HGCA

RESEARCH REVIEW No. 18

PHYSIOLOGY IN THE PRODUCTION AND IMPROVEMENT OF CEREALS

JANUARY 1990

Price £15.00

CONTENTS

Chapter 1 **INTRODUCTION**

Chapter 2 **FORM AND FUNCTION OF THE CEREAL PLANT IN THE CROP SITUATION**

Chapter 3 PHYSIOLOGY IN THE DECISION-MAKING PROCESS

Chapter 4 A STRATEGY TO EXPLOIT PHYSIOLOGY IN THE FUTURE : RESEARCH PROPOSALS

H-GCA RESEARCH REVIEW No. 18

PHYSIOLOGY IN THE PRODUCTION AND IMPROVEMENT OF CEREALS

Report of a working group written by
R. SYLVESTER-BRADLEY & R.K. SCOTT
with C.E. Wright as technical secretary

ABSTRACT

Background

1. This report focuses on the context in which decisions are taken during cereal production, and analyses the part that physiology can play in influencing those decisions. Using this approach we have identified the aspects of physiology on which more study has a good chance of improving production.

2. Before writing the report we took evidence, particularly about the views of the end users, and an initial working group of cereal physiologists was augmented with expertise on specific issues where necessary.

3. At the start, we set out the points of physiology on which there was general agreement and which could be seen as pertinent to the production of cereals (Chapter 2). Thus we begin by summarising the physiology relating to roots, leaves, tillers, ears and grains, but only identifying the points on which choices may turn in practice.

4. The most crucial element in the interpretation of cereal physiology is that aging (development) and growth should be perceived as independent processes.

    In analysing the potential for cereal production (Section 3.9, page 92), the extent to which potential is achieved clearly reveals much scope for improvement. The ranges in wheat performance from 6.4 to 8.6 t/ha over seasons in the 1980s and 6.2 to 8.2 t/ha between experimental husbandry farms of ADAS demonstrates the huge influence that environment has over performance. The exceptional performances at all sites in 1984 and over all seasons at Rosemaund EHF can both be attributed at least in part to **slow development with fast growth.** Hence, in making decisions crop by crop we can assert that growers should set their sights on both speeding growth and prolonging development.

5. Unfortunately the current disposition of institutions researching on crops too often allows their scientists to ignore that good decision-making must depend upon the combined forces of deduction and experience; the laboratory-based physiologist assumes that decisions must all be made by deduction whilst the field-based agronomist takes it for granted that all he can do is 'suck it and see'.

6. Our concern in the body of the report has therefore been to juxtapose the approaches of the physiologist and agronomist, so that the agronomist is reminded of the relevant physiology and the physiologist can see the relevant agronomy (Chapter 3). We contend that to provide for profitable decision-taking both influences should be harnessed; agronomic experience sets the limits within which a practice can sensibly be altered and, when relevant agronomic experience is deficient, physiological knowledge provides the means to reason how adjustments should be made.

7. Paradoxically, agronomic experience is becoming increasingly deficient. This is because of the ever more complex constraints under which growers have to work with the ever shrinking support for work on new developments. Thus, the industry will increasingly rely upon knowledge of crop function to decide what course to take at each stage in the production process.

Recommendations

8. Having consulted physiologists worldwide we have considered the requirements of breeders and biotechnologists (Section 3.10, page 103; Section 3.11, page 110) and identified opportunities for research in their support. However, we deliberately avoid saying that new funding of physiology should concentrate on preparing the ground for the genetic manipulator; the excitement that the new prospects have engendered guarantees investment without the assistance of levy funds.

9. That **choice of variety** (Section 3.2, page 28) is of consuming interest to growers is understandable; that this interest finds vent in so many uncoordinated trials is not. There is clear scope for coordinating official and private trials of varieties and amalgamating their results in order to improve the precision of the tests being made and the chance of fitting varieties to circumstances. Inclusion of meaningful agronomic characters when

distinguishing varieties would also help towards this end (Section 4.4.1, page 118).

10. The normal compromises struck in **date and rate of sowing** (Section 3.3, page 34) appear to leave unrealised much potential for growth and yield. With economic and other restrictions on the use of nutrients and pesticides the need is to fully harness any environmental strengths. We see some scope to explore and overcome the physiological obstacles which negate the benefit from intercepting extra light energy and nitrogen through early sowing and denser stands (Section 4.4.2, page 123).

11. With **weed control** (Section 3.5, page 57), stringent use of herbicides is the crucial object. To this end we endorse existing and new work on predicting the weed seed burden, determining weed thresholds for crop loss, determining how either crop or weed may tolerate chemical sprays, and determining the principles governing spray application techniques.

12. Looking in the same way at current strategies for **disease control** (Section 3.6, page 65) there appears scope for improvement through research into disease effects at different stages of crop development, especially on the main yield-forming leaves (Section 4.4.4, page 130), and direct effects of fungicides on crop growth.

13. Environmental repercussions of **nitrogen** (Section 3.4, page 44) now mean that, without the support of industry, more attention will be paid to the nitrogen left behind by cereals than to nitrogen forming the grain. Our view is that, given adequate techniques, cereals could be fertilised more effectively if the aim were to optimise canopy development rather than to supply a 'requirement' guessed at an early stage. Complementary research should focus on work to maximise recovery of applied N, to examine more precisely the relationship between N requirement and yield, to define how N can be used to modify the canopy for maximum crop growth, to develop the potential of foliar applied nitrogen (Section 4.4.3, page 126), and to deduce the optimum pattern of N application to conform with the needs of the malting and baking industries.

14. Both the recognition and restriction of **lodging risk** (Section 3.7, page 73) need close analysis (Section 4.4.5, page 133), particularly with winter barley, because so often lodging is what governs the benefit for both yield and

quality from decisions on nitrogen, as well as early sowing, seed rate change, and crop protection measures.

15. The grower is constantly exhorted to produce **high quality grain** (Section 3.8, page 80), and yet so often quality defies control. We assert (Section 4.4.6, page 135) that there is much existing physiological knowledge which could be used by the grower during those few crucial weeks, providing up-to-the-minute intelligence on which to monitor (and maybe mediate) the success of grain-filling as it unfolds, and focus his expectations. Quick and reliable tests must be developed for use, not only at the point of trade, but on the farm, to determine levels of germination, protein concentration, alpha-amylase and grain size characteristics.

16. It is woeful and perplexing that the industry can reach the penultimate stage in the long production process with little advance knowledge of its success. Intelligence for merchants, traders, processors and end users, let alone growers, of both the volume and the quality of grain that they are to handle is surprisingly weak until harvest is under way. It is high time that cereal physiologists addressed this conundrum (Section 4.4.7, page 138), not with the promise of perfect foresight, but to state the narrowing probabilities as growth proceeds.

17. Underlying all assertions in our Report rests a recurring reference to 'the model'. It is both undesirable and unfortunate that 'modelling' has been allowed to assume a mystique which alienates the layman (Section 4.2, page 114). Without doubt we are all modellers in our different ways; our thoughts on crops **are** models and modelling is at the root of communication in crop science. We therefore make no apology for homing in on models as the cornerstone of crop improvement programmes. We do not claim that they offer quick solutions, or a direct route to the laws of nature, but we do assert that, for what has been allowed to remain a most inexact science, recorded models can confer a common and beneficial discipline and provide that all-important access to physiological know-how.

18. With the many opportunities for physiological research identified in this summary and those others given in the full report (there is a list on page 116) we recognise the need to devise a strategy which will most effectively exploit resources limited in terms of finances and skilled staff. There are some projects which are not appropriate for extensive collaborative teams,

for instance the study of the origins of high amylase grain or of predicting dormancy. There are others for which a multidisciplinary approach seems essential, both for economy and synergy. An example is that in devising a technology for uptake of nitrogen through leaves, parts should obviously be played by the spray engineers, plant biochemists, formulation chemists and soil scientists, as well as by physiologists who can determine the N needed for growth.

19. However, in developing solutions to its fundamental problems, there is another synergism to be found, through harnessing more disparate interests in the industry. It becomes clear that **it would be of benefit if the industry were to become involved in the execution of research projects.** We therefore advocate that concerted programmes are constructed which allow cross communication through the grower-adviser-supplier-journalist-scientist chain of intelligence by forging specific partnerships which hold a focus on the problems in practice. We have looked at research needs, identifying areas where a 'vertical' collaborative stratagem could be used to good effect.

For instance:

a) Anticipation of crop performance during growth depends on the interest of growers and traders, and rapid communication through journalists, as well as the work of physiologists.

b) When analysing elements of the risk of lodging, observations must be garnered not only from agronomic experiments, but from specialists in structures, growers and advisers.

c) The integration of concepts of how leaf diseases affect yield needs epidemiologists, physiologists and meteorologists and holds a close interest for fungicide manufacturers.

20. If the admirable integration that the Authority has established on a horizontal plane between researchers were complemented by such a **vertical integration linking science through physiology to practice**, benefits would accrue to the industry on a scale far exceeding those which come from piecemeal funding of isolated projects.

This review, completed in January 1990 and with 156 pages in the full article, was funded by the HOME-GROWN CEREALS AUTHORITY, Hamlyn House, Highgate Hill, London N19 5PR.

REVIEW WORKING GROUP

Chairman	R.K. Scott	Professor of Agriculture and Horticulture, University of Nottingham.
Members	E.J. Allen	Director, Cambridge University Farms, Cambridge University.
	R.W. Clare	Director, Rosemaund Experimental Husbandry Farm, Hereford.
	W. Day	Institute of Engineering, Silsoe (formerly of Rothamsted Experimental Station).
	E.J. Evans	Department of Agriculture, University of Newcastle-upon-Tyne.
	B.J. Marshall	Scottish Crops Research Institute, Dundee, Scotland.
	J.A. McWha	Professor of Agricultural Botany, Queen's University, Belfast.
	G.F.J. Milford	Rothamsted Experimental Station, Harpenden.
	J. Moorby	Professor of Horticulture, Wye College, Kent.
	R. Sylvester-Bradley	Soil Science Department, ADAS, Cambridge.
Co-opted Experts	R.D. Child	Institute of Arable Crops Research, Long Ashton, Bristol.
	R.J. Cook	Plant Pathology Department, ADAS, Leeds.
	R.P. Ellis	Scottish Crops Research Institute, Dundee, Scotland.
	P.S. Kettlewell	Harper Adams Agricultural College, Newport, Shropshire.
	D. Royle	Institute of Arable Crops Research, Long Ashton, Bristol.
	D.T. Stokes	School of Agriculture, University of Nottingham.
	D.R. Tottman	Formerly Institute of Arable Crops Research, Broom's Bourne Experimental Station, Suffolk.
Technical Secretary	C.E. Wright	Formerly Chief Scientific Officer, Department of Agriculture for N. Ireland.

Acknowledgements

The Working Group acknowledge the excellent secretarial support provided by Mrs M. Secker and thank Mr. J. Whitehead of Hathern, Leicestershire for producing the typescript.

Chapter 1

INTRODUCTION

1.1 THE CONTEXT

1.1.1 General

More than ever before the cereal industry is faced with conflicting problems and pressures:

a) The large advance in yield which heralded the eighties could well be followed by as long a passive period as was seen from the fifties. Meanwhile we are faced with over production in the EEC and a fickle background of politics and climate in the world beyond.

b) There is an increasing volatility amongst consumers in their demand for cereal products and growers are being coerced in trade to meet ever higher standards of quality over which their control remains elusive. Escalating costs of production have been accompanied by veiled threats or meagre inducements over the use of synthetic chemicals.

c) A requirement for industry to fund and manage research and development has been imposed, coincident with a need to weigh up promises of the new 'biotechnologists', forthright advice from the commercial consultants, and puzzling portents of ever warmer weather.

