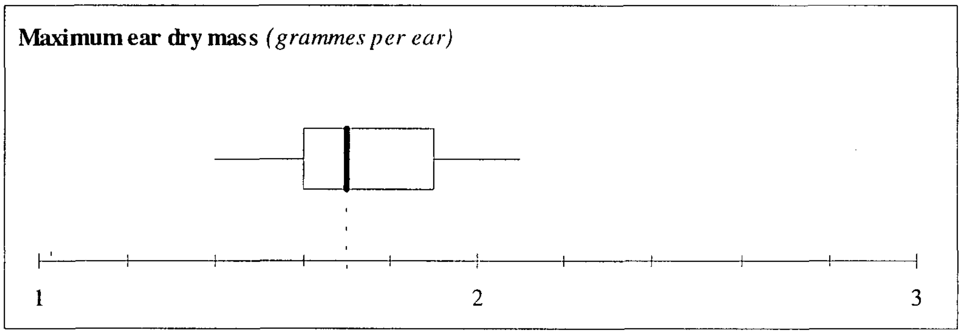
- The median number of grains per ear at harvest was 36.
- Grain number per ear tends to vary inversely with shoot number per m^2.
- Variation in the number of fertilised florets per spikelet is more important than variation in the number of spikelets per ear in governing the number of grains per ear.
- Insects such as the wheat blossom midge feed on the developing grains, reduce the number of grains and depress ear growth.
- Grains per ear is largely responsible for growth rate per ear and therefore for the demand for assimilates from the supporting shoot.



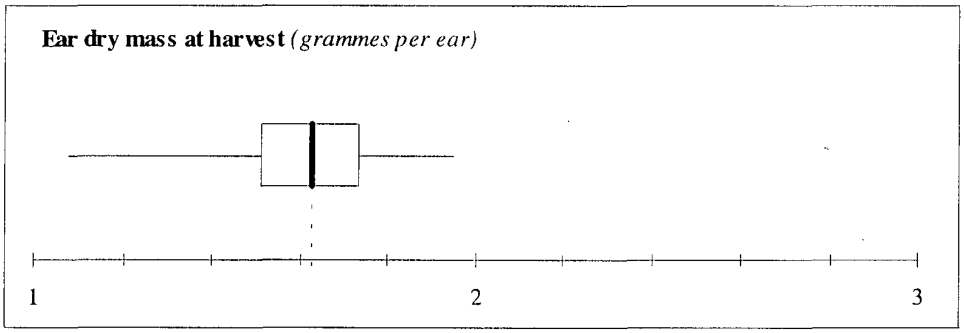
n=18

- The median growth rate was 40 mg per ear per day.
- During most of the grain filling period the ear crop growth rate is more or less constant (as can be seen in the sketch graph).

- The success of ear growth depends upon the supplies of assimilate both from concurrent photosynthesis and from reserve assimilate held primarily in the stem.
- Fungal disease on the glumes and lemmas will depress photosynthesis and reduce assimilates available for ear growth.
- Similarly, infestation by aphids which feed on assimilates will depress ear growth.
- Drought reduces ear growth.
- Grain yield will depend on both the duration and the rate of growth during this period (see Section 11, '*Grain Filling*').

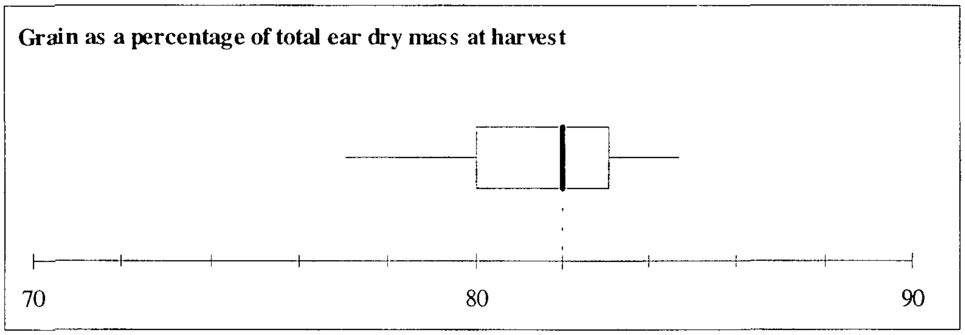


n=18



n=13

- Median maximum dry mass per ear was 1.63 g, including both chaff and grains.
- After growth ceases, the dry mass of the ears usually remains constant; in a few crops a small loss in dry mass is observed.
- Loss of ear dry mass is most likely to occur through respiration.



n=11

- The grain dry mass at harvest is generally more than 80 per cent of the ear dry mass.

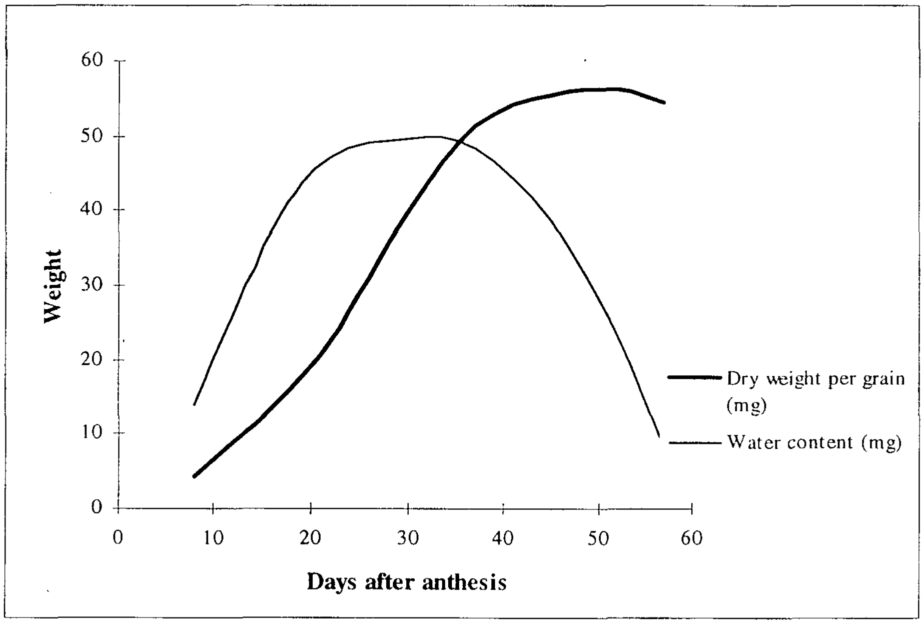
Husbandry implications

- Grains per ear is an important component of yield. Estimates of grains per ear can be used to predict grain yield (see Volume I part 3, *Forecasting Crop Progress for Wheat*).
- Few husbandry decisions can be influenced by grain number because it is difficult to observe before most decisions have been made.
- However, where grain number per ear is thought to be large, the return from maximising late growth, through late adjustments to crop protection and nutrition, is likely to be enhanced.

11...GRAIN FILLING

by P. S. Kettlewell

Grain filling determines the final dry weight per grain. The process is the last stage in the formation of yield and often influences grain appearance and the quality criterion, specific weight.



After anthesis grains grow largely by water uptake for about four weeks. Dry matter accumulation is slow for the first two or three weeks after anthesis, until cell division ceases. Grains then accumulate dry weight until about seven weeks after anthesis, when the grain is at about 45% moisture.

The fulfillment of grain filling depends on the balance between the 'sink' (i.e. the capacity of all grains in the ear) and the 'source' (mainly from concurrent photosynthesis by the upper leaves of the shoot, but also from carbohydrate stored in the stem; see Section 9, *'Stem Carbohydrate Storage'*). Where there is inadequate 'source' to satisfy the 'sink', for example due to late drought or disease, the grain will be inadequately filled and, after ripening, may appear shriveled. Conversely, where there is inadequate 'sink' to accept all assimilate available from the 'source', the grain will remain plump after ripening.

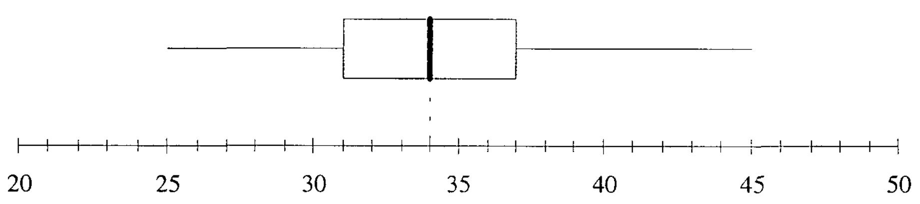
Measurements of water content at four weeks after anthesis can be used to estimate potential grain weight. This can be combined with measurements of ear number and grain number per ear to predict final yield. Methods are described in Volume 1 Part 3, *"Forecasting crop progress for wheat"*.

Reduced crop photosynthesis during the first two to three weeks of grain growth will reduce cell number and potential grain weight and will be reflected in lower maximum water content and a smaller potential grain weight.

Grain water content

Grains accumulate more water than dry matter up to approximately four weeks after anthesis (about 200°C days above base 9°C) when maximum water content occurs. There is a relationship between maximum water content and final dry weight per grain when the 'source' (mainly photosynthesis, but also stem carbohydrate reserves) exceeds the 'sink' (i.e. the grains). Thus a measurement of water content at four weeks after anthesis can be used to estimate potential weight per grain. The method is described in Volume 1 Part 3, *"Forecasting crop progress for wheat"*.

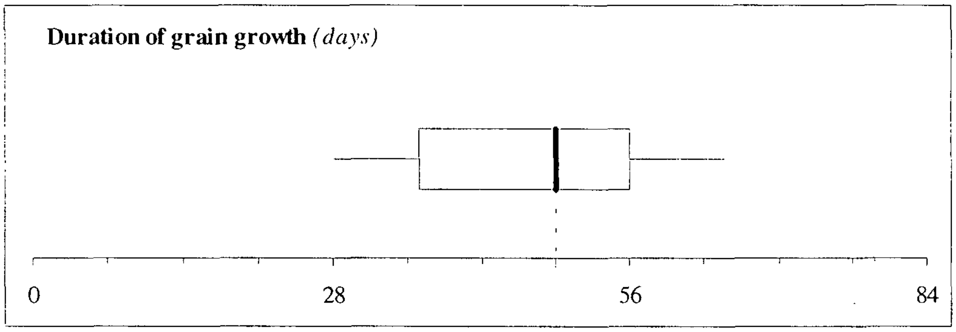
Grain water at 4 weeks after anthesis *(mg per grain)*



n=16

The fulfillment of the potential calculated from maximum water content depends on the balance between source and sink. Stem carbohydrate reserves do not completely compensate for reduced photosynthesis from drought etc. Counts of ear number and grain number per ear can give an indication of source and sink respectively. They can be taken into account in the calculation of potential grain weight to improve the estimate of final weight per grain. This method is also described in Volume I Part 3, *"Forecasting crop progress for wheat."*

Half the crops had reached maximum weight per grain by 49 days after anthesis (GS 61).



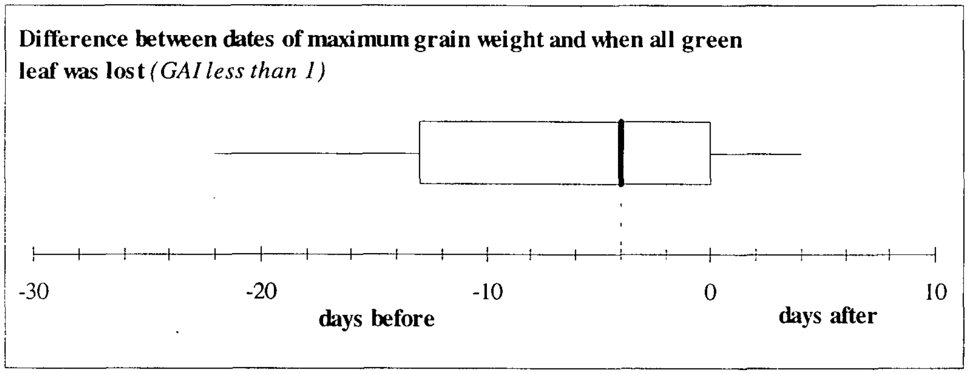
n=18

- Grains fill faster in hot weather, e.g. the median duration in the hot year 1995 was 42 days compared with 52 days in the cool year 1993. (The end of grain fill did not, however, occur at a consistent thermal time).
- Severe drought can shorten grain filling, e.g. the shortest grain fill period of 28 days was on the sandy soil at Gleadthorpe in the dry year of 1995.

Canopy duration relative to grain growth

The persistence of green canopy relative to the end of grain growth may change the importance of ear photosynthesis and stem reserves for grain growth. Senescence well before the end of grain growth may lead to greater reliance on ear photosynthesis and stem reserves. Conversely, ear photosynthesis and stem reserves may be of little consequence where the canopy persists beyond the end of grain growth. A very late-senescing canopy may delay combine harvesting, or require a desiccant to allow combining to take place easily.

Half the crops lost their green leaf (defined as GAI=1) by four days before maximum grain weight. The diagram below shows the number of days after maximum grain weight until GAI=1 was recorded.



n=18

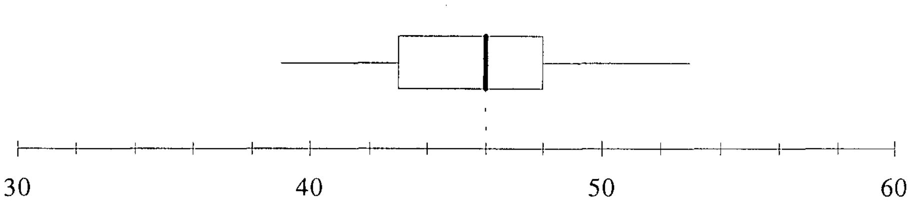
- The median date when GAI = 1 occurred four days before the date of maximum grain weight.
- Excessive nitrogen will tend to prolong canopy life beyond the end of grain growth.
- The canopy tends to persist beyond the end of grain growth in cool, moist weather, e.g. the median time before the end of grain growth was one day in the cool, moist year 1993, but four days in the hot, dry year 1995.
- Disease will tend to reduce canopy duration relative to the end of grain growth.

Weight per grain

Weight per grain is often referred to as 'thousand grain weight'. Weight per grain expressed in milligrams (mg) has the same values as 'thousand grain weight' expressed in grammes (g).

Weight per grain reflects the success of grain filling. Poor weight per grain can arise either through poor conditions during early grain filling restricting potential grain size, or from poor conditions during later grain filling affecting the deposition of carbohydrate.

Weight per grain from the combine harvester *(at 85%DM (mg))*



n=18

- Grain dry weight tends to exceed the weight of water it replaces.
- Grain weight differs between varieties as well as between growing conditions. Varietal differences are indicated in the Recommended Lists of varieties. Mercia has a moderate rating for weight per grain.
- Grain weight is reduced by drought - the minimum of 39 mg came from the sandy soil at Gleadthorpe in the dry year of 1995.
- Hot weather will reduce weight per grain by shortening the period of grain growth even when moisture supplies are adequate.
- Sunny weather can increase weight per grain.

- Crops at more northerly latitudes generally have greater weight per grain as a result of cooler temperatures prolonging grain fill and also longer days with greater solar radiation per day. Thus the highest weight per grain of 53 mg occurred at Edinburgh.
- Root or leaf diseases can lead to lighter grains e.g. take-all affected the crop at Harper Adams in 1993 (9% whiteheads) and weight per grain was the second lowest (40 mg).
- Grain weight will be reduced by aphid infestation, or by early lodging.

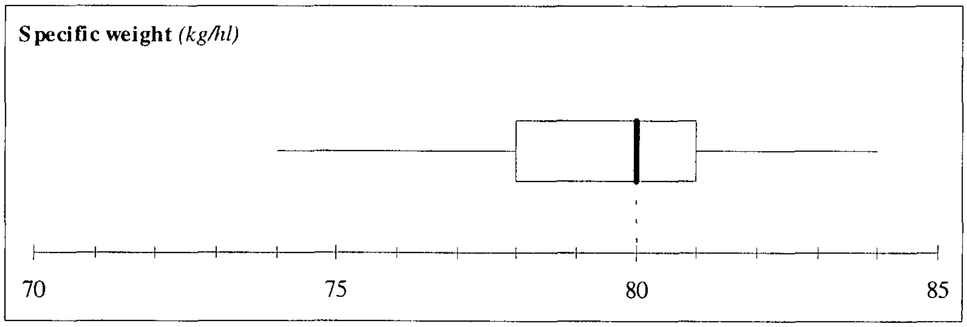
Specific weight

Specific weight or bulk density is the weight of grains (corrected for variation in moisture content) when packed in a standard way into a standard container and expressed as kilograms per hectolitre (100 litres). Thus it is influenced by :

- the density of the grains themselves
- the range of grain sizes
- any characteristics of the grains' surfaces that affect grain packing.

Specific weight is an important quality criterion. A typical requirement for milling or export is 76 kg/hl.

As well as being a quality criterion which affects the value of grain, specific weight affects the weight of grain which can be loaded into lorries and ships and thus the economics of transport.



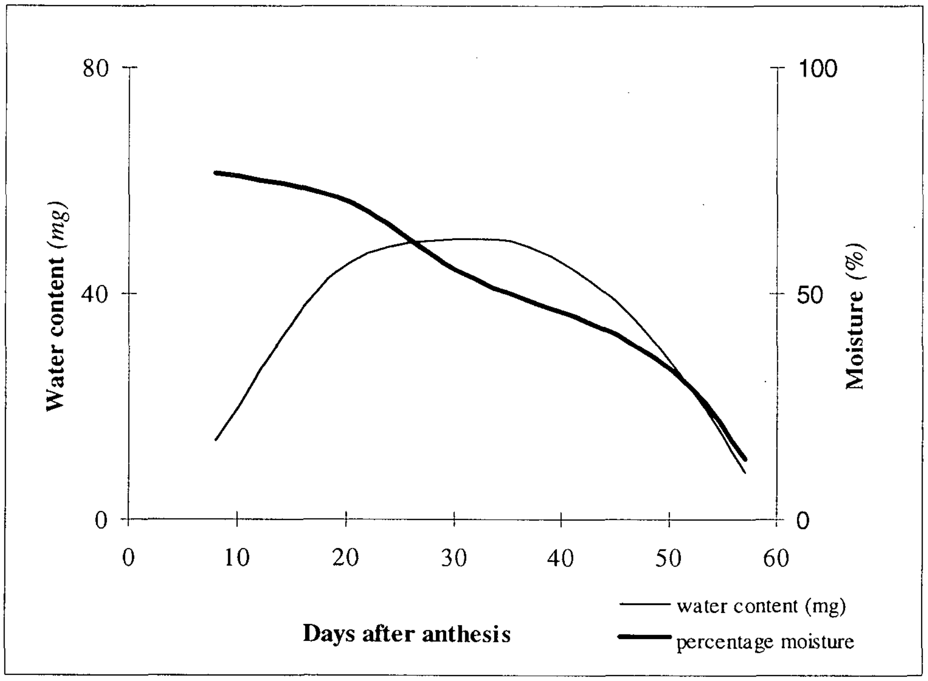
n=18

- Half the crops had grain of specific weight greater than 78 kg/hl (not adjusted for moisture).
- Factors that affect weight per grain tend also to affect specific weight in a similar way.
- Although there is no direct relationship between weight per grain and specific weight there is a crude tendency for crops with a large weight per grain to have a large specific weight. In addition to the above factors, late harvesting can reduce specific weight through weathering.

12. RIPENING

by P. S. Kettlewell

Ripening occurs from the time that the grain has reached its maximum dry weight to the time that it is dry enough to harvest. It involves changes in the capacity of the grain to germinate and changes in Hagberg falling number as well as changes in grain moisture content. However, moisture content provides the best index of grain ripening.



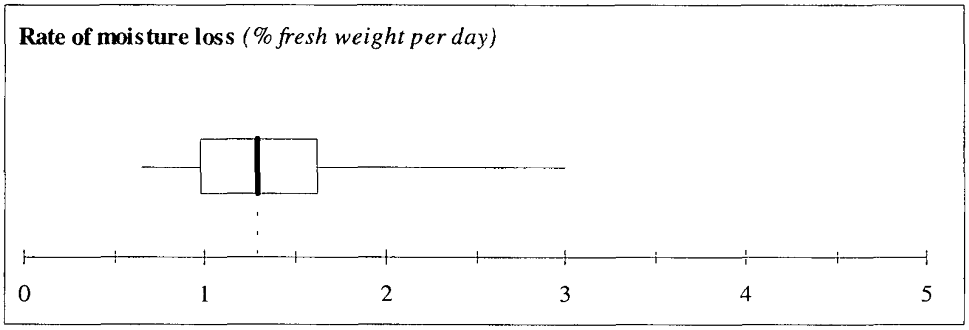
After maximum water content has been reached, changes in moisture content result firstly from further accumulation of dry matter and then from loss of water from the grain.

Drying rate

- Moisture content is commonly measured as the percentage of the fresh weight of the grain, using a meter calibrated against standard moisture contents.
- The rate of loss of water from grain determines how soon harvest can take place.
- The desired moisture percentage of harvested grain for most buyers and for safe short-term storage is 15%.

- The moisture percentage of the grain declines from about 70% to 50% by accumulation of dry matter: water content (mg per grain) remains constant over this period.
- From 50% moisture - at about five weeks after anthesis - the decline in moisture percentage also occurs because of water loss from the grain.
- Once the grain has reached maximum dry weight (see Section 11,'*Grain Filling*'), at about 45% moisture, the decline in moisture % is entirely a result of water loss.
- Once the moisture percentage drops below about 20% the grain can readily re-wet from rain and can then increase in moisture percentage.

Despite the different causes of decline in percentage moisture, the overall rate is normally approximately constant from 70% to 20% moisture and a single rate of decline can be calculated.



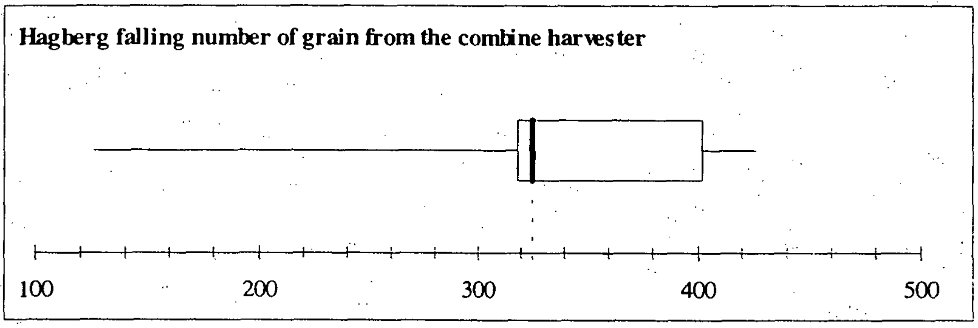
n=18

- At the median rate of moisture loss, the time taken for the grain to dry from 45% (grain filling complete) to 20% moisture (grain harvestable) was about 19 days.
- The rate of moisture loss is faster in hot, sunny weather (e.g. 14 days for sites in the hot, sunny year of 1995 compared to 26 days in the cool, dull year of 1993).
- Frequent rain will re-wet the grain and slow the rate of moisture loss, especially at lower moisture contents.
- Lodged crops may dry more slowly.
- Pre-harvest desiccants may be used to accelerate the rate of moisture loss.

Hagberg falling number

Hagberg falling number or colloquially 'Hagberg' is a measure of the gelling properties of flour made from the whole grain. In the laboratory a suspension of the flour is heated in water for a fixed period, and the time in seconds taken for a plunger to fall through the resultant gel is recorded as the 'Hagberg falling number'. The minimum value possible is 60 secs. Values greater than 250 secs are required if the grain is to be used for breadmaking, and greater than 225 secs if the grain is for export. Hence, Hagberg falling number affects the financial value of wheat grain.

- Poor gel formation results from the enzyme alpha-amylase which may form during or after ripening and which causes starch degradation in the grain.
- Alpha-amylase activity can arise in different ways, but is most commonly associated with initiation of the germination process, and hence with sprouting.
- Sprouting is induced by rain after dormancy.
- Alpha-amylase may also form in cool, wet weather during ripening, in the absence of sprouting and may reduce Hagberg falling number.



n=18

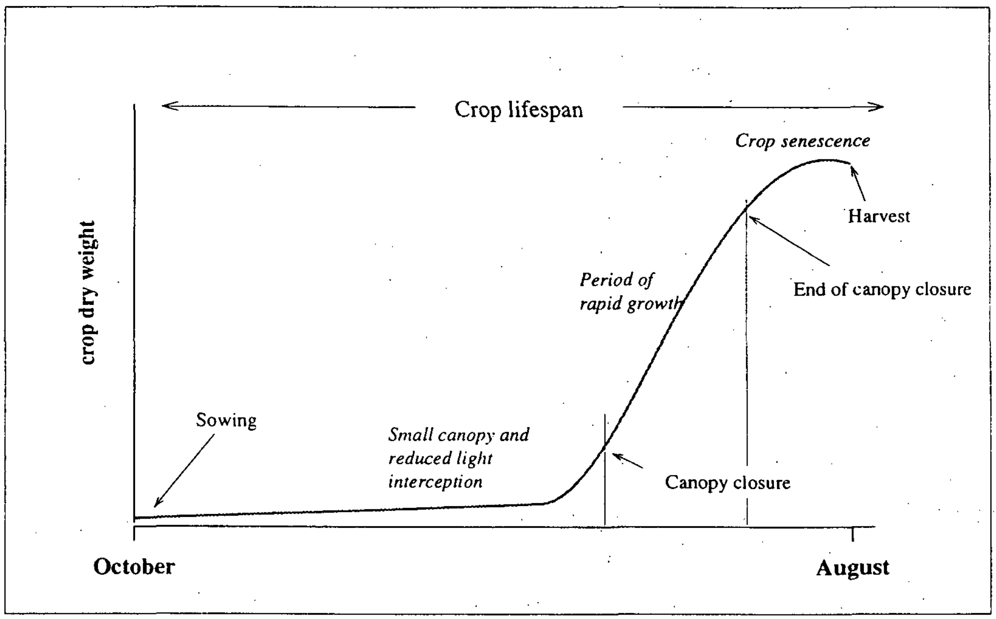
- The median Hagberg falling number was 325 secs. The crops in this set were grown in relatively good weather for ripening and there were relatively few low values of Hagberg falling number.
- Effects of husbandry on Hagberg falling number tend to be small and inconsistent compared to the effects of variety and weather.
- Varieties which differ greatly in their dormancy and varietal differences in Hagberg falling number are indicated in the Recommended Lists. Mercia and other bread wheats generally are classed as 'very high'.
- Sprouting risk is greater where harvest is delayed and wet weather occurs before harvest, e.g. as occurred at Edinburgh in 1993, harvested on 4th October giving a Hagberg of 126 secs.
- Hot weather during the grain dough stage can bring forward the end of dormancy and increase sprouting risk even with a normal harvest date e.g. as at Harper Adams in the hot year 1995, harvested on 17th August, when sprouting had started (although not visible) giving a Hagberg of 284 secs.
- Orange blossom midge damage may stimulate premature sprouting.
- Lodged crops are more prone to sprouting and reduced Hagberg than standing crops.

13. CROP GROWTH

by R. Sylvester-Bradley

- **Crop Growth** is the increase in above-ground dry weight with time.
  - variation in growth may arise from changes in its **rate**, or in its **duration**
  - in general, maximum growth occurs in bright and cool weather, since :

    … light energy primarily controls growth rate, and
    … temperature primarily controls growth duration



Rate of growth for wheat crops shows a consistent three phase pattern:

slow	before canopy closure, usually from sowing to early May.
fast	whilst the canopy is complete (sometimes called the 'grand' period of growth)
slow	as the canopy dies.

- Growth results from photosynthesis, thus its rate is controlled by:
    - the size of the green canopy (see Section 8 *'Canopy Expansion'*) and
    - the amount of light energy incident upon that canopy. Growth can be predicted from just these two factors (see Volume I Part 3, *Forecasting crop progress for wheat)*

      ... light energy is also referred to as 'incident solar radiation' or 'photosynthetically active radiation'
    - on average June is the brightest month and, compared to June, average monthly radiation is

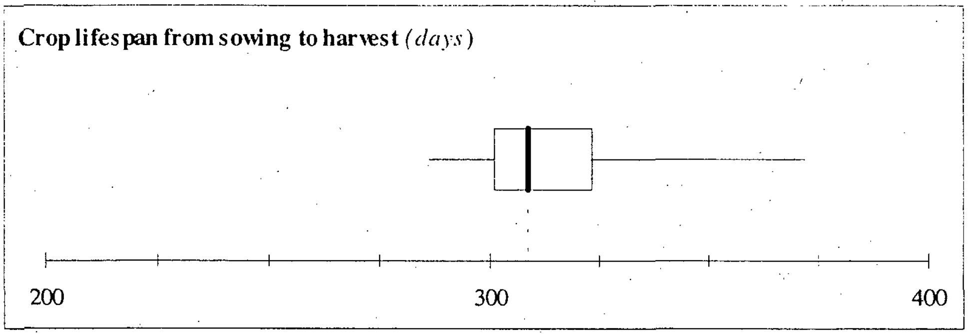
      ... an eighth in January
      ... a quarter in February
      ... a third in March
      ... a half in April
      ... nine tenths in May and July
      ... and eight tenths in August
    - average total solar radiation is slightly more in the south and less in the north (e.g. the June radiation in Northumberland is about 90% of that in Dorset).

Growth duration

- The stage of development (see Section 2, *'Plant Development'*) dictates the organs which will account for growth at any time. Hence, successive phases of the crop's life are described as:

  ... tillering
  ... stem extension
  ... ear expansion
  ... grain filling, and
  ... ripening.

Crop lifespan

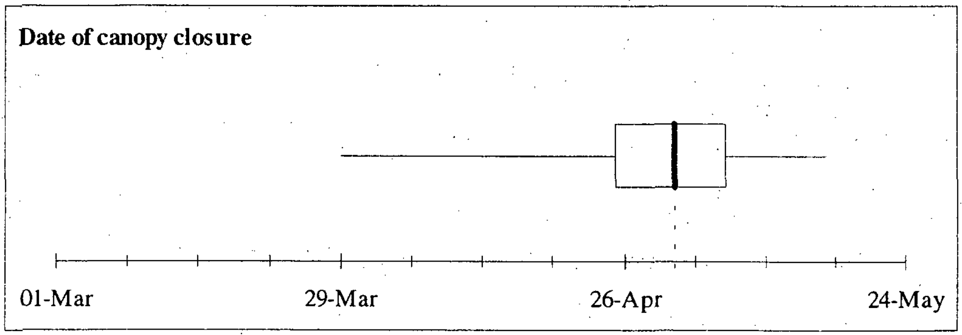


n=17

- From sowing to harvest was normally about 10 months, but at Edinburgh in 1992-3 it took a year.
- Growing periods tend to be lengthened with slow developing varieties and by earlier sowing.
- Long growing periods occurred where temperatures were cool. They were sometimes exaggerated when rain delayed harvest.

Growth before canopy closure

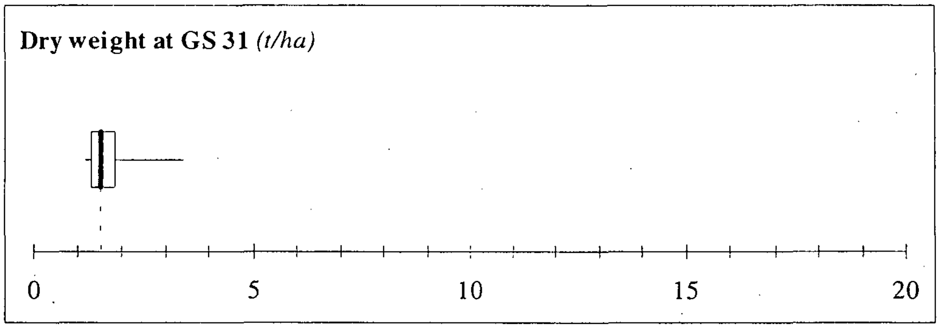
- From autumn to spring, photosynthesis and growth are slow because light levels are poor, temperatures are low and the green canopy is incomplete.
- When GAI exceeds 3 the canopy may be considered 'closed',. i.e. it intercepts more than 75% of the light.



(Omitting Edinburgh in 1994 where GAI never reached 3) *n=17*

- More than half the growing period elapsed before canopy closure.

- The median date of canopy closure was 1 May, only 9 days after the median first node stage (GS31).
- Thus, at canopy closure, almost all the dry weight is in the form of leaf blades and sheaths; the stem is still small.