The challenges to the industry are thus complex; most must be met with solutions through technology. Trial and error which have so often brought improved production levels in the past appear to hold less promise for the future. Not only is the industry having to reconcile a wider range of objectives during production but it needs increasingly to justify its decisions and activities. It must therefore adopt a well reasoned stance in most departments if it is to maintain the confidence of the public, and it will thus increasingly refer to and depend upon the relevant sciences.

Thus the challenge to science is to ensure its relevance and accessibility to the industry and, being the science of function, physiology must have a central role to play for cereals. It is the purpose of this review to explain and demonstrate this clear assertion.

1.1.2 Achievements of physiology

Many serious agricultural problems have proved amenable to help from studies of plant physiology over the years; of the numerous examples, one or two will suffice as background.

The recognition and amelioration by plant physiologists of mineral deficiencies and imbalances, involving both macro-nutrients (e.g. phosphorus, potassium, sulphur) and micro-nutrients (e.g. manganese, copper, molybdenum, chlorine) has had an enormous impact on agriculture throughout the world, transforming the potential of many areas. Identification of plant requirements and the limiting deficiency led to reliable, effective and economic treatments.

The isolation of plant growth substances, including auxins and gibberellins, led not only to predictable uses such as promotion of rooting in cuttings, induction of flowering, inhibition of sprouting, dormancy breaking, improved malting and maintenance of vigour in seeds but also opened the way to the whole realm of hormone weed control through selective herbicides. Importantly, this discovery simplified the major husbandry area of weed control while increasing the flexibility and timeliness of farm operations and making possible more intensive multiple cropping.

Plant physiology has assisted also with the formulation of ideotypes and has provided techniques for plant breeders. A recent example is plant tissue culture which, originally considered as unlikely to have practical application, now finds itself a cornerstone of the revolution in biotechnology and genetic engineering.

For cereals in particular, physiologists have elucidated the role of individual organs (stems, awns, flag leaf) and characteristics such as leaf angle, leaf area and leaf duration in controlling yield in parallel with a more fundamental understanding of such processes as light interception, photosynthesis, assimilate partitioning, respiration, translocation and transpiration.

1.1.3 The state of physiology

We find that physiologists approach their science in contrasting ways. For some it is an academic pursuit in which unravelling the ways of nature provides a central fascination, unattended by any conscious need to apply the findings. That such approaches are applied to economically important species is often a convenience rather than a necessity.

At another level, physiological data may be collected merely through a desire to confer an aura of scientific decorum upon a production practice for which credibility is sought.

Somewhere in between are those who strive to elicit the essential missing information and then piece together their disparate studies and experiences into a rounded whole so that they can profit by the careful reasoning which this allows.

At the outset it has therefore proved essential to reconcile the diverse stances of physiologists and extract the points on which there was a general consensus and which could be seen as pertinent to the production of cereals.

For various reasons, the number of physiologists involved in crop improvement programmes appears to have decreased year by year. It has to be recognised that physiologists have sometimes encouraged their sceptics; there are even physiologists who would submit that all they can offer the producer is explanations in hindsight of already proven practices. Any current indifference for physiology may to some extent be a reflection of such complacent introspection in much physiological research.

However, mistrust of physiology may also have resulted from the superficial physiological justification given by a few high profile protagonists for gimmicky or questionable new practices. Growers have sometimes been presented with an impenetrable physiological fog or, in ignorance, have been led into an over-expectant view of physiology. For example, the notions do not bear close scrutiny that a) autumn-sown cereal crops can be consistently manipulated to advantage by use of chlormequat in autumn, or b) their stage of development should be the critical factor in determining timing of nitrogen dressings in spring. The publicity given to such ill-founded ideas only serves to bemuse or, worse, delude the industry and eventually attracts general distrust for physiology's utility.

Nevertheless agronomists and breeders do inevitably seek to explain yield improvement in terms of crop function, and it is our contention that physiology is thus the medium through which progress in breeding and changing husbandry practices is rationalised. The potential exists to achieve this, but important opportunities can be missed if physiologists are not sufficiently involved and committed to crop improvement programmes.

For example — in the 1970s, the UK industry was confronted with having to decide the applicability, if any, of the 'whole systems' developed for winter wheat in Belgium and N. Germany. Each system was claimed to dovetail with a particular environment and market outlet, derived from a degree of understanding of crop growth and development in relation to yield.

The Laloux system aimed to achieve consistent performance in the Belgian climate (which is more variable than that in continental Schleswig Holstein) with moderate seed rates and with low nitrogen, growth regulator and fungicide usage. Physiologically the system relied on sowing few seeds and the stimulation of each plant to produce many tillers by the application of autumn nitrogen.

The Schleswig Holstein system, targeted to produce the maximum yield of high N grain, involving 50% greater plant densities and late application of nitrogen with more liberal treatment with growth regulators, herbicides and fungicides timed on calendar date, depended upon combining high seed rates and no autumn nitrogen to produce many plants and few tillers on each.

Tested in the UK, neither system consistently outyielded the other, nor the locally recommended systems. Lessons learned from this exercise were:

(a) similar yields may be achieved by different routes but not always at the same cost;

(b) systems comparisons in which many factors are confounded are not amenable to analysis, **but most importantly**

(c) adequate records of plant growth and developmental stages are necessary to test explanations of crop performance and deduce a way ahead.

There are many such examples where progress with husbandry depends on an explanation of its effect on yield. To unravel the effects, it is crucial to understand how yields were formed, by monitoring the way that crop growth proceeded.

Ideally, it is desirable to measure the success with which a crop absorbs the energy in sunlight and converts it to biomass at many points throughout its life in order to identify points (and thence causes) at which the potential for growth was not realised. However, the resources required for such intensive monitoring are not normally available. The crop at harvest presents a useful record of its life history in that the components of grain yield (numbers of ears, grains/ear, weight/grain) have been determined at different times and an assessment of their size can indicate the success of successive phases in the crop's development. Direct inferences can be misleading because interdependence between the components masks direct effects on their relative sizes. A few additional measurements of growth often prove necessary to adequately explain crop achievement.

1.1.4 The challenge for physiology

Many problems are facing farmers and ancillary industries now and need physiological explanations before suitable solutions can be developed and rationalised. Some crucial current questions are:

(a) Can we improve our control and prediction of yield and quality to maintain and increase our competitive edge over producers in other countries?

(b) Can we do this with demonstrably minimised risks to the environment?

(c) Given the possible scenarios —

i) that grain price falls to the level of the world market
ii) that there is legislation to restrict N use or
iii) restrict pesticide use or
iv) restrict crops to spring sowing

can we now define rapidly the limits of uncertainty and focus on the most advantageous questions to ask and investigational programmes to set up?

(d) Have we the conceptual framework to introduce end-products or direct the activities of those involved in the burgeoning and highly costly areas of genetic manipulation and biotechnology?

(e) Can we predict how UK cereal growing would be affected if, as the core scenario predicts, the carbon dioxide concentration in the atmosphere increases and that the south, central and eastern parts of England become drier and more semi-Mediterranean and the north of England and Scotland and N. Ireland warmer but not necessarily drier?

These and other challenges require a breadth of knowledge associated with the understanding of the responses of crops to soil conditions and weather and the interrelationships with crop husbandry.

In compiling this report we therefore focus on the context in which production decisions are taken and analyse the part that physiology can play in influencing those decisions in the mind of the producer who has a sound, well reasoned comprehension of the system. In this way we feel able to identify the aspects of physiology which are of importance now and those on which more study has a good chance of improving production.

The best way to overcome the shortage of physiologists will be to have a number of collaborative projects that exploit the complementary expertise and facilities of those that remain. It will then be possible rapidly to build and develop co-ordinated programmes in order to meet newly adopted challenges or restrictions in the industry.

The government proposal for growers to fund more of the research classified as 'near market' and to reduce its own funding of R and D could result in a polarisation of future activity. On the one hand, there would be that undertaken with direct farming and industry funding, perhaps with emphasis on immediate and local application. On the other hand, the research institutes and universities would pursue research that is much more fundamental and long term.

It is essential that interest in the middle ground, part of which is to understand and predict plant growth and development in the crop, is not lost. Without considerable attention to, and activity in, the middle ground and a strong interface between farming and non-near market investigations, the whole R and D structure could be rendered ineffective.

1.2 THE APPROACH

In reviewing the value of future physiological work on cereals for the Home-Grown Cereals Authority, our aims can be summarised as follows:

(a) to summarise key concepts of cereal form and function in the crop situation (Chapter 2)

(b) to consider the place of physiological knowledge in the commercial decision making process and to identify the future potential for physiological studies related to individual decisions (Chapter 3)

(c) to explore the possibilities for co-ordinated and collaborative submissions for multi-disciplinary projects identified as worthwhile for the industries (Chapter 4).

In the course of considering the material for the report a working group convened and supporting papers were prepared on:

Form and function	E Evans, G Milford and J Moorby
Varietal choice	R Ellis, B Marshall, C Wright and K Scott
Nitrogen	R Sylvester-Bradley
Sowing	K Scott, B Marshall, R Ellis and R Clare
Weed control	D Tottman
Disease control	R Clare, D Royle and R Cook
Plant growth regulation	R Clare, R Child, D Stokes and R Sylvester-Bradley
Control of quality	P Kettlewell
Breeding	C Wright and K Scott
Biotechnology	J McWha and J Moorby

Modelling and transmission of information	W Day and E Allen
Experimental strategy and integration of research proposals	R Sylvester-Bradley and K Scott

To support the review, particularly the sections on Breeding and Biotechnology, physiologists prominent on a world scale were consulted by post (see Appendix A).

Mr B Read and Dr J W Woodward provided submissions to the working group on the quality requirements of the industry. K Scott, R Sylvester-Bradley and C Wright visited the Flour Milling and Baking Research Association.

The report was written for presentation to the H-GCA by R Sylvester-Bradley and K Scott with C Wright as technical secretary.

The main emphasis in the report is given to winter wheat with frequent reference to winter barley, paying attention, as appropriate, to spring sown crops and minor cereals.

To include all references consulted would add very considerably and not usefully to the length of the report and detract from its readability; only selected references are cited in the bibliography.

Chapter 2

FORM AND FUNCTION OF THE CEREAL PLANT IN THE CROP SITUATION

2.1 INTRODUCTION

At the outset it was decided to present a series of succinct key points, unembroidered by provisos, that traces the life cycle of the cereal plant through the production of roots and leaves, tillering, ear development, flowering and grain growth to show how yield determination is now perceived.

- From sowing until harvest, crop weight may increase one hundredfold (Fig I.b) whilst the plants progress through a sequence of well-defined vegetative and floral developmental stages (Fig I.a) that lead to the production of leaves, tillers and floral structures of the ears (Fig I.c) which eventually give rise to the grains (Fig I.d).

- Although sometimes used synonymously, the terms crop **growth** and crop **development** refer to distinct physiological processes that progress alongside each other, but sometimes at different and unrelated rates because they are affected differently by variety, environmental conditions and aspects of husbandry. Growth refers to an increase in size or weight (Fig I.b); development refers to the series of changes in plant form, e.g. onset of tillering, stem extension, flowering, through which plants within the crop pass from sowing to maturity (Fig I.a). A crop that takes a long time from sowing to maturity is said to develop slowly.