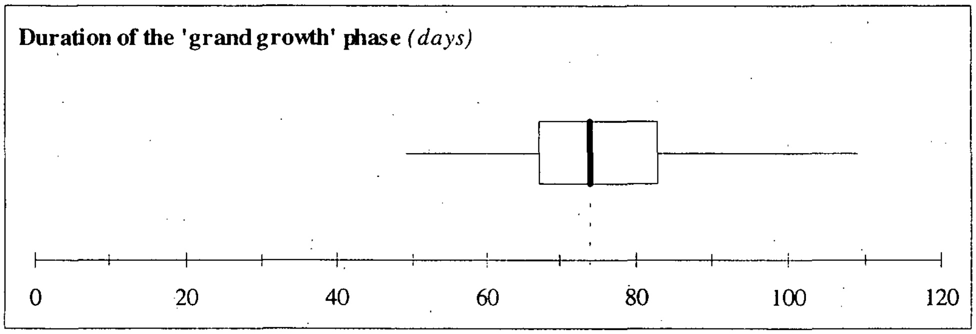


n=18

- From sowing to GS31, median dry weight was less than 10% of final dry weight.
- Canopy closure is hastened by early sowing, after warm winters and springs, and with plentiful supplies of N.

The 'grand' growth phase

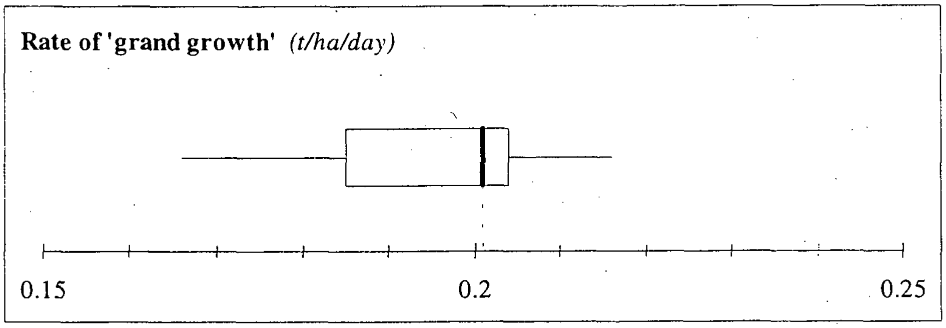
- 'Grand growth' is defined here as the period during which GAI exceeded 3.



n=17

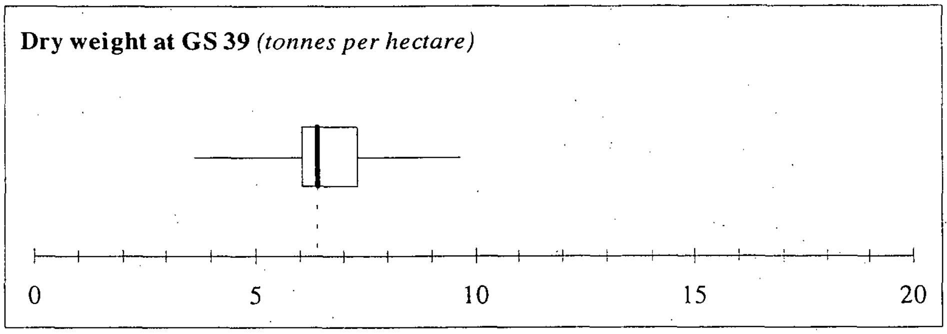
- It was a surprisingly minor part of the crop's lifespan.
- Canopy life is prolonged with high N availability and in cool conditions.
- Longer duration of growth in the cooler north tends to compensate for its slower rate in the duller light, producing a net advantage in total growth.

- Low incidence or good control of diseases such as *Septoria* at flag leaf emergence helps to prevent early senescence of the canopy.
- Dry weather results in early senescence on light soils, if irrigation is not applied.



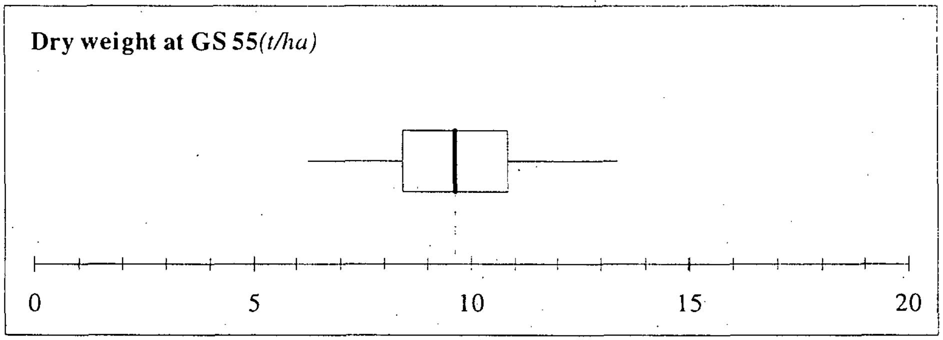
n=17

- Rates of 'grand' growth were such that one tonne of crop dry weight was formed every 4½ to 6 days.
- Over short periods growth rates closely relate to amounts of incident solar radiation.
- Most of the variation is due to clouds which reduce incident radiation by about 75%.
- Thus, growth in sunny weather can reach almost 0.5 tonnes per hectare per day, but is only 0.1-0.2 tonnes per hectare per day in dull weather.



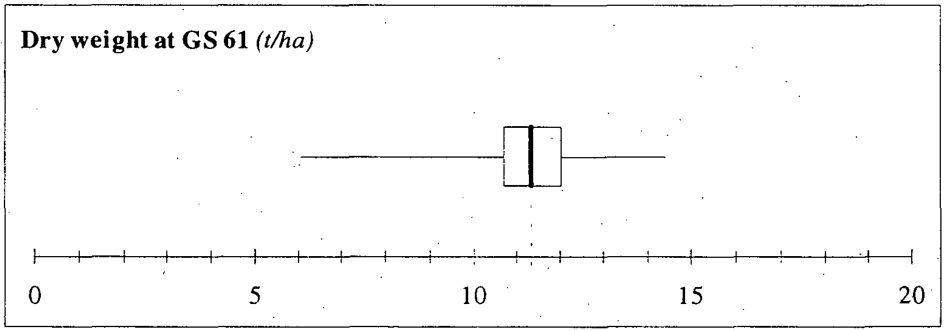
n=18

- Total crop dry weight increased by 4.8 tonnes per hectare during stem extension (GS31 to GS39).
- Poor growth during this period tends to reduce storage of soluble sugars in the stem, and may reduce shoot survival (see Section 9, '*Stem Carbohydrate Storage*').



n=18

- Dry weight increased by 4.7 tonnes per hectare between GS39 and GS59.
- Ear weight increased markedly during this phase.
- Poor growth during this phase reduces the development of fertile florets and tends to result in fewer grains per ear.

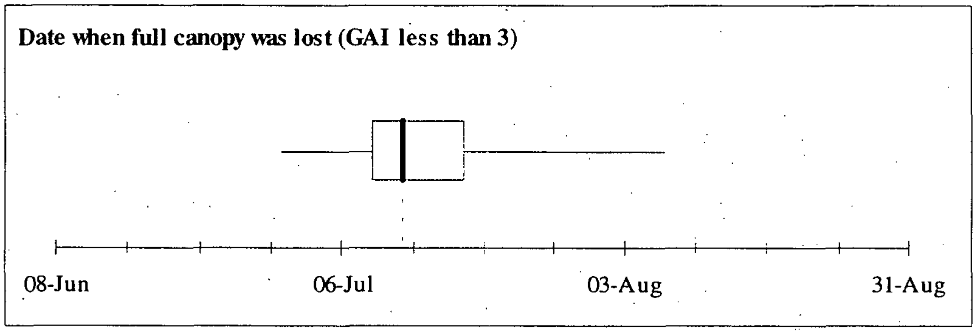


n=18

- Dry weight increased by 0.4 tonnes per hectare between GS59 and GS61.
- Outwardly, little growth is evident during this phase.
- Even in bright weather, slow growth may occur if storage capacity for new assimilate is inadequate, especially in the stem.
- Slow growth occurred when ear emergence was early and there was a longer-than-normal delay until flowering, as can happen with early sowings or after warm winters.
- Senescence of the canopy brings the 'grand growth' phase to an end.
- Grain formation (see Section 10, '*Ear Formation*') only takes place during the final month of 'grand' growth.

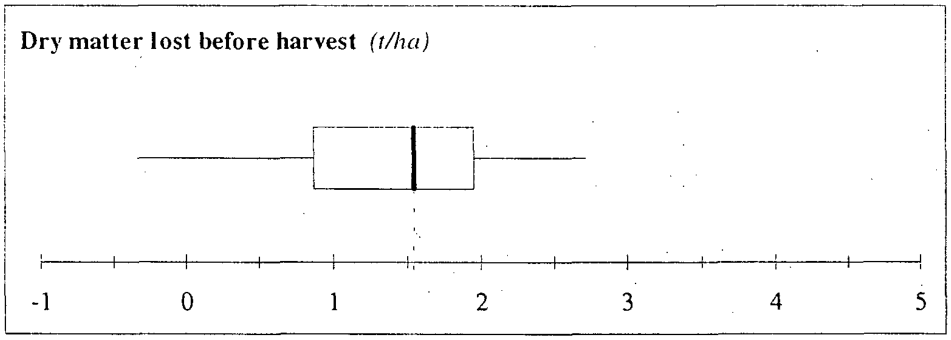
Senescence and the end of growth

- Growth slows as the canopy dies.
- Canopy senescence coincides with movement to the grain of proteins from the leaves where they were used in photosynthesis.
- Thus as grain protein (see the Section 14, '*Grain Protein*') increases, photosynthesis and growth are progressively slowed.



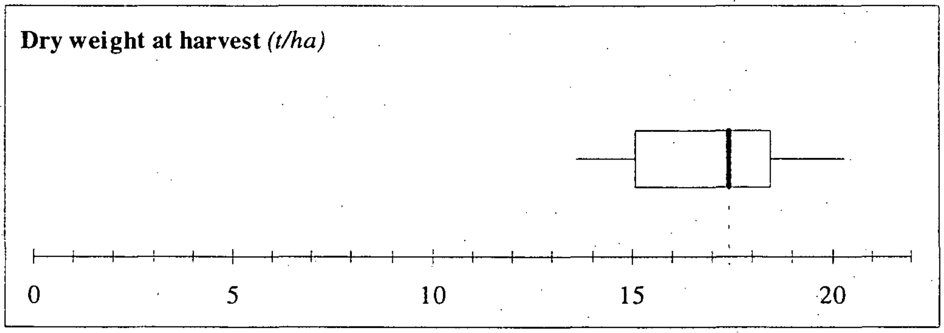
(Omitting Edinburgh in 1994 where GAI never reached 3) n=17

- The date at which full canopy capacity was lost (GAI<3) was about a month after flowering; it roughly coincided with the beginning of dough development in the grain.
- Most green tissue was lost (GAI less than 1) only ten days later.
- Canopy senescence is hastened by warm weather, leaf diseases, take-all or drought.
- Senescence is delayed where maximum canopy size is large, and where grain filling is slowed by cool weather.
- About 40% of total plant growth occurred after anthesis, but this proportion was very variable.
- Most of this growth occurred in the ear (see Section 10, '*Ear Formation*'). Other organs were losing weight over this period, especially the stem.
- There was less than one tonne per hectare of growth after the full canopy was lost.
- Sometimes crop dry weight decreased after the maximum had been reached.



n=18

- The median loss of dry weight before harvest was 1½ tonnes per hectare.
- This occurred partly through the loss of leaves but mainly through respiration of carbohydrates held in the stem.
- Dry matter was rarely lost from the ears.



n=18

- Total dry weight at harvest was about six tonnes per hectare more than at flowering.
- The components of the crop making up the final crop weight were
  - leaf .... 10 %
  - stem & sheath 35 %
  - chaff .... 10 %
  - grain .... 45 %

- Variation in these proportions (Harvest Index, see Section 15, *'Grain Yield'*) gives an indication of the most successful phases of growth.

- Variations in the rate and the duration of growth had equivalent effects on final crop weight.

Husbandry implications

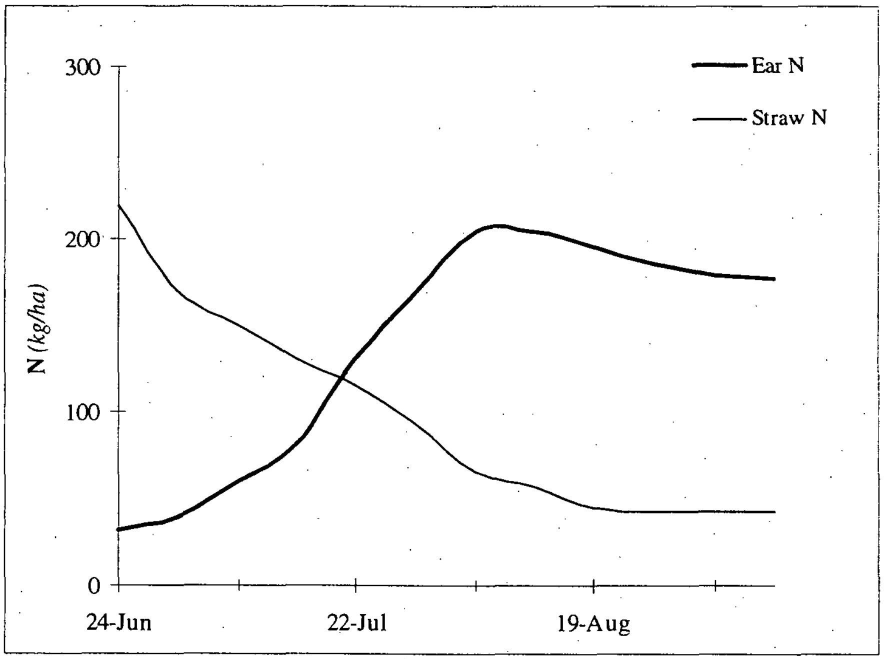
- As crop growth progresses, the amount of growth gives a progressively better (but always a crude) indication of potential crop yield.
- From sowing to flowering, crop dry weight relates to canopy size, but canopy size may often be the more useful character in guiding specific husbandry decisions, and it is easier to assess.
- Poor over-winter growth justifies increases in crop protection where there is also a threat to crop or shoot survival. For example,
  - use of fungicides to control mildew in winter and early spring, and
  - greater attention to controlling rabbit grazing over-winter
- Where successful growth indicates good yield potential, the large expected financial return may justify increased use of:
  - growth regulators to minimise lodging,
  - fungicides to control stem base and foliar diseases,
  - irrigation to alleviate risk of later drought, and
  - pesticides to control aphids.
- Successful growth may also indicate a greater need for fertiliser N. However, this effect is slight because larger crops also tend to show better N recovery.
- Where breadmaking varieties have a large yield potential there can be a case for increased late N applications.

14. GRAIN PROTEIN

by P. S. Kettlewell

Protein percentage in the grain is an important quality criterion, affecting the price per tonne. High protein percentage is associated with good performance when the grain is milled to flour and used in breadmaking. Nitrogen is transported into the grain to form protein during grain filling. Some nitrogen comes from uptake by the roots after flowering but most comes from the N mobilised from the stems and leaves as they die.

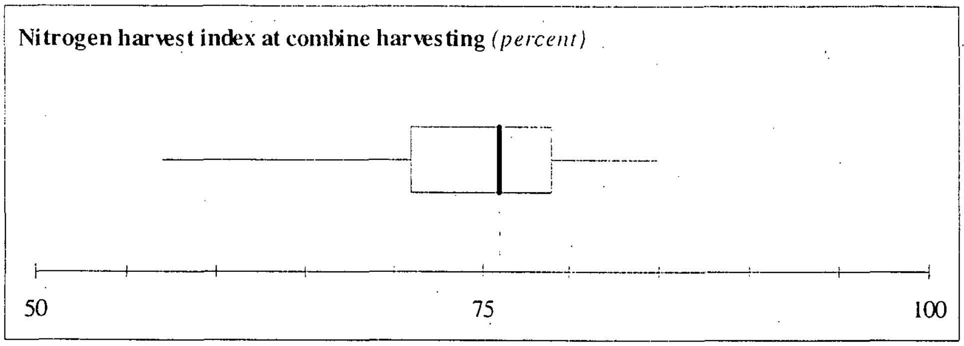
Changes in nitrogen in the ear and straw



Ear N increases up to the time of maximum grain weight, then declines slightly, whereas straw N decreases rapidly up to this time, and decreases more slowly thereafter.

Nitrogen harvest index (NHI)

The nitrogen harvest index indicates the proportion of the above-ground crop nitrogen which is in the grain at harvest.



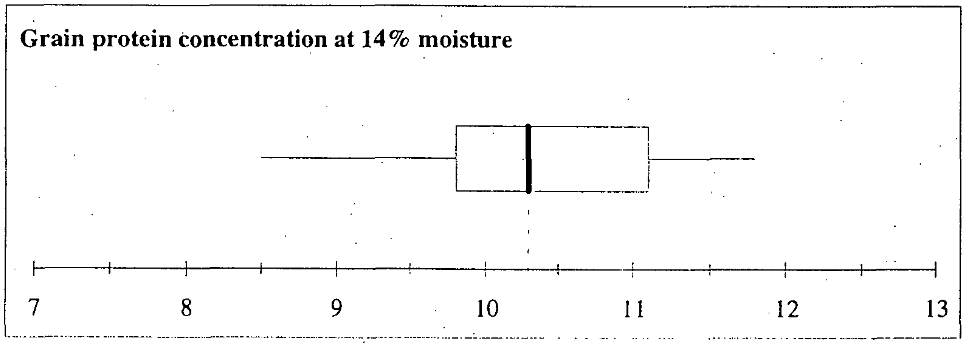
n=12

NB. These data are calculated from the quadrat sample taken in either the same week as combine-harvesting, or the nearest week. The values are for ear N (not grain N) as a proportion of total N, and thus will be slightly higher than NHI calculated from grain N.

- Varietal differences in nitrogen harvest index are generally small compared with husbandry and weather effects.
- Nitrogen harvest index may be lower in years with cool, moist conditions after anthesis which prolong N uptake and leaf life and may reduce nitrogen remobilisation until after the end of grain growth (e.g. in the cool year of 1993 the mean NHI over all sites was 69% compared with 77% in the hot, dry year of 1995).
- A high N harvest index is normally associated with a low concentration of N in the straw.

Grain protein

- High concentrations of protein in the grain can arise either from uptake of large amounts of N by the crop or from poor grain filling (see Section 11, *'Grain Filling'*)



n=18

- Varietal differences in protein percentage are small relative to those caused by site, season and husbandry.
- Nitrogen fertiliser increases protein percentage even if more N is applied than is optimum for yield. Generally the later the fertiliser is applied, the greater the increase. Applications of urea as a spray when the grain is milky ripe (GS 75) give the largest effects (but normally have no effect on yield).
- First wheats tend to have grain of lower protein percentage than second wheats, if both are fertilised for optimum yield - the protein of first wheats is 'diluted' by the greater yield.
- Conversely, any factor which reduces yield without affecting nitrogen transport to the grain may raise protein. For example:
  - Drought (e.g. in the dry year of 1995 the sandy soil at Gleadthorpe gave 11.8% protein).
  - Early lodging.
  - Disease (e.g. the take-all affected crop (9% whiteheads) at Harper Adams in 1993 gave 11.6% protein). Note that powdery mildew is an exception since it **lowers** protein percentage by interfering with nitrogen transport.

15. GRAIN YIELD

by R. Sylvester-Bradley

- **Grain yield** is the weight of harvestable grain.
  - The weight is expressed commercialy as tonnes per hectare, corrected to a moisture content of 15%, so yields must be converted to a dry weight basis for comparison with growth data in previous sections.
  - Grain losses occur at harvest, the proportion lost depending on whether the crop is sampled or 'combine harvested', as well as on its condition. Crops combined long after ripening tend to have high in-built losses.
  - Thus grain yields depend on the technique of measurement. Since growth can only be measured by crop sampling, direct comparisons of yields with growth can only be made where the yields were determined by crop sampling.
  - Yields from experimental plots, away from field margins, tend to exceed yields from whole fields.
- Grain yield is the product of ears per square metre (see Section 5, '*Tillering*'), grains per ear (see Section 10, '*Ear Formation*') and grain size (see Section 11, '*Grain Filling*').
  - these have been termed 'yield components'
  - yield components at harvest can indicate the success of the different phases of growth :

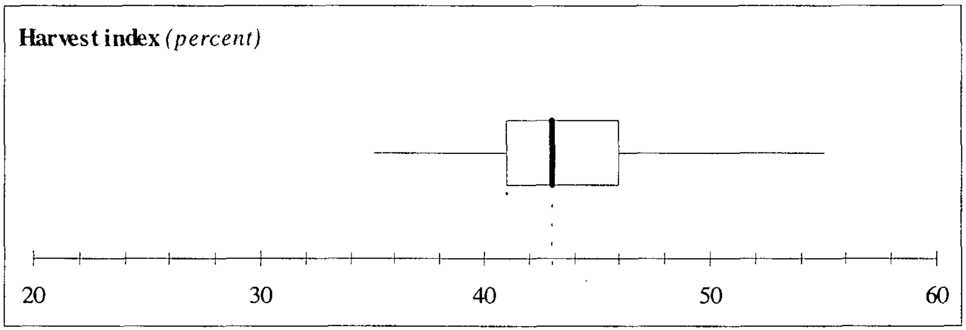
    ... ear numbers tend to indicate growth before flag leaf appearance (GS39)

    ... grains per ear tend to indicate growth from flag leaf appearance to flowering (GS61), and

    ... mean grain weight tends to indicate growth after flowering.
  - However, there are often compensations in each phase for the outcome of earlier phases.
- Grain yield is also the product of final crop dry weight (see Section 13, '*Crop Growth*') and 'harvest index',as described below.
- There is a widely held assumption in the UK that grain yield varies more through total crop weight than through harvest index. This is not upheld by the results reported here.

Harvest Index

- **Harvest Index** is the ratio between grain yield, on a dry basis, and the total crop dry weight at harvest.

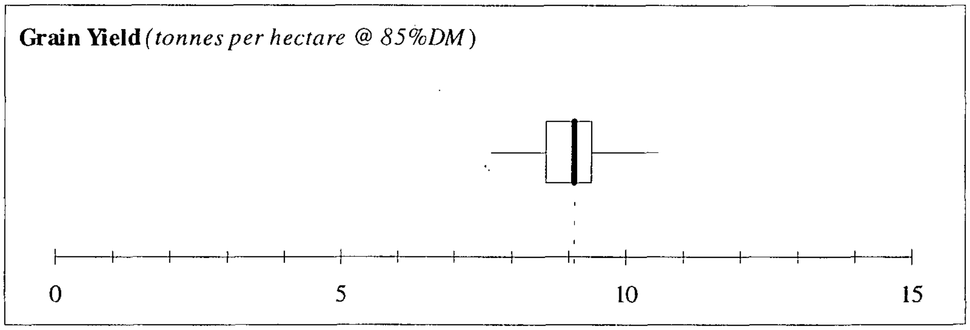


n=18

- Grain weight generally constituted less than half of final crop dry weight, but harvest index was very variable.
- In consequence, there was little relation between final crop dry weight and grain yield.
- The highest Harvest Indices were always from Edinburgh where total dry weight before flowering was low and growth after flowering continued much later in the year.

Grain yield

- Yields determined by sampling were slightly greater (median difference, 0.24 tonnes per hectare) than those determined by combine harvester.

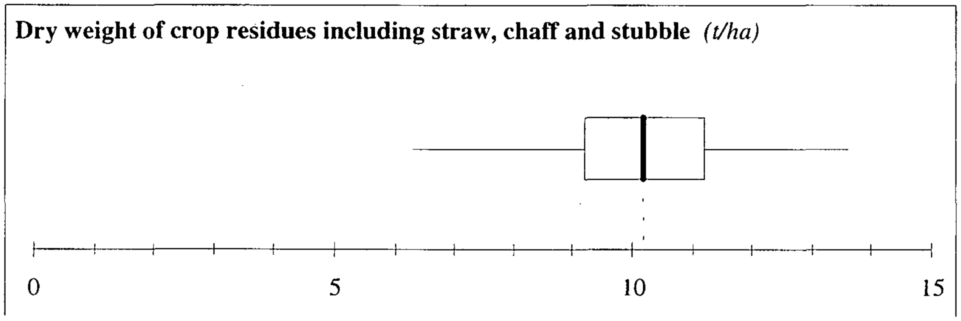


n=18

- The median grain yield from all 18 crops of Mercia was about nine tonnes per hectare.
- The three tonnes per hectare range of yields was smaller than would be expected for a wide range of sites and years.
- The maximum yield was from Sutton Bonington in 1994.

Crop residues after harvest (straw, chaff and stubble)

- Straw is normally taken to be the shoot material left after combine harvesting, excluding grain and chaff, and excluding the stubble.
- As such, 'straw' is only about half of the weight of all crop residues and will depend on the height at which the combine is set.

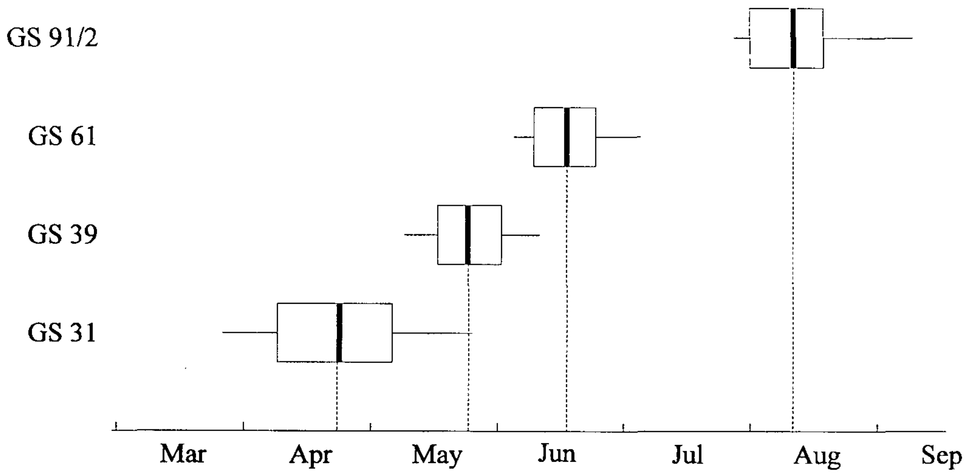


n=18

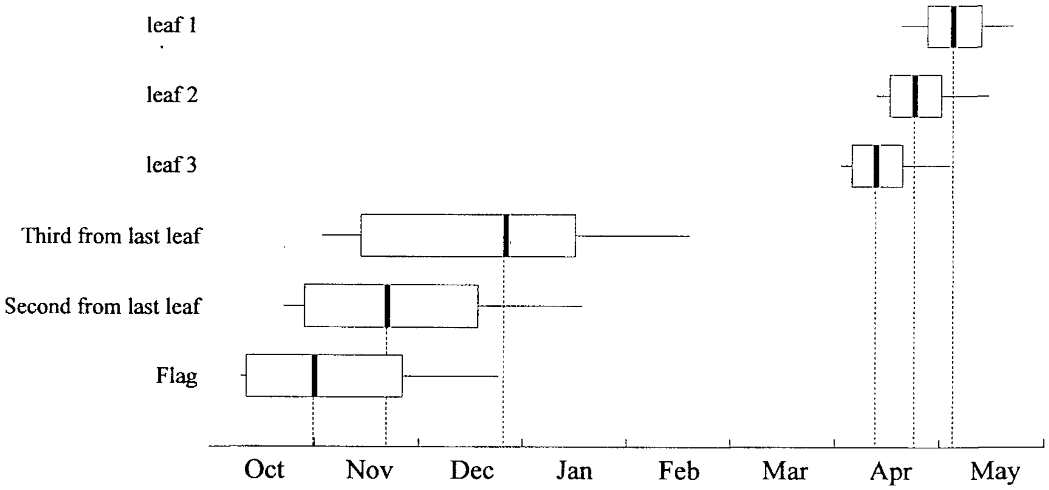
- Median dry weight of all crop residues was about ten tonnes per hectare.
- Dry weight of non-grain material varied considerably more than did grain yield.
- The weight of crop residues normally exceeded the yield of grain.

Summary charts 1

Median appearance of growth satge

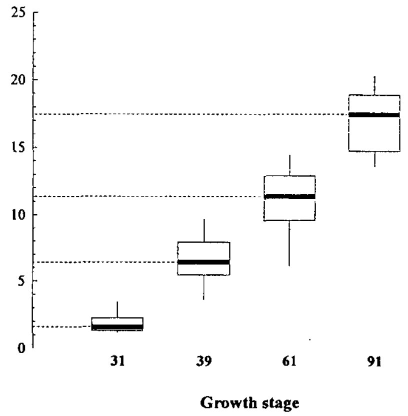


Date of leaf emergence

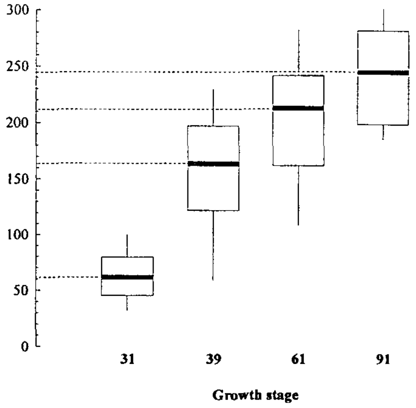


Summary charts 2

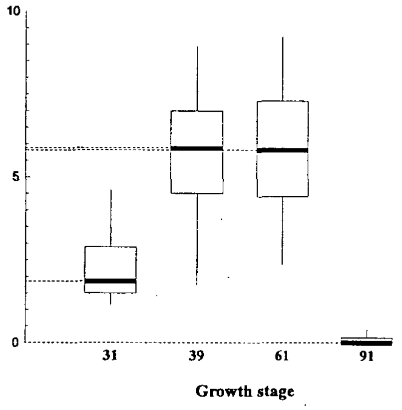
Dry weight *(tonnes per hectare)*



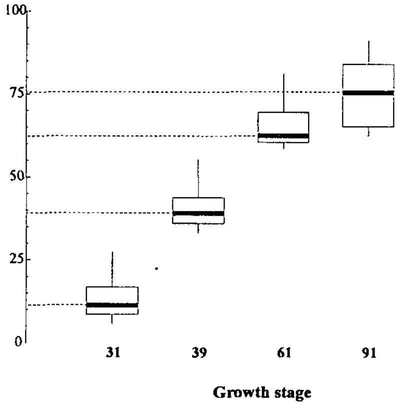
Nitrogen *(tonnes per hectare)*



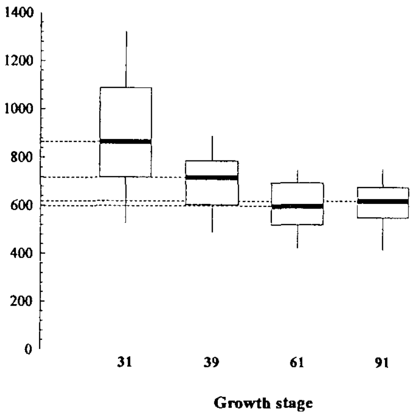
Green area index



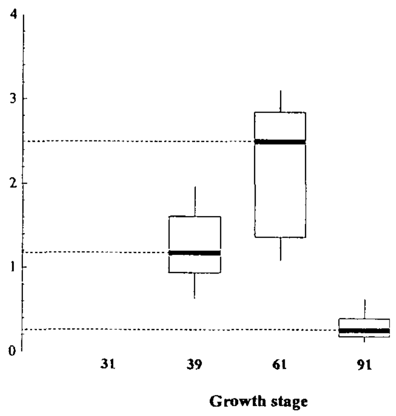
Height*(cm)*



Potential fertile shoots per metre^2



Water soluble carbohydrate *(tonnes/hectare)*



Part 2

Methods for In-Field Crop Assessment

by

G. RUSSELL, S. P. HOAD and A.P. GAY

CONTENTS

1. INTRODUCTION

This manual has been designed for those wishing to modify the management of cereals according to the physiological state of the crop.

The methods described should enable a field-walker to make accurate in-field assessments of the development and growth of the crop. These techniques can be used to obtain values which may then be compared with values in Part I of this volume: *"The Wheat Growth Digest"* to determine the extent to which there is a difference, and thus whether to modify management practices.

The techniques included are rapid, simple, inexpensive and repeatable. Some methods have been excluded because they are time-consuming or too complex for practical use in the field. Further improvements to measuring techniques are expected and, in the future, techniques using portable equipment such as canopy analysers or chlorophyll meters may become cheap enough for routine use on the farm.

Assessments have to be made on small samples of plants which are representative of the whole crop. The methods described here have been tested by comparing estimates with values obtained from the more comprehensive assessments used in contemporary research. However, the methods have not been tested in a commercial context.

The techniques described were developed using the winter wheat variety Mercia. However, the majority of techniques can be applied directly to other cultivars and to other cereal crops. The techniques for assessing Green Area Index and Crop Biomass involve the use of cultivar-specific conversion factors. These conversion factors vary, especially as a result of varietal differences in development or growth. Exact assessments performed on different cultivars and species need other conversion factors. Thus the techniques for calculating conversion factors are also described.

2. SAMPLING PROCEDURE

2.1 Introduction

It is generally not a good idea to make a single measurement in a field. Not only may there be errors in the measurement itself but there is often a considerable degree of variability across a field due to variations in soil properties, drainage and previous cropping. A sampling strategy should take sufficient measurements so that the average value is representative of the crop as a whole.