- The rate at which a crop grows and the eventual weight of all its tissues (roots, leaves, stems and ears) directly relates to the amount of energy from sunlight which the leaves and other green tissues absorb (Fig I.b); the key processes are those controlling the expansion and persistence of green leaf area — the major influence governing the amount of sunlight intercepted. Adequate supplies of nutrients and water (and freedom from root and leaf diseases) are the factors exerting control of growth.

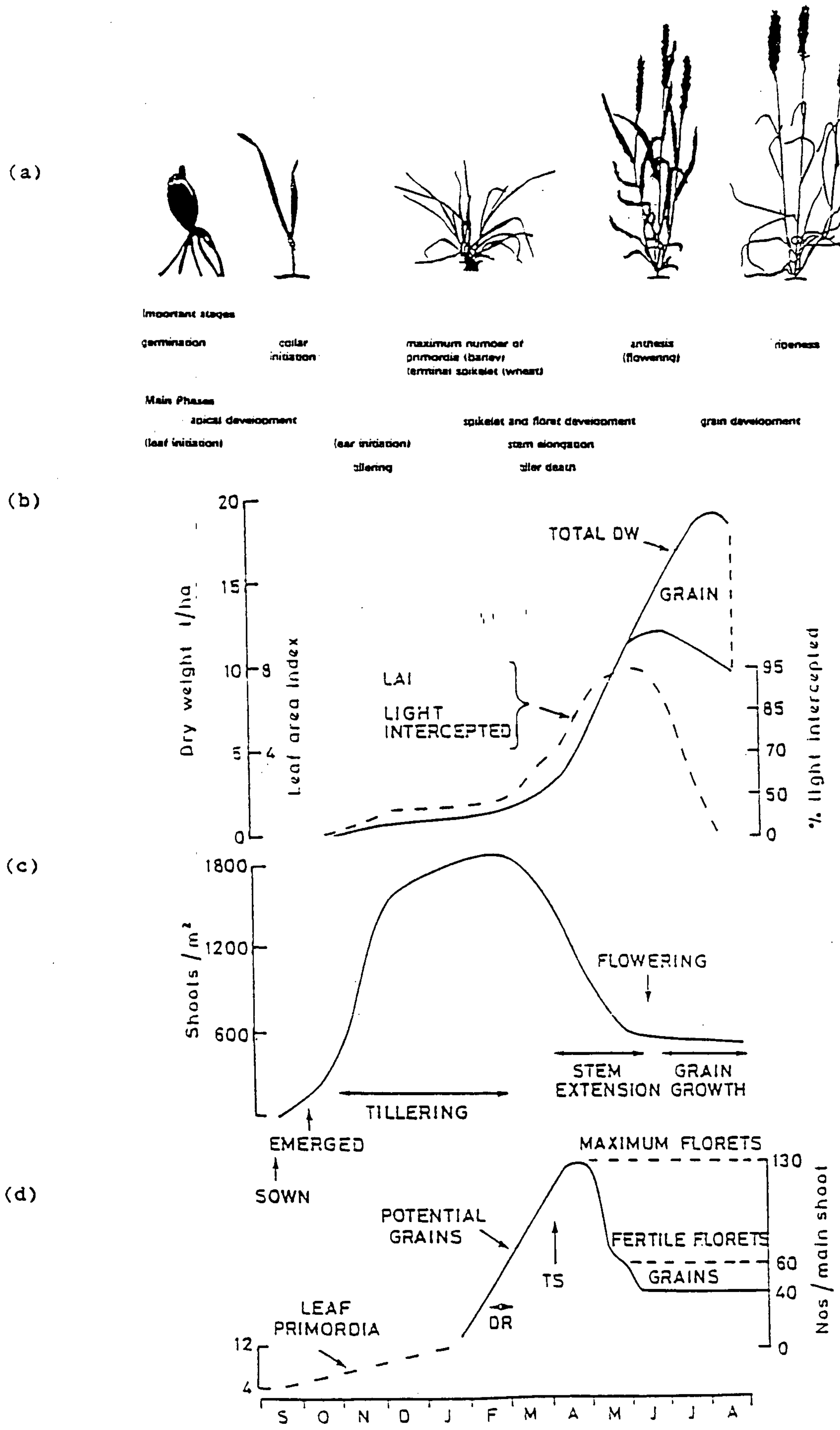

Figure 1. The growth and development of the winter wheat crop. (DR = double ridge, TS = terminal spikelet stages)

◇ The efficiency with which cereals convert absorbed energy to plant material averages 1.9-2.2 g dry matter/MJ. While efficiency decreases as green area is lost during the final stages of growth, it is sensitive only to some diseases and extreme nitrogen deficiency or drought conditions.

◇ Phases of growth are defined by a sequence of developmental events. The success in each phase determines the size of a yield component:

(a) tillering begins as the fourth leaf emerges and ends about the time that the apex forms double ridges. Tillers start to die as stem extension begins. Tillering influences the number of ears produced (Fig I.c).

(b) ear development begins with double ridge formation and is completed at flowering. This phase determines ear sizes and number of grains/ear (Fig I.d).

(c) grain growth begins at flowering and lasts a fixed interval of thermal time (the sum of daily mean temperatures above a base). This determines the size of individual grains (Fig I.b).

◇ These developmental events are driven largely by temperature and the seasonal cycle of daylengths. Because of the influence of temperature, the calendar dates by which crops reach particular developmental stages can change considerably from season to season and site to site.

◇ The size of the different components of yield depends on the balance between growth and development during the phase when the particular component is being determined. The **timing** of the initiation and formation of vegetative and reproductive organs is generally insensitive to the growth controlling factors — nutrition, water supply and disease — but the subsequent growth and survival of those structures are influenced by the amount of assimilate available. Large numbers of tillers per plant or grains per ear result when prolific growth occurs during the critical phase of the developmental time scale. Prolonged development (usually occasioned by cool conditions), though accompanied by slower growth, indirectly leads to more growth per unit of development.

◇ Of equal importance to the growth and developmental processes that determine the attributes of yield are those that govern the deposition of storage compounds in the grain, and so influence quality characteristics.

2.2 THE GROWTH OF LEAVES

Probably the most important principle that physiologists have established is that, in the crop situation, dry matter accumulation and crop yields are determined more by how much light the crop can capture by extending and maintaining its leaf surface than by the intrinsic photosynthetic activity of the leaves themselves. For instance, large increases can be induced per unit leaf area in the amounts of photosynthetic machinery (chlorophyll, carbon-fixing enzymes, etc.), using nitrogen, without effect on the measured rates of photosynthesis.

◇ In general, fast crop growth requires —

(a) the leaf area to expand rapidly and be kept healthy (eliminating disease and mineral deficiencies) so that all available sunlight is intercepted and

(b) adequate water supplies to prevent water stress decreasing the efficiency of conversion of the intercepted sunlight.

Heavy crops result when these conditions are maintained for a long time.

◇ In the early stages of crop growth, before there is a closed leaf canopy, growth rates depend on how quickly the leaf surface expands. With adequate water and nitrogen, leaf extension, i.e. the extension of the lamina from the sheath of the previous leaf, is directly proportional to temperature over the range 0-25°C. During periods of water stress or N shortage, leaf extension rates are slower than those predicted from temperature response curves.

◇ The leaf orientation of a variety affects light interception. For varieties with similar morphology to Huntsman wheat and Proctor barley, more than 5 ha of leaves for every 1 ha of field, i.e. a Leaf Area Index (LAI) of 5 is needed to intercept 90% of incident radiation.

◇ The number of leaves on the main shoot ranges from 9 to 15 in Avalon winter wheat and from 8 to 17 in Igri winter barley.

- Wheat leaves tend to be larger than barley leaves. Flag leaves and penultimate leaves of wheat are usually larger than those formed earlier, whereas in barley the leaves midway along the stem tend to be the largest. Leaves that emerge at the same time, whether on the main stem or on tillers, grow to a similar size.

- Nitrogen does not change the number of leaves on an individual main shoot or tiller or affect leaf appearance rate. It changes expansion rate and leaf size.

- All the leaves are produced by the time the ears emerge. From this point onwards, the persistence of green leaf area is then critical in determining crop growth rate. Leaves stay green longer in cool conditions provided that the crop has received adequate nitrogen and is kept free from drought and disease.

- Typically, photosynthetic activity of individual leaves rapidly increases to a maximum at or before full leaf area expansion, followed by a progressive decline with time. This decline in photosynthetic activity is associated with nitrogen movement out of the leaf. For the canopy, a more or less constant rate of net photosynthesis is maintained as long as the continued production of new leaves compensates for the senescence of older ones.

2.3 THE GROWTH OF ROOTS

The cereal root system consists usually of six 'seminal' roots growing directly from the seed and a variable number of adventitious roots (from nodes at the bases of the main stem and tillers) that do not begin to extend until the tillers appear.

- During the winter months, the weight, length and depth of the root system of autumn sown cereals increase steadily, with a mean extension rate of 5-6 mm/day in winter increasing to 18 mm/day in the spring. The maximum depth of rooting for winter wheat and spring barley can be about 2 m and the weight, which occurs at the time of anthesis, is about 1 t/ha. After anthesis, the total weight and length of live roots decrease, though root growth in the deeper layers may continue.

- Most of the roots are to be found in the top 50 cm of the soil where mineral nutrient concentrations are high. However, the deeper roots are important in times of moisture shortage when water in the upper layers of the soil is exhausted.

- Cereal roots appear to be extremely efficient at acquiring nutrients from dilute sources within the soil. At least until flowering, it is important that roots have the capacity to exploit new sources of nutrients within the soil volume.

- At times of maximum growth rate (i.e. May-July), cereal crops extract on average about 3.4 mm (0.14 in) of water per day (the actual rate is largely determined by weather conditions) in order to produce around 0.18 t/ha of dry matter and require an average uptake of about 3 kg/ha per day of both nitrogen and potassium.

- The majority of uptake of nutrients by cereals has generally occurred by anthesis and in a crop yielding 10 t grain/ha, the total uptake soon after anthesis can be of the order of 250 kg/ha of nitrogen, 30 kg/ha of phosphorus and 310 kg/ha of potassium and almost half the latter will have been lost from the shoot back to the soil by maturity.

- September sown crops of winter wheat produce a larger and more deeply penetrating rooting system than October sown crops.

- As with other attributes of crop growth and development, thermal time provides a basis for describing root growth from season to season.
- It has been estimated that about 3.5% of the root system dies and has to be replaced each day just to maintain the current system.
- The average extension rate of the individual root is about 1 cm per day. The total root length in mature wheat crops is about 30 km/m^2.

2.4 TILLERING

There are three components of final yield — ear number, grain number/ear and individual grain weight — and since the number of ears/unit area can be critically low, the timing of production, the size and the survival of tillers can influence final grain yield and its stability.