In order to truly represent a whole field, sample positions should be selected at random. However, a random sampling plan involves the taking of many measurements from all areas of the field, and assumes no fore knowledge of in-field variability, e.g. headlands, bare ground etc. As no sample is rejected the variability detected in a random sampling plan is high, so many samples are required. Due to constraints of time and labour the sampling strategy given below aims to be unbiased and representative rather than random.

2.2 Sampling

There are two stages to sampling:

- selecting the sampling point
- choosing the plants to be measured

The sampling point is the location at which individual measurements or a series of measurements are made. Each sample provides a single estimate of the character being assessed and should be taken from a representative part of the crop. Even experienced agronomists find it difficult to select a representative sample by eye so, unfortunately, effective sampling tends to be time-consuming and tedious. However, unless every effort is made to ensure good representative samples, there is little point in making the measurements.

Samples should be taken at different locations in the field within areas that are representative of the whole crop. Samples should be taken at least 20 paces from the edge of a field thus avoiding the headlands and gates where the growth is often poorer than in the rest of the field. A good practice would be to take at least one sample from each quarter of a field, arranging the quarters so as to reflect any known trends or differences. An example of a simple and unbiased sampling procedure is described below:

Box 2.2.1

To take a sample:

A. Walk along the tramlines to approximately the middle of the quarter choosing in advance a number of paces to walk up the tramline.

B. Choose in advance whether to sample to the right or left of the tramline.

C. Insert a stick into the crop and mark this position, using it as the near corner or the beginning of the sample area.

D. If the sampling position falls on an area of crop which is clearly not representative (<5% of the total) such as bare ground, it should be rejected and steps B-D repeated.

The number of samples taken will need to be adjusted according to the variability of the crop. The more heterogeneous the crop the more samples will be needed to provide a precise and representative result. In a more variable crop the familiar W-pattern of field walking used for soil sampling can be employed, and samples taken at more than four positions.

A simple rule of thumb can be followed to determine whether four samples are sufficient. If the average of the four samples is less than four times the standard deviation (as calculated on a scientific calculator, or in a spreadsheet) then it is advisable to take more samples.

It is preferable, for statistical reasons, to choose new locations on each occasion that samples are taken. In addition, the crop can be damaged and disturbed by sampling so it is best to avoid repeated sampling in the same location. In any case, permanent sample locations are generally inconvenient because markers can be lost or can interfere with machinery.

There is an increasing interest in 'precision farming' in which inputs are varied across a field to take account of within-field variability. The minimum way in which this might be applied would be by dividing a field into uniform blocks. This has a serious consequence for the sampling procedure employed since it would then be necessary to adequately sample each block.

3. IN-FIELD ASSESSMENTS OF CROP DEVELOPMENT

3.1 Introduction

The objective is to identify stages of development so that crop 'forwardness' or 'backwardness' can be compared to a standard to provide a quantitative assessment of differences from the norm. The most important stages of development are listed below with a brief definition. The industry already widely uses the "Zadoks" or "Decimal" Growth Stage key. A comprehensive description of these growth stages is given in the publication *The Decimal Code for the Growth Stages Of Cereals* by Tottman[1].

Decimal Code for the growth stages of wheat	
0-9	Germination
10-19	**Leaf Number (or emergence)**
20-29	Tillering
30-39	**Stem Extension**
40-49	**Booting**
50-59	**Ear Emergence**
60-69	**Flowering** (*Anthesis*)
70-79	Milk Development
80-89	Dough Development
90-99	Ripening

The criteria in the *Decimal Code* allow any plant to be coded on a scale of 0-100. However, problems occur when whole crops are assessed in the field as different plants, and even shoots on the same plant, are often at different growth stages. In most cases it is misleading to calculate an *average* growth stage; it is better to quote the median stage, that is, the stage which is exceeded by half the plants (or shoots) in the sample. This manual specifies how the most useful phases of the *Decimal Code* (shown in bold) can be applied to whole crops.

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[1] Tottman, D. R., illustrated by Broad, H. *The Decimal Code for the Growth Stages of Cereals* is Occasional Publication No. 4 by BCPE Publications Sales, Bear Farm, Binfield, Bracknell, Berkshire RG42 5QE available from the publishers on receipt of a self addressed label and two first class stamps or in Ann. appl. Biol. (1987) **110**, 441-454.

Also, as some previously described 'growth stages' such as tillering, constitute poor indices of plant development, this manual highlights the stages that best quantify development, and provides guidelines for making these observations in practice.

Since growth stage varies more from plant to plant than between parts of a field, these measurements need only be made in one place. Assessments of developmental stages up to GS 39 should be carried out on the main stem, whilst measures after this stage should represent all stems.

3.2 Leaf number

	Decimal Code
10	First leaf through coleoptile
11	1 First leaf unfolded
12	2 leaves unfolded
13	3 leaves unfolded
14	4 leaves unfolded
15	5 leaves unfolded
16	6 leaves unfolded
17	7 leaves unfolded
18	8 leaves unfolded
19	9 or more leaves unfolded

Growth stages 11 to 19 represent the number of fully emerged leaves on the main stem (usually the largest shoot on the plant; see the next section on how to identify this) including leaves which have already died. A leaf is 'fully emerged' when its whole blade (as far as the junction with the sheath) has appeared. Leaves which have died may not still be visible, but are usually identifiable through the presence of 'their' tiller (the tiller which they used to subtend). It is worth continuing with records of leaf number *after* tillering has started because this is a better index of plant development than tiller number. Mainstems produce from 8 to 15 leaves in the end, but it is difficult to count beyond the seventh or eighth leaf.

Box 3.2.1

To count the leaf number

A. Pull up five plants at random locations within an area of a few square metres.

B. *Identify the mainstem* which will be the only shoot present in the early stages (up to 3 leaves).

C. Count the number of fully emerged leaves; the first leaf is the smallest and usually has a more rounded tip than later leaves.

D. Calculate the average number of leaves.

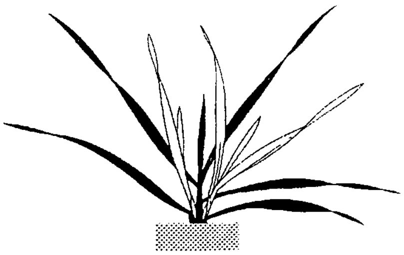
3.3 Tillering

	Decimal Code
20	Main shoot only
21	Main shoot and 1 tiller
22	Main shoot and 2 tillers
23	Main shoot and 3 tillers
24	Main shoot and 4 tillers
25	Main shoot and 5 tillers
26	Main shoot and 6 tillers
27	Main shoot and 7 tillers
28	Main shoot and 8 tillers
29	Main shoot and 9 tillers

A tiller is a secondary stem which grows from the main shoot. Tillering is usually first observed at the same time as the fourth leaf appears. Tillers emerge from the junctions of the lower leaves with the main stem and are likely to number from 2-10 per plant. In addition to tillers emerging from the main stem (*primary tillers*) additional tillers can emerge at leaf junctions on the primary tillers (*secondary tillers*).

GS 21 Main shoot and 1 side shoot
(Three leaves unfolded)

GS 22 Main shoot and two side shoots
(Four leaves unfolded)



GS 22 Main shoot and two side shoots
(Five leaves unfolded)

Figure 3.3 Emergence and growth of tillers

Although tillering is often cited as a developmental stage (GS 20-29) it is a very poor indication of plant development (i.e. progress to maturity). The degree of tillering is more influenced by crop husbandry practices, such as seed rate or the amount of nitrogen applied, than by the crop's age. Thus, in this document, tillering is treated as a growth phenomenon and is quantified as 'Shoot Number' (see section 4.2).

3.4 Stem extension

	Decimal Code
30	Ear at 1 cm
31	1st node detectable
32	2nd node detectable
33	3rd node detectable
34	4th node detectable
35	5th node detectable
36	6th node detectable
37	Flag leaf just visible
39	Flag leaf ligule just visible

This phase of development (GS 30-39) follows or sometimes overlaps the end of tillering. The onset of stem extension marks a time when important changes are going on in the plant and many key husbandry decisions have to be made.

Box 3.4.1

To identify the stem extension stages:

A. Pull up a plant at random and *identify the mainstem.*

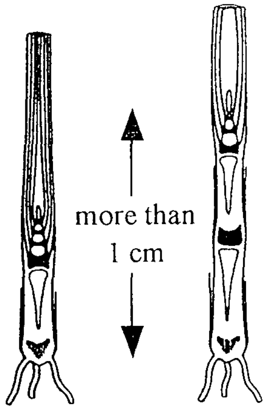
B. Remove the tillers from the base of each plant and split the mainstem along its length with a sharp knife.

C. Check whether the tip of the developing ear is more than 1 cm above the base of the plant (i.e. the 'crown' from which most leaves and roots arise). Growth stage 30 has been reached when more than half the plants have reached this stage.

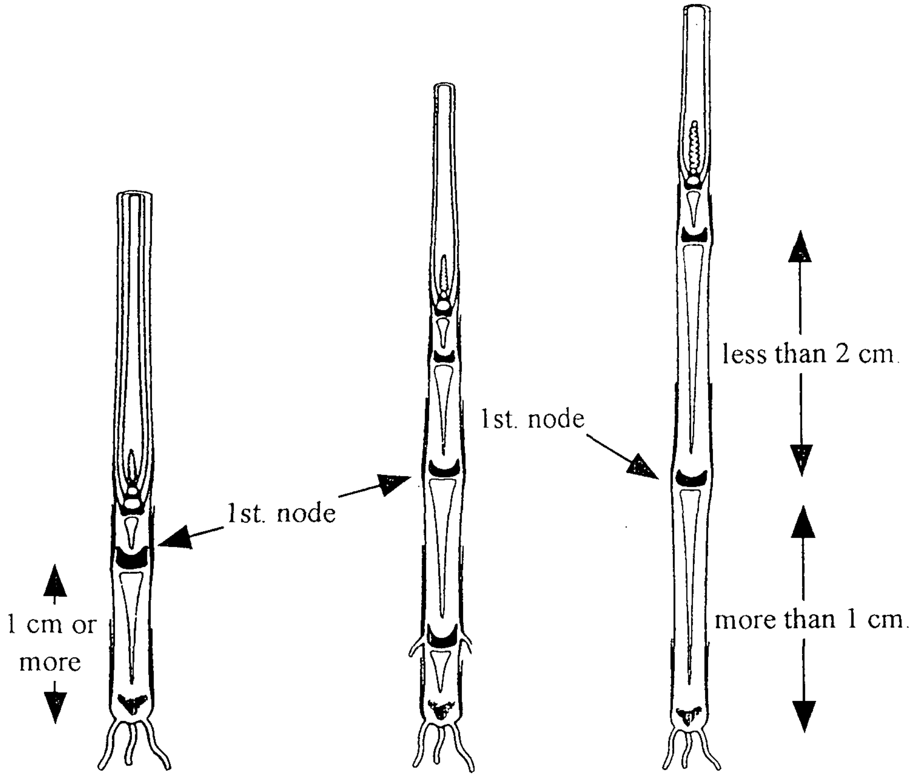
D. If the crop has passed GS 30, count the number of extended internodes. Growth stage 31 (first node detectable) occurs when the first visible internode is more than 1 cm. The second and subsequent nodes (GS 32 etc.) are counted when the internode below them is more than 2 cm.

E. Note that flag leaf emergence stages ('flag leaf just visible' GS 37, and 'flag leaf collar just visible', GS 39) may pre-empt stages defined by extension of the final internodes (GS 34-36).

F. Repeat A-D on 10 plants. The 'growth stage ' of the crop is the stage which has been equalled or exceeded by half the plants

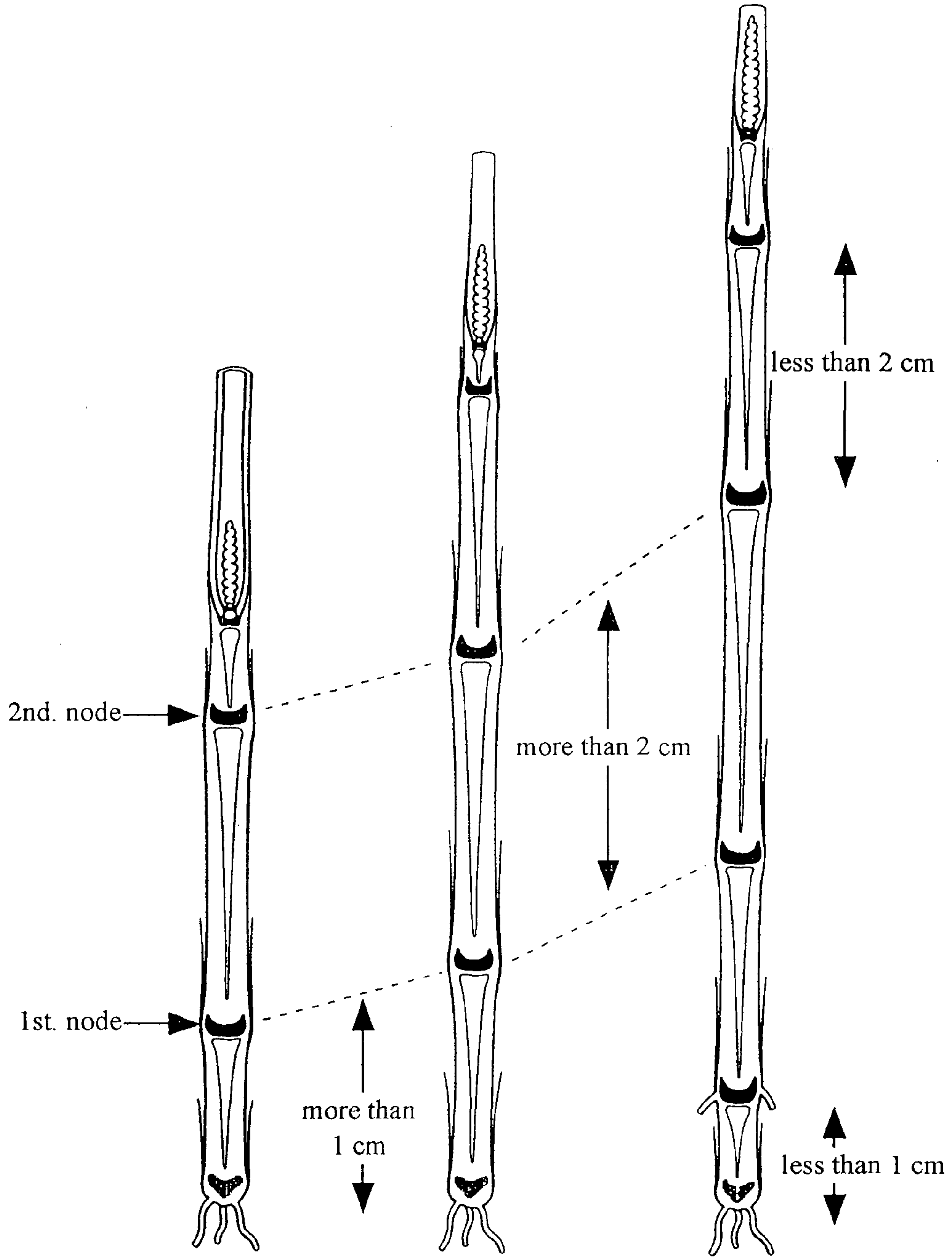


Growth stage 30: Ear at 1 cm



Growth stage 31: First node detectable

Figure 3.4a Stem extension stages - split stems GS 30 and GS 31



Growth stage 32: Second node detectable

Figure 3.4b Stem extension stages - split stems GS 32

GS 30 Ear at 1 cm- pseudostem erect
(Six leaves unfolded)
(Main shoot and 4 side shoots)

GS 32 Second node detectable
(Eight leaves unfolded)
(Main shoot and 3 side shoots)

Figure 3.4c Stem extension phases in the whole wheat plant

3.5 Ear Development

In this manual ear development covers the stages 'booting' and 'ear emergence' of the *decimal code.* From this phase until maturity, crop development is defined by the most common stage represented amongst *all shoots* present, rather than just the mainstem.

'Booting' describes extension of the upper internodes and swelling of flag leaf sheaths due to growth of the ear. Definitions of individual stages within the booting phase are relatively vague and sometimes difficult to discern. However, this phase of development takes only a few days so that mis-identification of stages seldom causes serious imprecision.

Booting

	Decimal Code
41	Flag leaf sheath extending
43	Boots just visibly swollen
45	Boots swollen
47	Flag leaf sheath opening
49	First awns visible

'Inflorescence' is the technical term for the ear. 'Heading', which is the process of ear emergence, begins when the flag leaf sheath opens and the tip of the developing ear emerges above the base of the flag leaf blade.