- ◇ Wheat crops need to maintain to harvest a minimum of around 400 ears/m^2 and barley 600-800 ears/m^2 for high yield; below this, the other yield components may fail to compensate.
- ◇ Each plant has the capacity to produce many tillers (which is an insurance against pest attack and adverse conditions) but by harvest many will have died, leaving a main stem and one to three bearing tillers. In winter wheat, grains on the main stem and first-formed tiller may account for as much as 80% of grain yield, while the grains on the main stem and three primary tillers account for 80% of the grain yield in spring barley and up to 95% in winter barley.
- ◇ Tillers are first visible as buds in the axils of the lower leaves. Every leaf has a tiller bud associated with it but at typical plant densities 5-6 tiller buds grow and emerge. Each bud receives assimilate from a particular source leaf; the one above the leaf in the axil of which it lies. Tillers emerge in an order and at a time related to the sequence of leaf appearance on the parent stem. The coleoptile tiller appears when the third leaf is unfolding; the tiller in the axil of the first leaf when the fourth leaf is unfolding, and so on.
- ◇ Tiller bud extension and tiller appearance cease earlier with winter wheat than with spring barley. In wheat, they stop shortly after ear development starts and well before stem extension begins. For spring barley, they stop as stem extension begins. Tillers have fewer leaves than the main stem (typically 8-9 vs 12 for winter wheat and 5-6 vs 9 for spring barley).
- ◇ For wheat at typical densities between one and four tillers/plant survive (the tillers from the axils of leaves 1 and 2 are most likely to bear ears); many die before flowering, e.g. the proportion of tillers produced by Maris Huntsman grown at Sutton Bonington that produced ears ranged from 10-20%.

- Tiller survival is encouraged by conditions that favour a large amount of dry matter production around the time of peak tillering. Cool, bright weather has this effect as low temperatures slow development but do not affect crop photosynthetic rate while light intensity increases crop photosynthesis proportionately, with development rate unaffected.

- Tiller production and survival are markedly affected by nitrogen fertilisation. Early spring N can lead to excess tiller production, water usage, etiolation and lodging and, particularly in barley, a microclimate conducive to disease infection. Later N is important in maintaining tillers in early summer.

- Late-formed tillers rarely produce grain unless the main stems and tillers are damaged. Although they form part of the leaf canopy, they do not contribute significant amounts of carbon assimilates to the productive parts of the plant during their lifetime and contribute no carbon and only half of their nitrogen as they senesce. These small, transient tillers have little significance in terms of grain yield but they are an insurance against loss of early formed tillers.

- In barley crops where grain filling has been curtailed by drought or lodging but good growing conditions ensue, new 'secondary' tillers may be initiated which inhibit harvest of the first formed grain but sometimes provide additional late yield.

2.5 EAR DEVELOPMENT

The grain producing organs are initiated and undergo their early development before and during rapid stem extension and therefore compete with the stems for the available supplies of carbon and mineral nutrients. There is some evidence in spring barley that inhibition of stem extension may increase grain yield.

2.5.1 Winter wheat

In an October sown crop, spikelet initiation starts when 4 leaves are unfolded; after 4 more leaves have unfolded, spikelet initiation stops and floret formation gets under way. With September/October sowing and warm temperatures, spikelet initiation may start in December but with later sowings and cold weather it may be delayed until the end of March. With late November and December sowings, the mainstems initiate fewer leaves and the various stages of ear development occur at earlier leaf unfolding stages.

- The need for a period of low temperature (vernalisation) to stimulate ear development of winter wheats is an important factor in winter hardiness. Spring wheats sown in early autumn will develop rapidly in mild temperatures and relatively long days and may have an advanced floral apex by winter, so being more susceptible to frost damage. Apices become vulnerable to frost when stem elongation begins. If a true winter type is sown in spring, when response to low temperature is insufficient to satisfy vernalisation requirements, plants will have more leaves and maturity will be delayed.

- Spikelets are initiated faster than leaves. For instance, under similar temperature conditions (6-7°C), Maris Huntsman produces one leaf every eight days and one spikelet every three days. In wheat, the initiation of spikelets ceases with the formation of the terminal spikelet; no terminal spikelet is formed in barley. The first spikelets to initiate florets are the larger ones just below the centre of the ear.

- For wheat, the average number of spikelets/ear changes little over a wide range of conditions; thus differences in grain number/ear are mainly attributable to differences in floret formation and survival.

- In wheat, each spikelet produces about five florets; in barley each spikelet produces only one floret. Florets towards the tip of the wheat spikelet or florets at the distal end of the barley ear appear to have poorly developed vascular systems. This may account for the low survival rate of these florets.

- A plentiful supply of assimilates and nutrients is required for floret survival and subsequent grain production.

2.5.2 Barley

Two main-stem leaves on spring barley have unfolded when spikelet primordia start to be laid down at the apex. On the main stem ear 35-45 spikelets are initiated, of which 50% usually die.

- Warm days accelerate the rate of spikelet production, so that the period of production is shorter: thus final maximum spikelet numbers are similar for early and late sowings.

- The largest spikelets occur just below the centre of the ear and show the first signs of floret differentiation.

- Differences in grain number/ear are attributable to abortion of spikelets principally at the uppermost end of the ear.

- Usually about 95% of spikelets that are fertile at anthesis bear a grain at harvest.

2.6 FLOWERING

The net effect of the interplay between temperature and day length on development is that, practically regardless of the weather, crops sown as far as six months apart at a site reach anthesis within a 2-3 week period.

- Of the five florets initiated in each wheat spikelet two and occasionally three normally survive to form grains. Wheat varieties are mostly open-flowering.

- In two-row barley varieties only the median spikelet is fertile. In six row types all three spikelets at each node are fertile. Winter varieties of barley are mainly open-flowering but flowering in spring types tends to be closed.

- Anthesis lasts only a few minutes during which the filaments of the stamens grow to several times their initial length (in open flowering varieties this pushes apart the lemma and palea) and two pores open at the tip of each anther releasing the pollen.

- Anthesis starts in all ears in a crop, whether on mainstem or tillers, within a few days. The middle spikelets in the ear are the first to flower and it is about five days before the bottom and top spikelets have completed anthesis.

- Ineffective pollination has seldom been seen as a cause of poor performance. Winter barley crops sometimes show fully formed but 'blind' spikelets at random positions in the ear which must be attributed to failure at or shortly after anthesis. The wheat variety Moulin failed to yield satisfactorily following its release in 1986, and this was attributed to inadequate pollen production.

2.7 GRAIN GROWTH

The initial phase of grain growth lasts 2-3 weeks from anthesis, during which there is intensive cell division. The numbers of cells and starch grains (amyloplasts) in the endosperm are determined during this period and the potential size of the grain is set. This is followed by a period of apparently constant growth in which there is expansion of endosperm cells and intensive synthesis and storage of starch in their amyloplasts. This phase of grain growth tends to be shorter in barley (25-30 days) than in wheat (40-45 days). The final stage of grain growth, maturation, is one of decreasing growth and hydration. Grain water content is lost slowly to 40% when growth ceases and then grains dry more suddenly to around 15%. It is not clear to what extent the decrease in water is the cause or a consequence of cessation of grain growth.

- In both wheat and barley, the heaviest grains are formed near the centre of the ear where floret development first starts. In wheat, the heaviest grains are found in the first and second florets, while grains in more distal florets are increasingly lighter. If assimilate supplies are short (e.g. due to disease or drought) all grains are affected equally.

- High temperatures shorten the period of grain growth proportionately more than they increase the rate of growth.

- The sources of assimilate for grain growth differ in wheat and barley. Ear photosynthesis contributes little (ca. 10%) in wheat, but the presence of awns in barley or awned wheat can double or more the rates of net photosynthesis of ears and their contribution to grain growth. The benefit from awns is usually more apparent in dry climates than wet ones. Under normal conditions, the major source of assimilates for the developing grain in both barley and wheat are the upper green parts of the plants including the flag leaves, though the flag leaf is relatively unimportant in barley, being quite small. In wheat, genotype differences in flag leaf longevity have been reported, together with increased rates of crop photosynthesis in varieties with erect flag leaves under high irradiance. This is of less importance in temperate areas. The benefit of erect flag leaves may be larger in crops with extensive leaf areas resulting from increased applications of nitrogen.

- Under more extreme conditions of increased temperature, nitrogen deficiency and water stress, there is greater use of reserves of carbohydrates created before flowering and stored in the stems. Up to half the weight of grains can come from such remobilisation.

- Nitrogen enters the ear in the form of amino acids and amides. Following interconversion, these are synthesised into the various forms of protein within the grain itself. In mature grain approximately 20% of the protein is contained in the germ and the remaining 80% in the endosperm. The percentage of nitrogen varies with the position of grain in the ear; upper spikelet grains and grains in the more distal florets have lower nitrogen contents. Under conditions where nitrogen uptake continues throughout crop growth, the nitrogen and protein content of the grains continues to increase linearly until near maturity and more than half of the grain protein may derive from nitrogen taken up during the period of grain filling. Application of nitrogen fertilisers, especially late, increases grain protein substantially.

- Under conditions where there is little nitrogen uptake during grain growth, much of the protein in the grain is derived by remobilisation from leaves and stems. About 75% of the plant's nitrogen taken up before anthesis may be remobilised in this way.

- There is no simple relationship between yield and the percentage nitrogen in the grain.

- Wheat has no obvious period of dormancy and in wet harvests is more prone to pre-germination than barley. This can lead to a low Hagberg Falling Number and poor baking quality from the flour. While some dormancy is desirable to protect from pre-germination in wet harvests, prolonged dormancy of some barley varieties, e.g. Triumph, can present problems for malting, especially when grown in the north.

2.8 HARVEST INDEX

Modern wheat varieties produce more grain than of older varieties but about the same biomass, and so their harvest index (the fraction of total biomass represented by the grain) is greater. The increase in harvest index has been associated with the search for shorter, stiffer straw to withstand lodging and/or direct selection for high grain yield.

- Because of the need to support the ear physically and to provide it with photosynthate from the leaf canopy, there must be an upper limit to cereal crop harvest indices estimated at 0.6-0.65. It seems unlikely that the rate of increase in yield of cereals can be maintained much longer by increases in harvest index and breeding programmes may have to aim at increasing dry matter production.

- Increased grain yields and harvest indices of modern varieties directly correlate with decreased stem weight. Leaf weight and leaf area are not diminished.

- Associated with less stem, but not necessarily as a direct consequence, some short varieties have more grains/ear than taller ones due not to increased spikelet and floret production but to improved floret survival.

- A typical harvest index range for the same variety of wheat in one season is 0.42-0.56; for a crop with a total biomass of 15 t/ha this represents a range in grain yield from 6.3-8.4 t/ha.

- The range of harvest indices is greater in barley than in wheat.

- Generally, when crops lodge, grain filling is restricted more than stem growth, producing a lower harvest index.

- Although grain yield has been improved by improving harvest index there is no clear relationship between total yield and harvest index. This is to be expected; total biomass is the end product of a series of complex events over 9-10 months while grain growth is completed within about 6 weeks. In general, crops that grow well up until flowering have many grains. If small amounts of dry matter were produced post-flowering and there was no retranslocation, many small grains and low harvest index would result. The reverse would also apply; limited dry matter accumulation pre-flowering would be associated with few grains which, with favourable conditions for growth post-flowering, would become very large giving a high harvest index. In practice, crops do not always behave in this way even in extreme conditions because retranslocation usually occurs to some degree, generally more so when the supply of current assimilates is restricted from flowering onwards.

- There is no close and consistent relationship between harvest index and any particular yield component.
- No single yield component predominates in determining yield. However, the combined value of ears/m^2 and grains/ear (grains/unit field area) is usually positively correlated with yield. This correlation can sometimes be broken by changes in mean weight/grain that are larger for winter wheat than for spring barley.

Chapter 3

PHYSIOLOGY IN THE DECISION-MAKING PROCESS

3.1 INTRODUCTION

The challenge for growers is to keep in mind that, whilst using resources most efficiently, they must harmonise the factors over which they have some control with the effects of factors over which they have none. At the same time, they must acknowledge the numerous agronomic constraints which only become apparent as a result of experience.

Unfortunately the current disposition of institutions now researching on cereal crops too often allows the scientists to ignore that good decision-making must depend on the combined forces of deduction and experience; the laboratory-based physiologist assumes that it must all be done by deduction whilst the field-based agronomist takes it for granted that all he can do is 'suck it and see'.

Our concern in this central chapter of the report has therefore been to juxtapose the two approaches, so that the agronomist is reminded of the relevant physiology and the physiologist can see the relevant agronomy. We contend that to provide for profitable decision-taking both influences should be harnessed; agronomic experience sets the limits within which a practice can sensibly be altered and when agronomic experience is lacking, physiological knowledge provides the means to reason how adjustments should be made.

Of topics important to growers, seven have been considered under the following headings:

varietal choice
sowing
nitrogen
weed control
disease control
plant growth regulation and
control of quality

It is recognised that these are not comprehensive, omitting for example,

cultivations
fertilisers other than nitrogen
irrigation
micronutrients
pest control and
harvesting

The Authority has already sponsored reviews of cultivations and the use of phosphate and potash, but other topics may well repay examination.

Each section (e.g. Nitrogen) is introduced by a general summary of relevant physiological facts, given as an ordered sequence of points, which provide the background that a well-informed practitioner would have in mind. The subject is then considered in terms of the decisions which the producer has to make (e.g. what form of nitrogen to use, or whether to apply nitrogen in autumn), and for each decision we give:

the normal practice,

the importance of the decision to the producer (e.g. in terms of potential effect on yield) and

the agronomic and physiological factors which influence the decision.

We found that it was a natural consequence of our analysis that there emerged a number of uncertainties, and these have given rise to the suggestions we have made at the end of each section for new physiological research that should lead to further refinement of the decision-making process.

There follows a section considering how husbandry can be tailored according to the characteristics of the site and the season. The final two sections deal with the physiological support necessary for breeders and biotechnologists.

3.2 VARIETAL CHOICE

3.2.1 General

New varieties have contributed greatly to yield increases on the farm. In the 36 year period 1947-1983, when 5-year average yields of wheat and barley in England and Wales rose from 2.42 and 2.31 t/ha to 6.47 and 4.96 t/ha respectively, the adoption of new varieties is estimated to have contributed 45% and 38% respectively to the increases achieved. Since 1977, new wheat varieties have contributed 3% per annum and new barley varieties 2% per annum to these yield increases.

- ◇ Newly bred varieties must be proved distinct, uniform and stable in their characteristics and to have value for cultivation and use before they are entered on the National List and can thus be offered for sale. In practice, few sales are made without recommendation of a variety by the testing organisations. Thus, the nature of the testing and the criteria for recommendation largely dictate the objectives of the breeders and the range of varieties available to the grower.

- ◇ It is important to realise that only those varieties which come through the testing and trials system to be added to the Recommended Lists (where the criterion for inclusion for general use is 'as good as the best in all important aspects of performance') are available to most physiologists to study. Over the 10-year period 1979-88, the average number of wheat and barley potential varieties submitted for National List testing was 126. Over the same period, on average only 4 varieties for general use and 2 for special use were added per annum, for example, to the England and Wales Recommended List. Thus, many 'varieties' which may well have unusual or possible valuable characteristics worthy of study and with potential if transferred to another variety (e.g. very good at compensating for poor establishment) are discarded without trace and without any physiological evaluation.

- ◇ For England and Wales varieties are tested in their first year without fungicides at about seven centres, and in their second year with and without fungicides at the same seven centres. If they then are accepted onto the National List, they will be considered for recommendation after one further year of testing with and without fungicides at about twenty centres. Comparable testing with fewer centres occurs in Scotland and

N. Ireland. Recommendation depends principally on average performance (in terms of yield, quality or other important characteristics, such as disease resistance) apparently exceeding average performance of varieties already recommended. Thus, varieties which only succeed in a small agroclimatic niche within the country tend not to be recommended. Consistent suitability to particular growing conditions could not be shown without a more intensive, and thus expensive, testing programme.

- ◇ No variety exists which can be universally recommended as having all required advantageous characteristics for any specified end-use as all varieties exhibit some weaker attributes. Plant breeding is a slow and laborious process and, without genetic engineering, the incorporation of even a single gene for an advantageous characteristic into a new variety and testing the variety takes 10-15 years.

- ◇ Genetic engineering will expedite the transfer of an advantageous gene of known chromosomal location to an otherwise acceptable variety but normal variety testing procedures will still be necessary to confirm the performance of the resultant variety. Several aspects of varietal performance, such as local adaptation of good performance on specific soils, are most likely to become apparent only after widespread farm use.

- ◇ Varieties capable of a good yield over a range of conditions may have more general value than those having specific requirements involving a high management input. Thus, the main emphasis in breeding and recommending will continue to be on such varieties.

- ◇ Apart from yield potential, which is clearly a dominant characteristic even within the range of varieties for a special market, the grower has to consider many other attributes in choosing a variety. The variation available to the grower is prescribed for the criteria used for inclusion in a Recommended List. When winter wheat on the Recommended List for England and Wales is taken as an example, the following variations, for a few characteristics of agronomic importance, are found.

    (a) Standing power, scored on a 1-9 scale from natural lodging data recorded within trials, varies from 3 (Brimstone) to 9 (Riband). Such scores are used in practice to indicate a need to use PGRs or/and restrict nitrogen to prevent lodging, especially with winter barley.

(b) Shortness of straw. There is a difference of 15 cm in height between shortest and longest recommended variety. There is a strong relationship between straw length and the need to use PGRs and between straw length and standing power. However, there are varieties which, though long, stand relatively well (e.g. Axona).

(c) Earliness of ripening. There is a difference of only four days between the recommended varieties, but a much longer difference between species. Spread of harvest is thus normally ensured by the mix of species grown.

(d) Winter hardiness. Species differ markedly in winter hardiness: winter oats are most and winter wheat least susceptible and 2-row barley varieties are usually more susceptible than 6-row varieties. The characteristics which confer hardiness are not well defined. Prostrate vegetative growth and high vernalisation requirements tend to be associated with hardiness. Hardiness decreases with age, so the precocious varieties tend to be more at risk from frost. However, it has been found for winter wheat that spring varieties can normally overwinter successfully in the UK.

(e) Latest safe sowing date. The potential to sow winter varieties up to early spring is related to vernalisation requirement — the period of cold temperature which a variety requires before it will proceed from the vegetative to the reproductive state. In the Recommended List for England and Wales, only broad times are given, e.g. 'End January' and 'Mid-February'. All current varieties of winter wheat can be safely sown at the end of January and Fenman can be sown as late as mid-March. Most winter barley varieties can be sown up to mid-February, but such varieties as Koala, Maris Otter, Panda, Vixen and Waveney have a lower vernalisation requirement and can be sown up to the end of February.

The effect of incomplete vernalisation is to cause the plant to form more leaves and to delay the date of stem extension and anthesis. This alteration in the balance of the life cycle can result in lower yield by reducing tillers, spikelet primordia and mean grain weight.

(f) Resistance to shedding. Varieties vary from 6 to 8 on a 1-9 scale. If a site is exposed, this is an important criterion which a grower should use to choose a variety.

(g) Resistance to sprouting. Resistance to sprouting is important, particularly in bread-making varieties, on fertile sites where lodging is common and in areas where ripening tends to be slowed by humid conditions.

(h) Specific weight. Wheat varieties vary by more than 5 kg/hl and winter barleys by more than 10 kg/hl. Growing conditions have a major influence on specific weight. However choice, according to specific weight, becomes particularly important in conditions, such as fenland, which are prone to 'poor finishing'.

(i) Protein content. Bread-making wheat varieties are of hard grain and high protein levels (at least 10.5% at 14% moisture) while varieties for biscuit making are of a soft milling type and have a lower level of protein. Varietal differences in amounts are small within each quality class. The large concentrations in bread-making varieties tend to have been achieved at the expense of yield. Husbandry and growing conditions exert the main influence on protein concentrations. However, quality of protein is highly heritable and variety choice is crucial in dictating suitability for a particular market.

◇ The importance of diseases in reducing yields is well established. The use of varieties resistant or moderately resistant to diseases likely to occur in a given region is advisable though, independent of resistance, yields can be maintained by fungicide use. Resistance to diseases and pests will become more crucial as pesticide use is discouraged.

◇ Growing more than one variety, each with different genetic resistance sources, will reduce the risks of disease spread, should conditions be favourable for the disease or should breakdown of a specific resistance (which is not uncommon) occur. The use of variety mixtures also reduces disease spread but can cause marketing difficulties.

- The reaction of varieties to various applied chemicals can be different. They tolerate or otherwise heavy doses of nitrogen, are susceptible or resistant to certain herbicides and benefit or not from PGRs. Susceptibility to some herbicides is related to the particular growth stage of the stem apex at the time of application.

- Choice of variety often dictates variation in husbandry because of differences in herbicide (particularly graminicide) resistance, disease resistance, standing power and rate of development. More subtle reasons for growing varieties in 'tailored' conditions have proved difficult to justify because interactions with rotational position, nitrogen amounts and soil types have proved small or inconsistent.

- Varieties which survive drought with minimal yield loss are available, but can be low yielding due to their early maturity and consequent short grain filling period. There is a tendency to associate short varieties with sensitivity to drought.

- Seed dormancy, which can lead to uneven germination and difficulties in malting, is related to both variety and weather (cooler ripening temperatures). Triumph was recommended as a malting variety in Scotland, but was found to have a long period of post-harvest dormancy.

3.2.2 Physiological research needed

3.2.2.1 Low input varieties

At present, varieties are only tested for their response to fungicides. Weeds and pests are controlled and ample nitrogen is provided. It is thus possible that varieties with high competitive ability, aphid resistance or efficiency at recovering nitrogen are not being identified. It will be necessary to examine (and design an efficient research method for so doing) these responses at the testing stage in order to fairly support low input production.

3.2.2.2 Varietal suitabilities

In practice, the interest in choice of variety amongst growers results in a far larger number of variety trials than are conducted by the recommending agencies (NIAB, SACs, DANI). It is possible that inclusion of such results (from advisory agencies, colleges, crop centres, seed merchants and the like) at an early stage in a variety's candidature would allow a more closely focused recognition of its suitabilities, thus giving more detailed breeding objectives and better exploitation of genetic potential. It is only after intensive testing that suitabilities, such as that of Brock as a first wheat, or perhaps Riband in northern latitudes, become evident. The cost of co-ordination, accreditation and interpretation of the intensive variety testing effort which exists within the industry would be small, relative to the improvement in information on varieties and the improved ability of breeders to fit varieties to specific requirements.

3.2.2.3 Characterisation of varieties

In the National List Test system to establish distinctness, uniformity and stability of submitted potential varieties, various characters (currently 90 for barley and 80 for wheat) are recorded. Of these, about one quarter could be considered to have 'agronomic' relevance and might be used to group varieties. More importantly, extra recording in the system on selected characters of agronomic importance (e.g date of double ridge stage) might produce a database of information of value for farmers. This research proposal is more fully developed in Section 4.4.1.

3.2.2.4 Varieties and sowing date

To allow farmers to fully exploit the potential of new cultivars early knowledge is needed of their rate of development, response to sowing date, and tiller production and survival to allow management decisions to be made.

Current testing and reporting of vernalisation requirements is crude and imprecise. Physiological understanding for some varieties is sufficient for latest safe sowings to be calculated according to a model but modified methods of observation should allow this to be applied to all varieties.