Ear Emergence

	Decimal Code
51	First spikelet of inflorescence just visible
52	1/4 of inflorescence emerged
55	1/2 of inflorescence emerged
57	3/4 of inflorescence emerged
59	inflorescence completely emerged

GS 49 Flag leaf ligule visible   *GS 47 Flag leaf sheath opening*   *GS 55 Half of inflorescence emerged*

Fig 3.5 Stages of ear emergence

Box 3.5.1

To assess ear development:

A. Examine crops daily for the first signs of swelling in the flag leaf sheath.

B. From the sampling position choose ten shoots by selecting every other shoot in a row, *disregarding any differences between mainstems and tillers.*

C. Record the degree to which the ear has developed.

D. The growth stage of the crop is the most common stage recorded.

NB. Ear emergence occurs rapidly and, to accurately record the date of emergence, observations need to be made every two days.

3.6 Flowering

	Decimal Code
61	Beginning of anthesis
65	Anthesis half-way
69	Anthesis complete

Flowering or anthesis is an important stage of development, marking the onset of grain growth. It generally occurs a few days to a fortnight after ear emergence and is defined by the appearance of anthers from the central spikelets of the ear. This usually occurs in the early morning when anthers are seen to be hanging from the spikelets. Since flowering occurs across a field crop within a few days, a single position is sufficient for sampling.

All the current varieties of wheat grown in the UK are at least partly open-flowering and the anthers can be seen immediately after flowering. However, many barley varieties are closed-flowering and flowering can only be determined by dissection of the ear.

Box 3.6.1

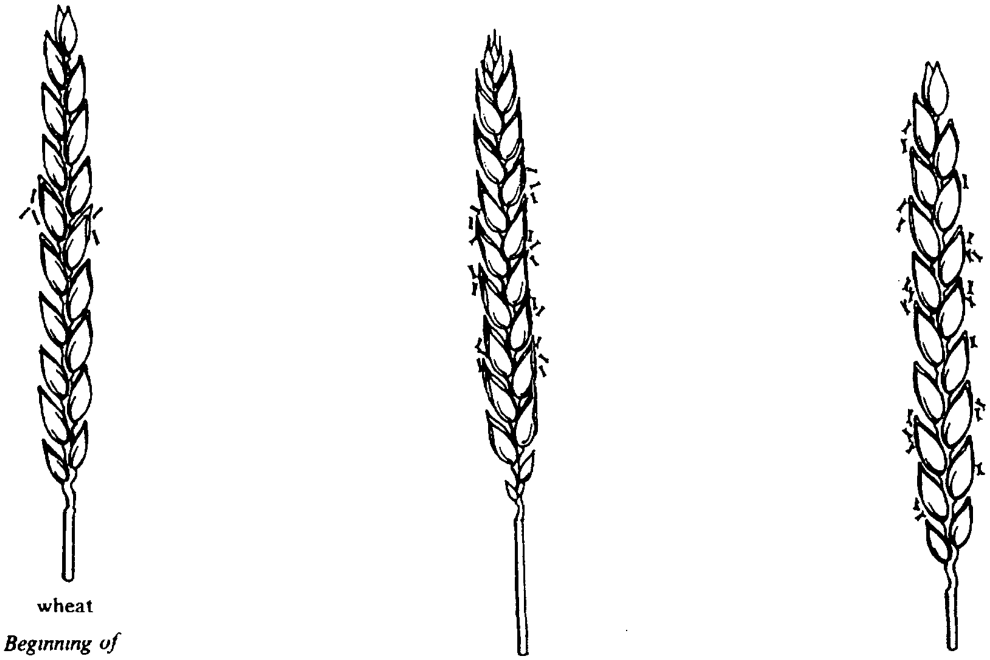
To assess flowering

B. Examine crops daily for the first signs of flowering.

C. When the first anthers are seen, choose ten shoots by selecting every other shoot in a row, *disregarding any differences between mainstems and tillers.*

D. Record whether anthers are visible in the central 1-5 spikelets of the ear (GS 61, beginning of anthesis), the central 5-15 spikelets (GS 65, anthesis half-way), or more than 15 spikelets (GS 69, anthesis complete,).

E. The growth stage with the greatest number of records is the growth stage of the crop on the sampling date.



wheat

Beginning of anthesis (61)

Anthesis half-way (65)

Anthesis complete (69)

Figure 3.6 Stages of anthesis

3.7 Grain filling and ripening

Progress through grain filling and ripening is defined by the *Decimal Code* according to the consistency of the grain's contents. Caryopsis is the technical term for the grain.

Decimal Code	
71	Caryopsis watery ripe
73	Early milk
75	Medium milk
77	Late milk
83	Early dough
85	Soft dough
87	Hard dough
91	Caryopsis hard, and difficult to divide by a thumb-nail
92	Caryopsis too hard to divide
93	Caryopsis loose in the ear

'Watery', 'milk', 'dough' and 'hard' are subjective assessments, which are difficult to standardise. An alternative approach which can be used to track the progress of grain filling and ripening is to monitor first the expansion of the grains within their florets, and then the moisture content of grains extracted from the ear. The implications of changes in grain moisture content are described in Part 1 of this volume: "*The Wheat Growth Guide*".

4. IN-FIELD ASSESSMENTS OF CROP GROWTH

4.1 Plant number

This assessment estimates the number of plants per square metre and would normally only be carried out after all the plants have emerged, in the autumn, or in early spring. Once plants have several tillers, the accurate assessment of plant number becomes difficult. The number of samples needed is larger than for the other measures, particularly if the field is variable, and at least eight are required for a typical field. Note that sample sites without plants should not be excluded. Since the plant population normally changes slowly after full emergence, measurements could be made over a period of several days. (see sections 10.2 and 10.3 of Volume II: "*How to Run a Reference Crop*").

Box 4.1.1

To count the number of plants per square metre:

A. Identify the sample area.
B. Place a 50 cm stick between two rows.
C. Count the number of plants along *both* sides of the stick.
D. Record the row width to the nearest whole centimetre.
E. Multiply the plant number by 100 and divide by the mean row width in centimetres to obtain the number of plants per square metre.
F. Take the average and round the answer to the nearest whole number.

4.2 Shoot number

Shoot number is important in guiding several management decisions. Also, this information is used in the estimation of green area index, and when shoots can be recognised as 'fertile' it provides an estimate of the number of ears per square metre.

The method for assessing shoot number per square metre is broadly the same as for plant number. Both mainstems and tillers are counted as 'shoots'. Before growth stage 39 all live shoots are counted.

Box 4.2.1

To count shoots before growth stage 39 :

A. Pull up 10 plants at random, ensuring that they are separate plants.

B. Count the total number of emerged, live shoots, *including the mainstem and all the tillers*. Tillers should be counted as soon as their tip is visible above the base of their subtending leaf blade. Exclude any shoot from the count if its newest expanding leaf has begun to turn yellow at its tip.

C. Calculate the average number of shoots per plant.

D. Multiply the number of shoots per plant by the number of plants per square metre to give the number of shoots per square metre.

After growth stage 39 the count is intended to reflect the number of shoots which will bear productive ears, i.e.those that are 'fertile'. Hence, after growth stage 39, shoots which are less than half the overall canopy height are excluded from counts on the assumption that they are unlikely to produce ears.

Box 4.2.2

To count 'fertile' shoots after growth stage 39 :

A. At each sampling position, place a 50 cm stick between two rows.

B. At half maximum shoot height, count the number of shoots along both sides of the stick.

C. Record the row width to the nearest whole centimetre.

D. Multiply the shoot number by 100 and divide by the mean row width in centimetres to obtain the number of 'fertile' shoots per square metre.

E. Take the average and round the answer to the nearest whole number.

4.3 Crop height

Crop height is really only a useful measurement after growth stage 30 at which time the height can range from 3 to 15 cm. It is measured from ground level to the base of the last fully expanded leaf blade on the mainstem or, if the ear has emerged, to the base of the ear. For practical purposes, the mainstem can be taken to be the tallest shoot on a plant.

Crop height is an important determinant of the risk of lodging because the force exerted by the aerial parts of the plant on the stem base and root system increases with crop height. Crop height depends not only on the stage of development but also on variety, nitrogen use, plant growth regulator use and water availability.

4.4 Ground cover

Ground cover is a measure of the fraction of land area obscured by leaves when viewed vertically from above and can be estimated with sufficient accuracy by eye. The method is of most use before the onset of stem extension (see section 3.4). Crop cover should be estimated for an area of at least 1 m^2 so that several rows are considered together. With practice, the sample area can be delimited by eye, although it may be found helpful to use a small hoop or rectangular 'quadrat'.

Box 4.4.1

To measure ground cover:

A. Choose a sample position, using the previously described procedure (see Box 2.2.1).

B. Look down on the canopy immediately in front of you so that your angle of sight is as near vertical as possible.

C. Estimate (to the nearest 10%) the proportion of the ground within the specified area that is covered by leaves.

D. At the same position, repeat step C but estimate the proportion of ground *not* covered by leaves and subtract the figure from 100.

E. Average the figures obtained in steps C and D to obtain the ground cover.

There is quite a good relationship between crop cover and Green Area Index (GAI). For a variety like Mercia, the typical values are as follows :

Crop cover	*50%*	*80%*	*90%*
GAI	*1*	*2*	*3*

At higher values of crop cover, the relationship with GAI becomes increasingly unreliable. Varieties with more erect leaves would have higher and those with more lax leaves lower GAIs at the crop covers indicated above.

4.5 Green area index

Green area index (GAI), which is the area of green tissue (leaf blade and sheath, stem and ear) divided by the area of ground it occupies, is a measure of the canopy size or leafiness of a crop. It reaches a maximum at about flowering. Crop cover (section 5.4) can be used to estimate GAI in the early stages (see previous section). However, where the GAI exceeds about three, crop cover may be almost complete and is an inadequate way of differentiating between canopy sizes, which may be as large as ten. Also for crops with extended internodes ground cover may underestimate the potential of the canopy to intercept light. Thus for leafy young crops and for crops which show some stem extension, a different technique is normally necessary.

The GAI is calculated from

$$\mathrm{GAI} = \frac{N_s \times N_L \times A}{10{,}000}$$

where N_S is the number of shoots per square metre

N_L is the number of green leaves per shoot

A is the average area per leaf, including the projected area of the corresponding shoots in square centimetres. (or average area per leaf and shoot)

10,000 is the scale factor which converts from square metres to square centimetres of ground.

The procedure used for estimation of area is given in the boxes below:

Box 4.5.1

To estimate green area index:

A. Choose a sample position (see section 2.2)

B. Count the number of shoots per square metre (see section 4.2)

C. Count the number of green leaves (Box 4.5.2)

D. Either use the procedure in Box 4.5.3 to estimate A (A_E) or measure A as described in Box 4.5.4

E. To obtain green area index use the equation above

F. The GAI should be rounded to the nearest unit.

This estimate of GAI relies on an estimate of the number of *green* leaves on all shoots (including tillers) and differs from the number of mainstem leaves recorded in the growth stage assessment (section 3.2).

Box 4.5.2

To estimate the number of green leaves:

A. Select a healthy plant from near the point that has already been identified (see box above).

B. Count the number of leaves on *all shoots on the plant,* counting a leaf when more than half its blade (as far as the junction with the sheath) has appeared and more than half its blade area is still green.

C. Repeat the procedure for five other nearby plants and calculate the average leaf number per shoot. Note: When plants are tillering, some newly emerged shoots will have no countable leaves. These shoots should nevertheless be included in the calculation of leaves per shoot.

The average area per leaf and shoot (A_E) can be estimated from the growth stage using Box 4.5.3

Box 4.5.3

To estimate the 'average area of leaf and shoot'

A. Define the growth stage (Chapter 3)

B. Use the table below interpolating as necessary between growth stage to find A_E

Growth Stage	Average area per leaf and shoot (A_E)
31	10
32	13
37	16
41-47	18
49 and above	21

At growth stage 30, the A_E is less than the mean area of mainstem leaves (because tiller leaves are smaller than mainstem leaves). As the crop develops, A_E increases to take account of the larger leaves and the contribution of the leaf sheaths.

The average areas per leaf and shoot given above were calculated from18 crops of Mercia grown with optimised fertiliser supply and which were kept pest and disease free. If crop growth is limited for example by lack of fertiliser or drought, then GAI may be overestimated by. A_E. If this is thought to be the case, or if the morphology of the variety used is distinctly different from Mercia then it may be worth using the methods described below in Box 4.5.4 to measure the actual value of A for the crop of interest.

Box 4.5.4

To estimate the average area per leaf and shoot factors (A):

A. Select a sample position and cut off ten shoots at the ground, using alternate shoots in a row.

B. Cut off each green leaf, either at the ligule if it is fully expanded, or where it emerges from the sheath if it is still growing.

C. Count the number of green leaves recovered.

D. Measure the length of each leaf in cm and its width (in cm) at the mid-point of the part cut off

E. Calculate the area of each leaf in square centimetres by multiplying length × width × 0.8

F. Measure the diameter of the remaining stem at internode positions at about ¼, ½ and ¾ of its height and calculate the average diameter (normally about 0.4 cm).

G. Measure the height of the remaining stem in cm.

H. Calculate the projected stem area by multiplying height by diameter

I. Sum the values of leaf area and stem area over the whole sample and divide by the total number of leaves in the sample. This is the 'average area per leaf and sheath' (A)

As experience is gained with the estimation of canopy size, it will become possible to make crude estimates *by eye* that are adequate for modifying husbandry decisions.

4.6 Crop biomass

Two methods for assessing crop biomass are provided; the first involves indirect estimation using a conversion from green area index, whilst the second involves direct estimation from plant samples.

Indirect estimation of crop biomass from GAI

This assessment provides an estimate of the dry weight of crop in tonnes per hectare and is based on the association between biomass and green area index which holds between plant emergence and ear emergence.

Box 4.6.1

To estimate the biomass from GAI

A. Measure green area index as described in 4.5

B. Multiply green area index by the conversion factor below.

Growth Stage	Conversion factor
30-32	0.8
33-39	1.0
41-49	1.3
57-59	1.6

Unfortunately, there is considerable year-to-year and site-to-site variation in the conversion factor and the figures given above should only be used as a guide.

The ratio between biomass and GAI depends on the amount of reserves stored in the straw and on the thickness of the leaves. The ratio increases with straw length, i.e. with stage of growth. There are also varietal differences and differences due to the supply of water and nitrogen.

Direct estimation of crop biomass from field samples

The main source of variation in crop biomass is the total fresh weight of the crop. However, as the crop develops, the percentage dry matter changes. The following method therefore uses as large a sample as possible for fresh weight, but a relatively small sample for assessing the percentage dry matter

Box 4.6.2

To measure the biomass

A. Select a sampling position and select an area of five rows by 1m at each position.
B. Cut off all plants at ground level.
C. Combine all samples and weigh (preferably to the nearest gramme)
D. Take a sub-sample of the fresh material (approximately 250-300g) and weigh to the nearest gramme
E. Microwave in a domestic appliance of at least 650W at high power for 10-15 minutes, turning 2-3 times during drying
F. Weigh the dry sub-sample to the nearest gramme
G. To calculate biomasss

$$\text{Sample size } (\text{m}^2) = \text{number of samples} \times \frac{(5 \times \text{row width in cm})}{100}$$

$$\text{Crop Biomass } (\text{t / ha}) = \frac{(\text{total sample fresh weight } \times (\text{sub sample dry weight / sub sample fresh weight})}{\text{sample size in m}^2 \times 100}$$

Acknowledgements

The authors wish to thank the other members of the project group, especially D. T. Stokes, and Mr M. bin Suhaili who tested the methods for estimating green area index at Sutton Bonington.

Part 3

Forecasting Crop Progress for Wheat

CONTENTS

INTRODUCTION

This project was undertaken to show that crop assessments are worthwhile. Assessments of 'current crop state' would be significantly enhanced by accompanying guidance on the way they relate to further crop progress and, ultimately, how they may indicate final crop performance.

Good prediction of crop performance has proved an intractable goal, despite it being the persistent ambition of crop scientists. Occasionally, useful indicators of final yield have been identified, but the proportion of variation accounted for has normally been small and confidence has been insufficient for their adoption in support of commercial decision-taking. Thus it must be recognised that there will be no quick or easy solution; improvements toward the ideal will continue to be slow and protracted.

Short-term predictions

The approach adopted here accepts that long-term predictions will remain unsatisfactorily imprecise. Rather, the aim is to develop methods which can provide satisfactory estimates of crop progress in the short term, say for up to a month. Thus, for example, the prediction of grain yield is only attempted during the final stages of grain growth. Earlier in the season, forward estimates of crop growth are possible, and that these should prove useful in supporting imminent husbandry decisions but, as each season unfolds, it will be necessary for such predictions to be regularly updated according to renewed assessments of the crop.