Testing should use the wide regional variation in overwinter temperatures to define conditions causing floral initiation in the field.

3.3 SOWING

3.3.1 General

The optimum sowing time for both winter wheat and winter barley is from the third week of September to early October. During that period, the weather is usually more suitable for sowing, a longer period for the establishment of a good root system is provided and there is more opportunity for herbicidal autumn weed control. The aim is to achieve early formation of primary tillers and rapid canopy expansion so that maximum foliage is available and maintained to capture as much as possible of the more intensive sunshine in the longer days that occur during spring and summer. When sown in warm soil in early autumn, seedlings may emerge in about 5 days, but when sown later, for example in November, emergence may take 4-5 weeks or longer.

- Where early sowing cannot be achieved, crops may be sown up to the end of November and even until mid-February, but later sowings result in a steady decline of yield potential until a point is reached when yield may be no better than for spring sown crops.

- September-sown winter wheat crops in situations of high take-all inoculum can suffer severe yield losses from high levels of infection. This is usually confined to the second or third wheat crop after an arable break crop.

- In late-sown crops, sub-optimal soil conditions for cultivation are more likely with an increased risk of soil compaction, inhibiting root growth. Root and shoot growth are limited before winter sets in and there is a greater risk of soil erosion and damage due to frost 'heaving'.

- For studies on sowing date, it is vital to follow effects on the processes through which the crop passes before the determination of final yield and there is seldom available a body of information which allows examination of the way total biomass yield and total grain yield are affected by the length of the growing season.

- What experiments do show is that a point is reached (not consistent from site to site or from season to season) where yield does fall with later sowing and this is generally due to the crop having fewer ears/m^2 and sometimes lighter grain but with little effect on number of grains per ear.

◇ The development of late-sown crops is accelerated producing a concertina effect with the duration of each developmental stage progressively reduced as sowing becomes later. Thus, date of maturity and harvest are relatively unaffected by sowing time.

◇ The telescoping of development as sowing is delayed is achieved at the expense of leaf initiation and often a reduction in the maximum number of tillers. For example, delay of sowing of winter wheat from September to December can decrease from 14 to 10 the number of leaves on the mainstem, and the number of tillers/plant from 6 to 1 in barley.

◇ In some parts of the world, delay in sowing means that the crop is going into a severe winter (Canada) or into hot, very dry conditions at the end of the season (South Australia) but, in the maritime climate of NW Europe, there are no comparable distinct cut-off points. However, the risk that any delay in ripening associated with late sowing will have a critical effect is increased in the north.

◇ Establishment is the major factor that accounts for the less than consistent yield responses to delayed sowing. There is no consistent association from site to site or season to season between sowing time and seedbed conditions either because, for early sowing, the seed bed is too dry and too cobbly or, for late sowing, too wet or waterlogged. For any of these reasons, a particular sowing date can give unusually poor establishment.

◇ The risks of poor establishment are greater the later the sowing time because, in late sown crops, the telescoping of development decreases the opportunities for compensation through increased tiller production or tiller survival. It is possible, however, that even for early or mid-season sown crops, establishment can be so poor that the individual plant is not able to compensate for the sparse nature of the population as a whole, despite its longer growing season and slow rate of development.

◇ Straw disposal, post-harvest cultivations, seedbed preparation and sowing cause a peak workload on the intensive cereal farm. In practice, machinery, labour and climatic limitations prevent most crops on any one farm being sown at the optimum time.

- Satisfactory yields can be obtained from a range of sowing rates as both winter wheat and winter barley have a high tillering capacity and can compensate when only low plant populations are achieved at sowing or are caused by pest attack. Through compensatory tillering, a wide range of plants per square metre established can lead to adjustment in the yield components and similar yield.

- An acceptable plant population is about $250/m^2$ with allowance in seed rate made for likely losses which increase with lateness of sowing and poor soil type and condition. Eventual density of plants depends on initial seed rate, seedling mortality and plant losses resulting from pest or disease attack or environmental stresses.

- Sowing a given number of seeds/m^2 can result in very different ultimate plant populations on differing soil types and in years of contrasting weather or pest or disease incidence. Under very favourable conditions, 95-100% of seeds sown from seed lots will establish seedlings but it is more usual for establishment to be in the region of 50%. Emergence in the field is linearly related to percentage germination in the laboratory, poor seed lots giving proportionally poorer performance in the field.

- There have been instances when poor yields have occurred as a result of early sowing but there has been no clear association with bad establishment or severe disease infection. Such situations can arise because the same weather pattern can have different effects on crops that have reached different developmental stages.

- The situation is not so complicated when late sowing of spring-sown crops (from February to May) is considered. The later-sown crops, whilst still experiencing variation in seedbed conditions, are more susceptible to drought than earlier sown crops in which rooting would be more extensive and development would have progressed to a greater extent before the soil dries out.

- Number of grains/ear tends to be consistent over a range of sowing times due to almost complete compensation of increased rate but shortened duration of spikelet initiation and similar survival as sowing is delayed.

- Later-sown crops are more likely to produce lighter grains (spring sown crops are especially vulnerable to drought and disease). In general, leaves of early sowings stay green longer as, on average, conditions are cooler in early summer. Moreover, reserve material in stems may be greater allowing for buffering against variable conditions during grain filling.

- It is possible that very early autumn sown crops (August) may advance too rapidly and stem extension occur too early. Thus assimilate per unit of development may be less so that the plants are less well buffered.

- As plant population density increases, with modern varieties and use of PGRs, the decrease in yield at the upper end of the density range is small, if any, e.g. grain yield falling by only 25% at abnormally high densities ($> 1000/m^2$). With older varieties, yield declines at lower densities and more markedly, mainly due to lodging. Plants crowded together have longer, weaker lower internodes, can have more disease (especially eyespot) due to the prevailing microclimate and are therefore more prone to lodging.

- As population density increases, mutual shading is more severe and there is an increase in gibberellin levels that enhances leaf sheath and leaf lamina extension and accelerates development.

- For a time, closer spacing leads to a more extensive leaf canopy, but later formed leaves are smaller and senescence is more rapid.

- As plant population density increases, there is a progressive increase in ear population density with high density crops consisting of plants with only mainstems. In high density crops, the maximum number of tillers formed is reduced because tiller mortality increases through extensive shading and competition for nutrients.

- Despite the fact that high density crops have only mainstem ears, the number of grains/ear decreases with increasing population density. This reflects accelerated development and shortening of the period of spikelet initiation and sometimes increased spikelet and floret death.

◇ Conventional drills place seeds at a wide range of depths around the target depth of 2-3 cm, which gives adequate soil cover. Experiments indicate that there is likely to be only a small yield penalty even if sowing is up to twice the target depth. The maximum length of the sub-crown internode is less in some varieties with semi dwarfing genes and this may reduce their establishment when sown too deeply. Each extra cm that the seed is buried increases the time to seedling emergence by about 8 degree-days.

◇ The seed dressing Baytan reduces potential extension of the sub-crown internode and thus increases the effect of deep drilling on establishment.

3.3.2 Sowing rate

3.3.2.1 Normal practice

From 100 to 200 kg/ha seed is sown, adjustments being made by weight. Exceptionally, to achieve a target plant number, seed number and individual seed weight are taken into account. In most cases about 400 seeds/m^2 are sown to give a population of 200-300 plants/m^2.

3.3.2.2 Importance of decision to grower

It is essential to have greater than a critical minimum of plants (50-100/m^2) established to achieve potential yield. Very low plant numbers or very high plant numbers produce lower yields. At the worst, costs and difficulties of redrilling may be incurred due to poor establishment.

3.3.2.3 Influences on decision

a) Agronomic

- Depending on ground preparation and weather and soil conditions, wide differences in anticipated establishment ranging from 25% to 95% of seed sown can cause altered seed rates.
- It is economic to use more seed if it is home-grown and therefore cheap (e.g. £120/t) than if it is C_1 or basic and thus expensive (e.g. £300/t).

b) Physiological

- As plant number increases, total biomass and grain yield increase to a point where no further increase occurs. In some cases, 200 plants/m^2 are more than adequate to give maximum biomass and grain yield.
- There is a broad plateau for plant number which will achieve high yields (e.g. in one experiment 100 and 800 plants/m^2 produced 8.4 and 8.9 t/ha grain respectively).
- Over a considerable density range, increased ear number and decreased grain number/ear cancel each other out and result in a similar total grain number/unit area.
- Where high density crops lodge, they tend to produce lighter grains. In the absence of lodging, grain weight of barley hardly changes with population density; in wheat, grain weight tends to increase slightly with density associated with generally heavier grains on mainstem ears.
- In general, cereals are insensitive to planting pattern (i.e. the choice of row width and inter-seed spacing) over a considerable range of plant population densities.

3.3.3 Sowing time

3.3.3.1 Normal practice

Winter barley as soon as possible after mid September.
Winter wheat as soon as possible after late September
Spring wheat as soon as possible after late October
Spring barley as soon as possible after late January.

3.3.3.2 Importance of decision to grower

Experiments and experience show that yields can decline with later sowings, losses of the order of 25% occurring with long delays.

Loss of yield over the period from mid-September to mid-October is more consistent with winter barley than with winter wheat. Yield reductions due to delayed sowing of spring crops average 0.2 t/ha/week.

3.3.3.3 Influences on decision

a) Agronomic

- Soil conditions are particularly affected by rainfall and harvest of the previous crop and are crucial in determining the time at which an adequate seedbed can be prepared.
- The post-harvest and autumn sowing period is the time of maximum workload. In practice, it is not possible to sow all the crops on the ideal date, even if it were known, due to labour and machinery workload considerations.
- Improvements in weed control and soil management and abandoning of traditional rotations now give the opportunity to sow crops in early September, even August.
- The later the sowing time, the greater the chances of events occurring that are detrimental to the crop.
- The risk of disease attack (e.g. mildew) is increased with earliness of sowing in the autumn due to the 'green bridge' between succeeding crops and the warmer conditions in early autumn being conducive to disease spread and severity. There

are clear cut examples where crops sown in September have failed to outyield those sown in October and November because they have been heavily infected, e.g. by BYDV.

— Vulnerability to common or sharp eyespot and take-all is greater with earlier sowing and varieties susceptible to eyespot may not perform well with early sowing.

— Early sowings are more vulnerable to frost damage (leaf scorch) and later sowings to soil heaving caused by frost.

b) Physiological

— For both autumn and spring sown crops, the longer the growing season, the greater the total production of biomass, mainly because for earlier sown crops —

i) The root system is more extensive and is active longer before the soil dries out and

ii) The leaf canopy is produced earlier (higher LAI) so more radiation is intercepted especially in April, May and June.

— In theory, potential grain yield should be increased also by early sowing. At the same stage of development, the spring temperatures would probably be lower for early sown crops so that the interval between sequential developmental stages would be longer and in all probability the amount of radiation intercepted for each development interval greater. Thus, the size of the leaf canopy and of the whole plant would be greater than for later sown crops that develop in warmer conditions and in longer days.

— There is a 'concertina' effect, illustrated by crops sown as much as six months apart reaching anthesis as little as ten days apart. Date of harvest of autumn sown cereals is little affected by sowing date (only up to 2 weeks with 2-3 months delay in sowing).

— Some varieties of wheat and barley will not initiate an inflorescence without experiencing a sufficiently long period of cold temperature. Varieties differ in their cold requirement and this is the key to understanding the latest safe sowing date for particular varieties. There is a reluctance to sow spring types as early as winter types because they are felt to be more prone to frost.