For example, it is felt that plans for a first fungicide application could be usefully supported, after an observation of GS30 in March, by predicting that the third from last leaf will emerge, say in early May. Similarly, judgement of nitrogen applications could be improved by predicting how large the canopy is likely to become at the beginning of June, based on an observations at GS31. However, it may be necessary to upgrade any prediction, according to observations made in the intervening weeks, and to adjust subsequent decisions accordingly.

Representing knowledge of wheat as simple rules rather than complex models

The only objective way to improve the prediction of crop progress is to introduce a credible theory which (a) embraces some underlying (i.e. quantified and documented) causes for each effect, thus conferring an ability to reason about the outcome, and (b) has been proven better than other theories when applied to a set of crops which played no part in their development.

The determination of growth and performance of wheat crops in UK fields undoubtedly depends on multifarious factors interacting with considerable complexity. Such complex systems can be represented by detailed 'simulation models' only solvable by computers. The alternative is to devise simple 'rules-of-thumb' which only recognise the most salient causal factors but which often can be resolved by 'mental arithmetic'.

What follows tends toward the latter approach. We have attempted to summarise understanding as simple relationships often described by just one equation. Where the equations were at all complex we have tabulated their predictions. Not only does this have the advantage that any wheat grower, whilst in the field, can make a quick analysis of the prospects for his crop but, more importantly, simple rules are more easily communicated and discussed, reducing the danger of spurious complexity. Simple rules also confer on the careful observer and wheat researcher a simpler and more rigorous route to improvement, in that it is more straightforward to prove (or alternatively challenge) that a new rule improves a prediction, rather than to prove that a particular element of a detailed model is unnecessary and can be rejected.

The weather

As well as deficiencies in understanding, which compromise our capacity to predict, predictions of crop progress will always have attendant uncertainties due to the vagaries of the weather. Simplifications are useful here too. Weather patterns over sites and seasons within the UK are sufficiently consistent that it is possible to predict sunshine and temperature within limits which usefully improve crop predictions. Furthermore, although the variability in rainfall is large and important for crop growth, a majority of soils in the UK on which wheat is grown hold sufficient water for variation in rainfall to be of minor consequence. The methods that follow are therefore not seriously compromised by the long-term unpredictability of weather.

Of all weather 'factors', temperature has the most important influence on wheat progress, primarily through its effect on the rate at which the crop develops. Anyone wishing to predict wheat progress in the short term will find that an appreciation of development, and therefore temperatures, is fundamental. The 'rules' described here are based upon the concept of 'thermal time above 0°C '. Thermal time has been adopted as a simple way of integrating the effects of temperature. When maximum and minimum temperatures are above 0°C the average temperature each day is added to those of previous days, producing a sum for the period of interest. (An exact account of how to calculate thermal time in cold weather is given in Appendix 1.) A concept based on thermal time, 'T-sum', (an approximation of thermal time accumulated from 1 January) has been readily adopted by grass producers for timing of fertiliser applications. It is felt that thermal times for appropriate periods could become equally important for wheat managers.

Whilst observations of 'current crop state' can be interpreted in the light of known variation in temperature, intelligence of future site-specific temperatures are bound to be limited. Predictions of further crop progress must therefore depend on *average* temperatures for the locality and for the time of year. Table 1 provides the long-term average thermal times for three main regions where wheat is grown in the UK. The accuracy of predictions will be improved by using measured maximum and minimum temperatures rather than average data.

Week beginning	East Anglia	The North, including Scotland & Northern Ireland	The Midlands, South and West
2 September	103	85	97
9 September	97	80	94
16 September	95	78	89
23 September	90	74	85
30 September	85	72	82
7 October	80	64	74
14 October	69	57	66
21 October	67	55	63
28 October	63	49	58
4 November	53	42	50
11 November	42	33	41
18 November	40	31	41
25 November	34	29	36
2 December	36	28	35
9 December	32	28	33
16 December	35	25	33
23 December[1]	43	30	40
1 January	28	21	29
8 January	30	21	27
15 January	29	21	28
22 January	32	22	31
29 January	27	24	31
5 February	30	22	30
12 February	22	17	23
19 February	30	23	29
26 February	32	27	34
4 March	40	33	39
11 March	42	33	42
18 March	45	31	41
25 March	47	35	45
1 April	46	34	46
8 April	53	42	53
15 April	61	50	59
22 April	60	52	61
29 April	67	54	64

continued overleaf

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[1] The thermal times for the week beginning the 23 December are for 9 days

Week beginning	East Anglia	The North, including Scotland & Northern Ireland	The Midlands, South and West
6 May	76	62	75
13 May	80	64	76
20 May	86	70	82
27 May	89	75	85
3 June	95	81	92
10 June	98	84	97
17 June	101	87	99
24 June	107	89	103
1 July	113	95	107
8 July	113	93	110
15 July	112	95	110
22 July	114	98	111
29 July	117	96	110
5 August	116	96	109
12 August	116	94	108
19 August	110	94	107
26 August	106	91	104

Table 1. Averages of thermal times accumulated per week (°C d, base 0 °C) for wheat growing regions of the UK [1].

Limitations and uncertainties

The 'rules' given here have arisen through interpretation of data from research on the wheat variety Mercia. The methods were either developed on data collected before the outset of this project or on data collected from this project in the years 1992-3 and 1993-4 (these are the data described in Part 1 of this volume: '*The Wheat Growth Digest*'). All of the methods have been checked against independent data.

There are known to be both genetic and cultural effects on several crop attributes (such as radiation conversion efficiency and nitrogen per unit of canopy) which are taken to be constant in these rules. There will be an increasing element of uncertainty, the more that the crop in question differs from Mercia grown to the standards described in '*The Wheat Growth Digest*'. Whilst we believe these rules are the best quantitative method currently available to predict crop progress in the UK, they are by no means perfect. Comparisons between these methods and observed data suggest that the overall level of uncertainty will be of the order of 20% of the absolute value predicted.

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[1] The sites chosen to represent the regions are Arthur Rickwood near Ely, for East Anglia, Bush house Edinburgh for the North and Rosemaund, Herefordshire for the Midlands, South and West

Crop Development or 'Growth Stage'

by A. P. Gay and E. J. M. Kirby

Kirby (1994) has reported a method of predicting growth stages in wheat. This was further tested on the data collected from the Mercia crops grown in this project and found to provide reasonable agreement (Kirby & Weightman, 1996). The method relies on knowledge of temperature, sowing date, latitude (hence daylength) and the particular vernalisation, photoperiod and temperature responses of the variety in question. Development does not appear to be influenced by other factors such as nutrient or water supply, or by disease, except in extreme circumstances.

In using the model to produce the tables below, the following simplifications were made :

a) Latitude, which was used to calculate the rate of change of daylength at seedling emergence, was fixed at 52°, since changes between 50 and 55°N gave relatively small effects.

b) The 35 year averages of temperatures for ADAS Rosemaund were used to calculate the dates of emergence and of full vernalisation, which then set parameters controlling the rate of development according to thermal time.

To estimate the likely time of the next growth stage

1) Choose one of the two tables below according to whether the variety in question develops slowly (equivalent to Beaver) or fast (equivalent to Mercia). Then select the line nearest to your sowing date from those provided and note the interval in thermal time between first appearance of the current growth stage and first appearance of the next growth stage. If you are working in a season when crop emergence has been delayed, for example by dry conditions after sowing, then do not use the actual sowing date but the date of 50% crop emergence less the time taken to accumulate 150°C days of thermal time, either using actual temperatures and Appendix 1, or estimated from Table 1 on page 5.

Fast developing varieties (e.g. Mercia)

Date of sowing	Sowing to GS 30	GS 30 to GS 32	GS 32 to GS 39	GS 39 to GS 55	GS 55 to GS 61
	Thermal time (degree °C days, base 0 °C)				
16 September	1226	222	123	218	110
7 October	1046	219	121	215	108
4 November	869	202	112	199	99

Slow developing varieties (e.g. Beaver)

Date of sowing	Sowing to GS 30	GS 30 to GS 32	GS 32 to GS 39	GS 39 to GS 55	GS 55 to GS 61
	Thermal time (degree °C days, base 0 °C)				
16 September	1390	246	137	242	121
7 October	1215	243	134	238	119
4 November	1025	223	122	218	109

2) From local or published records, note the thermal time that has elapsed since the date that the current growth stage was first reached. If no records are available, a rough estimate can be made by using Table 1 and making adjustments if the weather was warmer or cooler than usual, as follows :

Average thermal time per week (from Table 1)	20	60	100
		day degrees	
Add for warm week	13	7	8
Subtract for cool week	13	10	7

These adjustments are based on quartiles; adjustments should be greater in periods of extreme difference.

Estimate how long it will take, at the relevant time of year, to accumulate the necessary thermal time, using Table 1. To do this, identify the appropriate column in the Table according to region and from the date of the current growth stage add together thermal times, estimating appropriate proportions for parts of weeks. The date of the next growth stage is predicted to occur when the appropriate thermal time interval has been accumulated.

Crop Growth and Canopy Expansion

by A. Gillett and N. Crout

These two methods are considered together because the method developed for prediction of growth in dry weight is dependent on a prediction of canopy expansion. A description of these methods is given by Gillett (1996).

Canopy size

In an analysis of data from this project and the HGCA project *"An integrated approach to N Nutrition for Winter Wheat"* (0070/01/91A), the factors found to account for significant components of the variation in canopy size were the nitrogen supply to the crop, both from the soil and from fertiliser, and the temperatures which the crop experienced.

The relationship of canopy size to nitrogen supply is given by:

$$\sum GAI = 15.7N + 2198$$

where $\sum GAI$ is the integral of GAI with thermal time above 0°C over the whole season, and N is the total nitrogen supply (soil N plus fertiliser N in kg/ha).

Nitrogen supply

The nitrogen supply is considered here as the sum of mineral N in the soil to 90 cm depth in spring and the fertiliser applied in spring. Obviously it is best to measure soil mineral nitrogen directly since it depends on many factors. However, in the absence of measurements, soil N supply can be roughly estimated using the following table; it must be accepted that the table estimates may be subject to large errors.

Previous crop	Sands and light loams	Medium loams and clays
	soil mineral nitrogen (kg / ha)	
linseed	30	50
sugar beet	30	50
barley (winter or spring) for malting	40	60
barley (winter or spring) for feed	40	70
winter wheat	50	70
winter wheat for breadmaking	50	80
potatoes (unirrigated)	60	90
legumes (peas & beans)	60	90
oilseed rape	80	120

Prediction of GAI at a given thermal time

Using the value of $\sum GAI$ calculated above, the canopy size at any given thermal time can be calculated using:

$$GAI = \frac{\sum GAI}{\sigma\sqrt{2\pi}} e^{\left(-\frac{1}{2}\left(\frac{TT-\mu}{\sigma}\right)^2\right)}$$

where TT is the thermal time in day degrees C from sowing and μ is the thermal time to maximum GAI, defined by:

$$\mu = 3074 - 4.96\, d_J$$

with d_J the date of sowing expressed as day of the year (counting January 1 as day 1) and σ the canopy duration estimated from μ by:

$$\sigma = 0.12\,\mu + 197$$

Other canopy expansion models were tried. Those dependent on other climatic variables such as photosynthetically active radiation worked well, but the data are less generally available. Those involving separate description of canopy senescence and canopy expansion had unstable parameters. The model presented here is only dependent on sowing date and thermal time so that it can be applied easily at any site.

On a particular site the major influences on temperature are latitude, altitude, soil type, exposure and season. The only husbandry factor which can influence the temperatures experienced by a crop is its date of sowing. This is taken into account by providing a separate table for each of three dates of sowing.

Checks of this method of predicting canopy size have shown that the canopy senescence phase is not described as well as the canopy expansion phase (i.e. the predicted fall in GAI appears to be slower than is generally observed.) Thus the estimates are less reliable in the later stages of crop growth.

To predict maximum canopy size, and changes in canopy size :

1. Estimate available soil N as explained above and add to this (a) any fertiliser N (kg/ha) that has been applied already, and (b) any fertiliser N that will be applied within the period in question.

2. Estimate current canopy size using the method described in PartII: *"In-field crop assessment"*.

3. From local or published records, note the thermal time since sowing. If no records are available, a rough estimate can be made by using Table 1 and making adjustments if the weather was warmer or cooler than usual, as described in Section 2: *"Crop Development"*.

4. Select one of the three tables starting on page 12 according to the sowing date of the crop in question and find the cell for the present thermal time and N supply. If the sowing date lies between the dates of two tables use both tables to estimate an intermediate value.

5. Compare the current observation of canopy size with the calculated current value and, depending on whether most uncertainty attaches to the N supply, the thermal time or the current observation, identify a more appropriate cell in the table.

6. To predict maximum canopy size, look down the column containing this cell until the maximum value is found.

7. To predict canopy size by a certain date or growth stage use Table 1 or the Section 2: *"Crop Development"* to estimate the average thermal time interval for that period and look down the column from the selected cell to find the expected canopy size when that thermal time has elapsed.

Crop growth

Crop growth occurs through photosynthesis, which is an energy conversion process dependent on the amount of solar radiation intercepted by the crop's green canopy. Some of this energy is lost by respiration, and some is used in providing material for root growth. Only the net effects on above-ground components of the crop are considered here. For the data collected from Mercia crops, the best interpretation of crop growth was obtained using canopy size and sunshine hours. The size of the green canopy determines the proportion of the light that the crop intercepts and sunshine hours relate closely to the solar radiation which the crop experiences.

The relationship can be expressed in the following equation :

$$\frac{dW}{dt} = \varepsilon I(1 - e^{(-kGAI)})$$

where dW/dt is the change in total above-ground dry weight with time (tonnes/hectare/day), ε is the conversion coefficient from PAR to biomass for Mercia (2.755 gMJ^{-1}) and k is the extinction coefficient for Mercia (0.45). I is the photosynthetically active radiation in MJ m^{-2} d^{-1}. GAI can be estimated from thermal time as before.

So that estimates could be made without knowledge of photosynthetically active radiation (PAR), calculations of daily growth were made using the 30 year averages of temperature and PAR for each day of the growing season at Sutton Bonington. This was done by first calculating the GAI for each day for the appropriate sowing date and nitrogen level using the equation for prediction of GAI given previously. The value of GAI and the appropriate average I was then used in the equation above to calculate net daily growth. The daily dry weights were then summed for the season to date, as were daily thermal times and values interpolated at the standard thermal times given in the tables starting on page 13.

To predict crop growth and maximum crop dry weight :

1. Using the method described in the previous sub-section, make best estimates of :
2. current thermal time since sowing and
3. current canopy size.
4. Having selected the appropriate cell for thermal time and N supply in one of the tables of canopy size, current dry weight is indicated by identifying the analogous cell in the adjacent table.
5. To predict maximum dry weight, look down the column containing this cell until the maximum value is found.
6. To predict further crop growth to a certain date or growth stage use Table 1 or Section 2: '*Crop Development*' to estimate the average thermal time interval for that period and look down the column from the selected cell to find the expected total dry weight when that thermal time has elapsed.
7. Note that predictions across a range of climate and soil types show extreme differences of up to 20% for a well fertilised canopy.