— As sowing of winter wheat is delayed the stems become shorter, while stems of winter barley become longer.

3.3.4 Physiological research needed

3.3.4.1 Physiological obstacles to yield enhancement through heavy seed rates

Assimilates are not totally retranslocated from infertile tillers, and fertile tillers have a slightly shorter life than mainstems. Marginal improvements in grain formation and thus quality should be possible by increasing seed rates and accentuating the contribution of mainstems to yield. The physiological basis for the failure of the crop to respond to population density in excess of 200 plants/m^2 needs to be investigated. Particular attention should be given to determining the relative contribution to growth, yield and quality of main shoot, primary, secondary and tertiary tillers over a wide range of plant populations and whether there are circumstances in which the tillering process can be wasteful. Within the project, there would be the opportunity to investigate the effect of density on rate and duration of spikelet initiation in tiller as compared to mainstem ears and the factors determining floret mortality under conditions of environmental stress. The opportunity to relate the origin of the ear and the origin of the seed within the ear to final grain size, protein content and alpha-amylase level might be exploited.

3.3.4.2 Possible physiolcgical disadvantages to very early sowing

Sunlight in late August and September should cause significant growth in very early drilled crops which should thus have the potential for very high yields. Opportunities for very early sowing arise following the early harvest of break crops, especially oilseed rape. The physiological basis for apparent lack of response to very early sowing (August) should be investigated. This would focus attention on any relationships of final yield with events during vegetative growth. It is possible that disadvantageous aspects of vegetative growth of very early sowings would be amenable to control by plant growth regulators. This proposal is more fully developed in Section 4.4.2.

3.3.4.3 Disassembling the influences of photoperiod and temperature on crops sown at different dates

Although predictions of development have proved a successful application of cereal physiology there remain some fundamental uncertainties in the way processes are currently described which, if resolved, may overcome the inaccuracies which occur in conditions such as very late or very early sowing. Differences between 'spring' and 'winter' wheats should be used to test whether the significance of a 'vernalisation' effect has been overestimated. Differences between early and late sowings and between latitudes should be used to test whether effects of photoperiod and temperature are best described as being additive or multiplicative.

3.4 NITROGEN

3.4.1 General

Nitrogen from soil is inadequate for crop growth more often, and to a greater degree, than any other nutrient. Without fertiliser N, crops often produce only half or less of their potential grain yield.

- Nitrogen is so cheap (relative to grain) that commercial production need fall little short of the crop's biological potential. However, environmental concerns necessitate that the determination of how much and when N is applied takes into account more than just the crop's growth potential.

- Compared to slightly deficient crops, those which are well supplied with N show:

  a) larger leaves
  b) longer lived leaves
  c) taller stems
  d) longer roots
  e) more tillers
  f) longer lived tillers
  g) greater water use
  h) more dry weight gain
  i) more grains
  j) larger grain yields
  k) higher protein concentration
  l) smaller grains

- Such effects have positive benefits but also adverse repercussions. Larger leaves intercept more light; larger root systems provide more assured nutrient and water supplies and help to overcome root disease such as take-all, but larger, softer leaves are more prone to disease infection, and longer weaker internodes leave the crop more prone to lodging.

- The efficiency with which crops use N varies widely — between 20-90% of applied N is directly absorbed by the plants.

- The N which is not taken up by the crop may be:

  a) lost from the plant/soil system through run-off, leaching, denitrification or ammonia volatilisation

  b) made unavailable to the plant through immobilisation in the soil

  c) temporarily become inaccessible to the plant through lack of water.

The incomplete recovery of fertiliser N and the mobility of unused residues represent a major financial loss to the grower and an environmental problem to the industry.

3.4.2 The form of fertiliser nitrogen

3.4.2.1 Normal practice

Prilled ammonium nitrate.

3.4.2.2 Importance of decision to grower

The effect on input costs is normally from £10 to £40 per ha. Effects on grain quality are known, but not normally significant.

3.4.2.3 Influences on decision

a) Agronomic

- Prilled ammonium nitrate is, and will continue to be, readily available, comes conveniently packed and is easily spread with cheap machinery.
- Use of straight N, as compared to N in a 'compound' fertiliser, allows the matching of applications of other nutrients (P, K, Mg) to soil shortfalls as estimated by analysis.
- Urea is lighter per kg of N.
- Liquids can be applied more uniformly than prills.
- Pesticides can be applied with liquids.

b) Physiological

- Though seldom proven to be less effective, N from urea can be lost by volatilisation. Urea is thus less favoured for applications to dry soil (thus normally affecting late applications) and to soils with free lime in the surface.

3.4.3 Autumn nitrogen

3.4.3.1 Normal practice

None applied.

3.4.3.2 Importance of decision to grower

The cost of autumn N is small and the effect on yield is normally undetectable (average +0.05 t/ha for 84 trials on winter barley). The losses of nitrate nitrogen by leaching and run off are well recognised so the decision principally affects the image of the industry in the eyes of the public which seeks to see responsible management of the farmed environment.

3.4.3.3 Influences on decision

a) Agronomic

- Autumn nitrogen may be used purely because its exclusion from the fertilisers is inconvenient or its inclusion is more costly.
- Field trials show immobilisation, low recovery and lack of response in terms of final grain yield.
- Direct drilling (which can lead to inadequate mineralisation of soil nitrogen and consequently a need for applied nitrogen) has declined.
- There is greater use of spring nitrogen causing larger soil N residues to be available to the next crop in the following autumn.

b) Physiological

- Growers appreciate the potential for adequate release of N from the soil in autumn.
- Autumn nitrogen, when used, is intended to supplement soil supplies which may be low because of:
  - i) depletion by the previous crop,
  - ii) immobilisation by incorporated straw, chaff or stubble,

iii) inadequate disturbance by cultivation to stimulate leaf, tiller or root expansion in stands poor due to —

inadequate establishment
late or deep drilling
pest (slug or wheat bulb fly) attack.

3.4.4 Total amount of spring and summer fertiliser nitrogen

3.4.4.1 Normal practice

From 60 to 300 kg/ha. (In England and Wales, the 1985-88 average use was 190, 150 and 100 kg/ha for winter wheat, winter barley and spring barley respectively showing increases over the previous decade of 100, 60 and 30 kg/ha respectively.)

Increased use of N was stimulated by:

i) development of varieties more resistant to lodging

ii) development of techniques to counteract consequences of over-use of nitrogen (through growth regulators to control lodging and fungicides to control foliar diseases)

iii) an increasing tendency to associate low yield with low N usage

iv) (for wheat) the increasing dependence of marketability on protein concentration in the grain.

Increased use was smaller for barley than for wheat because profit margins were lower, lodging control was not so successful and marketability depended on low grain nitrogen concentrations.

3.4.4.2 Importance of decision to grower

A major decision, as inaccurately anticipated amounts commonly cost growers £50 per ha and can cost £150 per ha.

3.4.4.3 Influences on decision

a) Agronomic

Past practice will be modified according to:

— recent changes in yield achievement on the individual farm and profitability

— different estimates of soil N supply depending on previous crop, soil type and overwinter rainfall

— environmental pressures.

b) Physiological

Past practice will be modified according to:

— The intended market for the grain requires different grain N concentrations.

— Propensity to lodging based on cultivar, use of growth regulators, field situation and crop appearance in spring.

— Modified yield expectation based on crop appearance in the spring.

3.4.5 The number of nitrogen applications (between which the total amount is divided)

3.4.5.1 Normal practice

Two applications (but three for wheat grown for bread or one for barley for malting purposes).

3.4.5.2 Importance of decision to grower

Divided nitrogen applications incur little extra cost and, on average, produce a small yield advantage (0.2 t/ha). They may result in lower losses of N from the soil. Nitrogen applied during stem extension or later has a greater effect on grain N concentration than nitrogen applied earlier.

3.4.5.3 Influences on decision

a) Agronomic

— Amounts of nitrogen applied are now often large and need to be divided for convenience of spreading, sometimes in three or four applications. In practice, small amounts of nitrogen (less than 100 kg/ha) are rarely divided.

- Smaller amounts of N can be spread quickly and their use reduces the chance of poor weather preventing application to part of the area or delaying applications until a dry spell has started. Repeated application reduces variation in fertiliser distribution over the field.
- Crops infected with take-all benefit from an application in early spring.

b) Physiological

- There is appreciation that, for unimpeded growth, nitrogen should be available as required and that there is a need to minimise risk of nitrogen losses by matching nitrogen supply to the progress of crop growth.
- Earlier drilling causes earlier depletion of residual nitrogen in the soil and more protracted deficiencies, observed as yellower crops.
- Large levels of residual N are not exhausted by early spring and avoid the need for early applications.
- Linking applications to each of several stages of development has been in vogue but remains unproven.
- Applications may be combined or divided to accentuate their effect on grain N concentration.

3.4.6 Amount and timing of early spring nitrogen

3.4.6.1 Normal practice

Small amount (40 kg/ha N) applied in late February or early March.

(**N.B.** The UK practice of applying a relatively standard early amount contrasts with that, for example, in Denmark, Germany, Holland and Belgium where alterations in total nitrogen amount are normally achieved through adjustments in this first application.)

3.4.6.2 Importance of decision to grower

Differences in timing or amount of early spring N rarely cause detectable difference in yield (> 0.1 t/ha) or grain N concentration except where they are the crucial cause of lodging.

3.4.6.3 Influences on decision

a) Agronomic

- — Timing depends on ground conditions which permit spreading.
- — Further needs can be met at a later date so small amounts are used.
- — Early N may be increased in amount or advanced in timing where take-all risk is high.

b) Physiological

- — The aim is to optimise the balance between soil supply and crop demand.
- — The assessment of crop demand takes into account:
  - i) the extent of root exploration
  - ii) amount of leaf tissue present
  - iii) tiller populations
  - iv) projected temperature and light environment
  - v) intended N concentration in the grain at harvest.
- — Assessment of soil supply takes into account N residues from previous crops and rainfall projections with respect to risk of:
  - i) leaching of N from the rooting zone
  - ii) waterlogging causing possible denitrification.
- — The amount taken up by the crop at this stage is not large enough to suggest a need for more. There is local variation in the requirement (e.g. up to 60 kg/ha on heavy silt soils).
- — Large amounts tend to be associated with lodging later.

3.4.7 Timing of main application

3.4.7.1 Normal practice

The start of the stem extension.

(**N.B.** Barley crops intended for malting normally receive the main application in March, even if stem extension has not started, in order to minimise grain N concentration.)

3.4.7.2 Importance of decision to grower

Mistiming is unlikely to have an effect larger than 0.2 t/ha. However, where delayed applications are affected by surface dryness, yields can be reduced by up to 2 t/ha.

3.4.7.3 Influences on decision

a) Agronomic

- Other farm operations, such as establishment of spring crops and application of herbicides and fungicides, may take priority.
- Wet soil, rain or wind prevent spreading.

b) Physiological

- Nitrogen is needed in proportion to the rate of growth which increases as stem extension starts and as radiation levels increase.
- Deficiency, as shown by the colour of leaves and reduced tiller survival, becomes evident if no N is applied.
- The start of stem extension varies according to date of sowing, winter and early spring temperatures and variety.
- The need to avoid applying to a dry topsoil dictates that main applications are made by early May, irrespective of whether or not stem extension has started.
- Applying most of the N before stem extension has started (March) for winter barley which encounters conditions conducive to disease (SW England) can cause increased disease or require greater use of fungicides than where applications are delayed until April.