Prediction tables for canopy and dry weight

Early sowing

Predicted canopy size (green area index) for wheat with an early sowing date (13 September) during an average season

	Nitrogen available (kg/ha)					
Thermal time (day-degrees)	50	100	150	200	300	400
0	0	0	0	0	0	0
100	0	0	0	0	0	0
200	0	0	0	0	0	0
300	0	0.01	0.01	0.01	0.01	0.01
400	0.01	0.01	0.02	0.02	0.02	0.03
500	0.02	0.03	0.03	0.04	0.05	0.06
600	0.04	0.06	0.07	0.08	0.1	0.13
700	0.09	0.11	0.13	0.16	0.2	0.25
800	0.16	0.2	0.24	0.29	0.37	0.45
900	0.28	0.35	0.42	0.5	0.64	0.79
1000	0.45	0.57	0.69	0.81	1.05	1.29
1100	0.7	0.88	1.07	1.25	1.62	1.99
1200	1.02	1.29	1.56	1.83	2.36	2.9
1300	1.4	1.77	2.14	2.51	3.25	3.99
1400	1.82	2.3	2.78	3.26	4.21	5.17
1500	2.23	2.81	3.4	3.98	5.15	6.32
1600	2.57	3.24	3.92	4.6	5.95	7.3
1700	2.8	3.53	4.27	5	6.48	7.95
1800	2.87	3.63	4.38	5.14	6.65	8.16
1900	2.78	3.52	4.25	4.98	6.45	7.91
2000	2.54	3.21	3.88	4.55	5.89	7.23
2100	2.19	2.77	3.35	3.93	5.08	6.24
2200	1.79	2.26	2.73	3.2	4.13	5.07
2300	1.37	1.73	2.09	2.45	3.17	3.9
2400	0.99	1.25	1.51	1.78	2.3	2.82
2500	0.68	0.86	1.03	1.21	1.57	1.93
2600	0.44	0.55	0.67	0.78	1.01	1.24
2700	0.27	0.34	0.41	0.48	0.62	0.76
2800	0.15	0.19	0.23	0.27	0.35	0.43
2900	0.08	0.1	0.13	0.15	0.19	0.23
3000	0.04	0.05	0.06	0.08	0.1	0.12

Predicted total dry weight (t/ha) for wheat with an early sowing date (13 September) during an average season

	Nitrogen available (kg/ha)					
Thermal time (day-degrees)	50	100	150	200	300	400
0	0.0	0.0	0.0	0.0	0.0	0.0
100	0.0	0.0	0.0	0.0	0.0	0.0
200	0.0	0.0	0.0	0.0	0.0	0.0
300	0.0	0.0	0.0	0.0	0.0	0.0
400	0.0	0.0	0.0	0.0	0.0	0.0
500	0.0	0.0	0.0	0.0	0.0	0.0
600	0.0	0.0	0.0	0.0	0.0	0.1
700	0.0	0.1	0.1	0.1	0.1	0.1
800	0.1	0.1	0.1	0.1	0.2	0.2
900	0.1	0.2	0.2	0.2	0.3	0.3
1000	0.3	0.3	0.4	0.5	0.6	0.7
1100	0.6	0.8	0.9	1.1	1.3	1.5
1200	1.2	1.5	1.7	2.0	2.4	2.8
1300	2.1	2.5	2.9	3.3	3.9	4.4
1400	3.2	3.8	4.4	4.9	5.7	6.3
1500	4.4	5.2	5.8	6.4	7.4	8.1
1600	5.7	6.7	7.5	8.2	9.2	10.0
1700	7.3	8.4	9.4	10.1	11.3	12.2
1800	8.5	9.8	10.8	11.7	13.0	13.9
1900	9.9	11.3	12.5	13.4	14.8	15.7
2000	11.2	12.8	14.0	15.0	16.5	17.5
2100	12.2	13.9	15.3	16.3	17.9	19.0
2200	13.1	15.0	16.4	17.6	19.3	20.4
2300	13.8	15.8	17.3	18.6	20.4	21.6
2400	14.5	16.6	18.2	19.6	21.5	22.9
2500	14.9	17.1	18.8	20.2	22.3	23.7
2600	15.2	17.4	19.2	20.6	22.8	24.3
2700	15.4	17.7	19.5	21.0	23.3	24.9
2800	15.5	17.8	19.7	21.2	23.5	25.1
2900	15.6	17.9	19.7	21.3	23.6	25.3
3000	15.6	17.9	19.8	21.3	23.7	25.4

Medium sowing date

Predicted canopy size (green area index) for wheat with a medium sowing date (6 October) during an average season

	Nitrogen available (kg/ha)					
Thermal time (day-degrees)	50	100	150	200	300	400
0	0	0	0	0	0	0
100	0	0	0	0	0	0
200	0	0	0	0.01	0.01	0.01
300	0.01	0.01	0.01	0.01	0.02	0.02
400	0.02	0.02	0.03	0.03	0.04	0.05
500	0.04	0.05	0.06	0.07	0.09	0.11
600	0.08	0.1	0.12	0.14	0.18	0.22
700	0.15	0.19	0.23	0.26	0.34	0.42
800	0.26	0.33	0.4	0.47	0.61	0.75
900	0.44	0.56	0.68	0.79	1.03	1.26
1000	0.7	0.88	1.07	1.25	1.62	1.99
1100	1.04	1.31	1.58	1.86	2.4	2.95
1200	1.44	1.82	2.2	2.58	3.35	4.11
1300	1.89	2.39	2.88	3.38	4.38	5.37
1400	2.32	2.93	3.55	4.16	5.38	6.6
1500	2.68	3.39	4.1	4.8	6.21	7.63
1600	2.91	3.68	4.44	5.21	6.74	8.28
1700	2.97	3.75	4.53	5.31	6.88	8.44
1800	2.84	3.59	4.34	5.09	6.59	8.08
1900	2.56	3.23	3.91	4.58	5.93	7.27
2000	2.16	2.73	3.3	3.87	5.01	6.15
2100	1.72	2.17	2.62	3.08	3.98	4.89
2200	1.28	1.62	1.96	2.3	2.97	3.65
2300	0.9	1.14	1.37	1.61	2.08	2.56
2400	0.59	0.75	0.9	1.06	1.37	1.68
2500	0.37	0.46	0.56	0.66	0.85	1.04
2600	0.21	0.27	0.33	0.38	0.49	0.61
2700	0.12	0.15	0.18	0.21	0.27	0.33
2800	0.06	0.08	0.09	0.11	0.14	0.17
2900	0.03	0.04	0.04	0.05	0.07	0.08
3000	0.01	0.02	0.02	0.02	0.03	0.04

Predicted total dry weight (t/ha) for wheat with a medium sowing date (6 October) during an average season

	Nitrogen available (kg/ha)					
Thermal time (day-degrees)	50	100	150	200	300	400
0	0.0	0.0	0.0	0.0	0.0	0.0
100	0.0	0.0	0.0	0.0	0.0	0.0
200	0.0	0.0	0.0	0.0	0.0	0.0
300	0.0	0.0	0.0	0.0	0.0	0.0
400	0.0	0.0	0.0	0.0	0.0	0.0
500	0.0	0.0	0.0	0.0	0.0	0.0
600	0.0	0.0	0.0	0.1	0.1	0.1
700	0.1	0.1	0.1	0.1	0.2	0.2
800	0.2	0.3	0.3	0.4	0.5	0.6
900	0.5	0.6	0.7	0.8	1.0	1.2
1000	0.9	1.2	1.4	1.6	1.9	2.3
1100	1.6	2.0	2.3	2.7	3.2	3.7
1200	2.5	3.0	3.4	3.9	4.6	5.2
1300	3.6	4.3	5.0	5.5	6.4	7.2
1400	4.9	5.7	6.5	7.1	8.2	9.1
1500	6.2	7.2	8.1	8.8	10.0	10.9
1600	7.5	8.7	9.7	10.5	11.8	12.8
1700	8.7	10.0	11.1	12.0	13.3	14.3
1800	9.9	11.3	12.5	13.4	14.8	15.9
1900	11.0	12.5	13.8	14.8	16.3	17.4
2000	12.0	13.7	15.1	16.2	17.8	18.9
2100	12.9	14.7	16.1	17.3	19.0	20.2
2200	13.6	15.5	17.1	18.3	20.2	21.5
2300	14.1	16.1	17.7	19.0	21.0	22.4
2400	14.4	16.5	18.2	19.6	21.7	23.2
2500	14.7	16.8	18.6	20.0	22.2	23.8
2600	14.8	17.0	18.8	20.3	22.6	24.2
2700	14.9	17.1	18.9	20.4	22.7	24.4
2800	15.0	17.2	19.0	20.5	22.8	24.5
2900	15.0	17.2	19.0	20.6	22.9	24.6
3000	15.0	17.2	19.1	20.6	22.9	24.6

Late sowing date

Predicted canopy size (green area index) for wheat with a late sowing date (5 November) during an average season

	Nitrogen available (kg/ha)					
Thermal time (day-degrees)	50	100	150	200	300	400
0	0	0	0	0	0	0
100	0	0	0	0.01	0.01	0.01
200	0.01	0.01	0.01	0.01	0.02	0.02
300	0.02	0.02	0.03	0.03	0.04	0.05
400	0.04	0.05	0.06	0.07	0.09	0.11
500	0.08	0.1	0.13	0.15	0.19	0.23
600	0.16	0.2	0.24	0.29	0.37	0.46
700	0.29	0.37	0.45	0.52	0.68	0.83
800	0.5	0.63	0.76	0.89	1.16	1.42
900	0.8	1.01	1.22	1.43	1.85	2.27
1000	1.19	1.5	1.81	2.12	2.75	3.37
1100	1.65	2.08	2.52	2.95	3.82	4.69
1200	2.14	2.7	3.27	3.83	4.96	6.08
1300	2.59	3.28	3.96	4.64	6.01	7.37
1400	2.94	3.71	4.48	5.25	6.8	8.34
1500	3.1	3.92	4.74	5.55	7.19	8.82
1600	3.06	3.87	4.68	5.48	7.09	8.71
1700	2.82	3.57	4.31	5.05	6.54	8.02
1800	2.43	3.07	3.71	4.35	5.63	6.91
1900	1.95	2.47	2.98	3.5	4.52	5.55
2000	1.47	1.85	2.24	2.62	3.4	4.17
2100	1.03	1.3	1.57	1.84	2.38	2.92
2200	0.67	0.85	1.03	1.2	1.56	1.91
2300	0.41	0.52	0.63	0.74	0.95	1.17
2400	0.23	0.3	0.36	0.42	0.54	0.67
2500	0.13	0.16	0.19	0.22	0.29	0.36
2600	0.06	0.08	0.1	0.11	0.14	0.18
2700	0.03	0.04	0.04	0.05	0.07	0.08
2800	0.01	0.02	0.02	0.02	0.03	0.04
2900	0.01	0.01	0.01	0.01	0.01	0.01
3000	0	0	0	0	0	0.01

Predicted total dry weight (t/ha) for wheat with a late sowing date (5 November) during an average season

	Nitrogen available (kg/ha)					
Thermal time (day-degrees)	50	100	150	200	300	400
0	0.0	0.0	0.0	0.0	0.0	0.0
100	0.0	0.0	0.0	0.0	0.0	0.0
200	0.0	0.0	0.0	0.0	0.0	0.0
300	0.0	0.0	0.0	0.0	0.0	0.0
400	0.0	0.0	0.0	0.0	0.0	0.0
500	0.1	0.1	0.1	0.1	0.1	0.2
600	0.2	0.2	0.2	0.3	0.3	0.4
700	0.3	0.4	0.5	0.6	0.7	0.9
800	0.7	0.9	1.0	1.2	1.5	1.8
900	1.2	1.5	1.7	2.0	2.4	2.8
1000	2.0	2.4	2.8	3.2	3.8	4.4
1100	2.9	3.5	4.0	4.5	5.4	6.1
1200	4.0	4.8	5.4	6.0	7.0	7.8
1300	5.3	6.2	7.0	7.7	8.8	9.7
1400	6.4	7.5	8.3	9.1	10.3	11.2
1500	7.7	8.9	9.9	10.7	12.0	13.0
1600	8.9	10.2	11.3	12.1	13.5	14.5
1700	9.9	11.3	12.5	13.4	14.8	15.8
1800	11.1	12.6	13.8	14.8	16.4	17.4
1900	11.9	13.5	14.8	15.9	17.5	18.6
2000	12.5	14.3	15.7	16.8	18.5	19.7
2100	13.2	15.0	16.5	17.8	19.6	20.9
2200	13.6	15.5	17.1	18.4	20.3	21.7
2300	13.8	15.8	17.5	18.8	20.8	22.3
2400	14.0	16.0	17.7	19.1	21.2	22.7
2500	14.1	16.1	17.8	19.2	21.4	23.0
2600	14.1	16.2	17.9	19.3	21.5	23.1
2700	14.1	16.2	17.9	19.4	21.5	23.2
2800	14.2	16.2	18.0	19.4	21.6	23.2
2900	14.2	16.2	18.0	19.4	21.6	23.2
3000	14.2	16.2	18.0	19.4	21.6	23.2

Weight Per Grain, Grain Yield and Grain Quality

by J.E. Macbeth, P.S. Kettlewell & R. Sylvester-Bradley

Weight per grain is an important component of final grain yield and is determined at the end of the crop's life. Hence, predictions of grain yield are best delayed until it becomes possible to predict weight per grain. Both methods are presented together here.

The method described has been developed from initial work by Schnyder and Baum (1992) in Germany and adapted to wheat crops such as are currently grown in the UK by Macbeth (1996). It has not proved possible to make predictions based entirely on weather and cultural information. Thus the predictions depend upon assessments made during grain filling of :

- grain fresh weight and dry weight,
- grain number per ear and
- ear number per m^2.

The methods for these assessments are described in the accompanying Volume II: '*How to Run a Reference Crop*' and depend upon more technical support than is normally available on farms. It is thus envisaged that the predictions will be generalised from a crop representing one season and locality, rather than being made on a series of individual crops.

The equation given below for the prediction of weight per grain has been calculated from the relationship between maximum grain water content and weight per grain, as modified by the number of grains per unit area. The measurements are timed to coincide with the maximum grain water content which occurs approximately four weeks after anthesis.

The same measurements must be made for both prediction of weight per grain and prediction of grain yield. The estimate of potential grain yield that can be obtained from these measurements is crude, and there is an inherent bias in the method since combine losses are excluded (Bloom, 1986).

Weight per Grain

1. Calculate the average fresh and dry weight per grain (mg) for each sample taken four weeks after anthesis by dividing the total grain fresh weight and dry weight in grammes by the number of grains in each sample and multiplying by 1000.

2. Calculate grain water content in mg by subtracting the grain dry weight from the grain fresh weight.

3. An example is given below:

Grain number per sample	Fresh weight per sample (g)	Dry weight per sample (g)	Fresh weight per grain (mg)	Dry weight per grain (mg)	**Grain water content (mg)**
28	1.92	1.04	68.6	37.1	**31.5**

Calculate the predicted weight per grain (as harvested by combine) in mg at 85% dry matter (i.e. 15% water) using the data calculated above, as follows :-

Predicted weight per grain

$$= 44 + (0.51 \times \text{grain water content}) - (0.24 \times \text{grains/ear}) - (0.01 \times \text{ears/m}^2)$$

For example, in a sample where grain water content is 31.5 mg, grains per ear is 38.1 and ears/m^2 is 636, the predicted weight per grain is:-

$$44 + (0.51 \times 31.5) - (0.24 \times 38.1) - (0 .01 \times 636)$$

$$= 44.6 \text{ mg @ } 15\% \text{ moisture}$$

Grain yield

Yield predictions can also be made from the same data as follows :

Predicted grain yield at 15% moisture

$$= \frac{\text{predicted weight per grain (mg)} \times \text{ears} / \text{m}^2 \times \text{grains} / \text{ear}}{100{,}000}$$

For example, the predicted yield from the example above (using the values of 636 ears/m^2 and 38.1 grains per ear quoted above) would be calculated as :

$$\text{Predicted yield} \;=\; = \frac{44.6 \times 636 \times 38.1}{100{,}000} = 10.8 \text{ t / ha @ 15\% moisture}$$

Grain quality

Significant changes in grain quality occur during ripening which compromise attempts to make satisfactory predictions of grain quality much before the crop is harvested. This applies particularly to Specific Weight and Grain Protein concentration. Taking hand-collected grain samples during ripening, the only satisfactory predictions are of Hagberg falling number.

Hagberg Falling Number

The method relies on collecting ears by hand any time from 40% moisture content of the grain (between grain soft and hard dough stages). The ears are threshed and the grain dried, milled and Hagberg falling number determined.

The Hagberg falling number measured on the hand-collected grain gives an approximately equivalent value to that of the combine-harvested grain. The hand-collected value will be less reliable the earlier the ears are collected, and more reliable the nearer to harvest the ears are collected. The hand-collected value may be very unreliable if severe weather occurs between hand-collecting and combine-harvesting.

Appendix 1 Calculation of accumulated thermal time for forecasting crop progress in wheat

The influences of time and temperature on crop development can be summarised through the concept of 'thermal time'. This is calculated by accumulating daily temperatures, in relation to a base temperature below which the process of interest stops. Different base temperatures are used according to the process being studied. For example, 0°C is used for leaf development but 9°C is often used for grain development. Ideally, the accumulation of temperature should be continuous through the diurnal cycle. However, a simplified calculation, which provides a good estimate, only requires measurements of daily maximum (max) and minimum (min) temperatures. This method is as follows :

> Each day start from condition 1 and, if this condition is not met, go on to next condition, until you have a successful match. Then calculate the daily thermal time as shown on the right of the table. Accumulated thermal time is the sum of the daily values over the period of interest.

Condition	Daily thermal time
1. base less than min	mean - base
2. base less than mean	(max - base) / 2 - (base - min) / 4
3. base less than max	(max - base) / 4
4. max and min less than base	0

Note: mean is calculated as (max + min)/2

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