3.4.8 Amount of extra N applied to bread-making wheats

3.4.8.1 Normal practice

30 kg/ha N.

3.4.8.2 Importance of decision to grower

The decision is sometimes crucial in attempting to obtain a premium price. However, extra N may not succeed in enhancing protein level above a specified threshold level, in which case it can be wasted.

3.4.8.3 Influences on decision

a) Agronomic

- Grain may be rejected not for protein level but through:
  - i) high moisture
  - ii) high impurities
  - iii) low Hagberg Falling Number
  - iv) low specific weight.

b) Physiological

- The greater the yield at a given level of uptake, the more the grain nitrogen will be diluted and the lower its concentration, e.g. high nitrogen content grain is less easily achieved in first wheat crops after a break in rotation, than in second wheat crops.
- With amounts of N used for feed varieties, bread-making varieties do not consistently show protein contents which attract premium payments.
- Extra nitrogen almost always increases grain protein concentration.

3.4.9 Form, method and timing of late N applications to bread-making

3.4.9.1 Normal practice

Prilled ammonium nitrate, broadcast a few weeks after main application. The alternative is a solution of urea sprayed during grain filling (used by a minority of growers).

3.4.9.2 Importance of decision to grower

Differences in effectiveness between forms of late N seldom affect acquisition of premiums. Effects on the value of grain for bread-making are suspected but unproven.

3.4.9.3 Influences on decision

a) Agronomic

- Application of prills is more convenient than sprays and does not necessitate a specific purchase.
- Costs of both methods of application are similar.
- Urea sprays can have fungicidal effects.

b) Physiological

- Sprayed urea is likely to leave a smaller soil N residue than prilled ammonium nitrate.
- Weather is important, as uptake from prills can be delayed by soil dryness, i.e. sprays can substitute at a later date (up to milky ripe stage).
- Urea sprays may cause leaf scorching but are perceived to cause large increases in grain protein concentration. Yield reductions have been associated with scorch but yield enhancement is also sometimes observed.

3.4.10 Physiological research needed

3.4.10.1 Maximising recovery of soil-applied N

Applications of N which give optimum cereal yield cause increases in N uptake which range from 40-90% of the amount applied. Most unrecovered N is immobilised by soil organisms whence release is slow. Unrecovered N represents a financial loss to growers and compromises their image as responsible managers of land.
The proportion of N recovered by only one crop appears remarkably constant over a range of amounts applied. Recovery thus appears to be governed by the particular condition of the crop and soil to which it is applied. Studies to define influential conditions for crop uptake and soil immobilisation would allow decisions on N form, amount and timing to be directed at maximising recovery of soil applied N. Experiments should focus on the few days following N application, testing a wide range of soil types, temperatures and moisture conditions for their effects on immobilisation and crop uptake.

3.4.10.2 Relationship between N requirement and yield

Most advice on fertiliser use currently advocates that applications are adjusted according to expected yield. Successive series of response trials show an association between yield potential and N requirement. However, the axiom that large yields contain large amounts of N may be misinterpreted when deciding on use of fertiliser. Much of the variation in yield potential is associated with seasonal differences which are largely unpredictable at the time fertiliser must be applied. There is now some evidence that where a crop yields well, due to (more predictable) field differences, its recovery of fertiliser N is good so that it may not need a proportionately large dressing.

There is a wealth of data against which this possibility should be examined and a detailed review is needed. However, not all the necessary comparisons are available. New experiments should examine whether N requirement is affected by site factors (such as variety, sowing dates, soil conditions and root disease) which can cause predictable differences in yield.

3.4.10.3 The least nitrogen that will optimise crop structure

The canopies formed by contemporary cereal crops receiving normal levels of nutrition appear larger than is needed to fully intercept light energy in May and June. On the other hand the crop's green area often fades before its grain has fully filled and thereby much intense mid-summer energy may not be converted to yield. It would seem that the second half of the nitrogen currently applied to winter cereals, which only increases yield by 10%, may be a particularly crude way of increasing leaf life.

An investigation is needed to test whether there is scope to modify the normal growth and persistence of a canopy to meet more closely the optimum for intercepting light. The paramount means of influence must be through judicious applications of nitrogen. This suggestion is discussed more fully in Section 4.4.3.

3.4.10.4 Foliar application of N to maximise recovery and minimise soil N residues

Fertiliser N applied to leaves avoids interaction with the soil. Foliar application might thus be appropriate for much fertiliser N. The technical obstacles to providing through leaf uptake the entire shortfall between crop uptake of N for optimum yield (say 200 kg/ha) and N available from rainfall and soil organic matter (say 40 kg/ha) should not be underestimated. However, the potential economic and environmental benefits from demonstrably not exacerbating N losses from soil would more than justify the development programme. Techniques for maximising N uptake by leaves have not been intensively studied. Small amounts of urea N are commonly sprayed at a late stage onto wheat to increase the protein concentration of the grain. Recovery is often equivalent but seldom better than that of soil applied N. However, sprays can cause scorch and reduce yield. Experiments should identify the rate by which N enters leaves and the way that the N is assimilated and translocated and its efficiency in causing leaf expansion. They should also examine the extent to which foliar urea is incorporated into, or influences the formation of, the various structural and storage proteins that determine bread-making qualities. Formulations should be assessed for their effect on N retention by the leaf, efficiency of N uptake and scorch. Application techniques should be tested for their ability to cause retention by particular parts of the crop canopy, e.g. by comparing electrostatic, air assisted and conventional spraying of cereal plants of different ages. Assessments should be made of the fate of unrecovered foliar applied N. This research proposal is more fully developed in Chapter 4.

3.4.10.5 Timing of N applications to malting barley

Malting barley often receives all applied N in early spring to minimise unwanted increases in grain N concentration. On the light soils commonly used, this risks loss of N and may not be compatible with responsible N use. There is evidence that early application of only part of the total requirement minimises the grain N effect. Experiments should be used to identify the patterns of early N uptake which minimise both N loss and grain concentration.

3.4.10.6 Timing of N applications to wheat

Contrasting systems of N timing are adopted in different countries of north west Europe. In the UK, the accent is on completing application by early May, despite the range of rainfall patterns in which cereals are grown. The UK practice of depending on the soil to hold N received in spring efficiently and release it through the summer should be compared with practices more common on the continent, which rely on more widely spaced applications, allowing adjustments for perceived changes in crop performance.

3.5 WEED CONTROL

3.5.1 General

Farm use of herbicides is still dominated by the perceived need for a 'clean crop'. Most grower complaints centre around the survival or recovery of some weeds after herbicide application.

- For certain very aggressive and competitive weeds in winter cereals, such as blackgrass and cleavers, the 'clean crop' approach is justified. Given current cultivation and rotation practices, present herbicides are only barely capable of the necessary control levels. If the occurrence of herbicide 'resistant' blackgrass continues to increase, crop rotations may have to be altered to allow effective herbicides to be used.

- However, in spring cereals, the yield losses attributable to the normal populations of many broad-leaved weeds are often small but other benefits from their control accrue, such as easier harvesting, less weed-seed contamination in the grain, less weed-seed return to the soil and hence lower weed infestations in subsequent crops.

- Most grass weeds and the more aggressive broad-leaved species germinate in the autumn.

- Weeds that germinate early will generally grow larger, become more competitive and produce more seed than those that germinate later.

- Falling cereal prices, increasing costs of production and public concern about the environment are encouraging growers to reduce pesticide use. The need to spray fields infested with small numbers of weeds is being examined more closely. Weed thresholds, below which treatment may be considered unnecessary and undesirable, are being explored, but site to site variation in weed vigour and patchy weed distributions make such thresholds difficult to apply in practice.

- There is evidence to suggest that more cost effective weed control might be obtained by varying herbicide doses in relation to the prevailing weather conditions. However, attempts to reduce herbicide doses may present a difficulty to the manufacturers, who take legal responsibility for their efficacy.

- The threshold concept in winter cereals involves identifying whether or not there is a significant autumn weed problem which requires pre- or early post-emergence spray, with the option of further sprays in spring if —

  (a) the autumn spray has been ineffective or could not be applied (due to poor soil and/or climatic conditions or late sowing) or

  (b) if a significant flush of a spring germinating weed species has appeared.

- Spray thresholds, based on weed numbers but qualified by weed competitive ability, relative times of weed and crop emergence and potential seed return, need to be developed for advisory use. Their value is currently limited due to difficulty in predicting the competitive ability of similar weed populations on different sites and in different seasons.

- Recommendations for herbicide timing are an attempt to resolve the sometimes conflicting requirements for:

  (a) weed removal before the onset of competition

  (b) the growth stages at which the crop will tolerate the herbicide

  (c) favourable weather conditions for herbicide activity

  (d) a balance between the persistence of the herbicide and the prospect of subsequent weed germination.

- The 'hormone' herbicides, e.g. MCPA, can cause ear deformity or poor grain filling if applied during leaf and ear initiation or meiosis respectively. While many modern herbicides are tolerated by cereal crops over a wide range of growth stages, there remain several in common use for which the accurate identification of plant development is required if crop injury is to be avoided.

- With a view to reducing herbicide input, consideration is being given to integrating herbicide use with a return to systems involving crop rotation and more traditional husbandry. Application technology to deliver herbicides more precisely to their sites of action is being improved and the potential of alternative control agents, such as myco-herbicides, is being explored for specific weed problems.

◇ Presently, most herbicides are the product of empirical screening programmes. The more targeted approach of agrochemical manufacturers in attempting to synthesise new chemicals which can interfere with specific biochemical pathways suggests that, despite the high costs of developing herbicides to the industrial production phase, selective herbicides will continue to be produced in the future for use in cereals as they occupy a substantial world acreage.

◇ Because they are so effective and labour saving, herbicides will continue to be used in cereal production systems for the foreseeable future. Ways of reducing herbicide dose to give optimum effect in a range of situations with minimum waste, possibly aiming not at outright weed death but at minimising weed competition and seed return, are imperative to respond to tighter profit margins and to public pressures for environmentally sensitive weed control.

3.5.2 Weed control in autumn

3.5.2.1 Normal practice

Pre- or early post-emergence herbicide application for control of autumn-germinating grass and broad-leaved weeds.

3.5.2.2 Importance of decision to grower

Autumn control of high populations of aggressive grass weeds offers an economic yield benefit over spring treatments.

Weeds are generally easier to kill when they are small.

3.5.2.3 Influences on decision

a) Agronomic

— Minimal cultivations aggravate grass weed problems because seed germination and emergence are favoured by shallow incorporation in the soil, while traditional ploughing reduces successful emergence.

- Crop sequences in which cereals predominate demand more vigilant control of grass weeds than sequences with break crops which allow more effective graminicides to be used.
- Minimal cultivation, especially combined with straw burning, increases the adsorption of certain herbicides and reduces their efficacy.
- Soil and weather must be fit to allow accurate application.

b) Physiological

- The choice of herbicide, dose and timing depends on:
  - i) the weed spectrum present and their numbers
  - ii) the relative emergence dates and stage of development of crops and weeds
  - iii) the relative competitive abilities of the weeds and crop
  - iv) the seed production potential and population dynamics of the weed species
  - v) the weather and its likely effect on herbicide performance and crop safety.
- Herbicide effectiveness tends to be improved where conditions favouring plant uptake are exploited. Sprays tend to be best applied to young plants during rapid growth, with a moist soil surface and without likelihood of frosts.

3.5.3 Weed control in spring

3.5.3.1 Normal practice

Apply herbicide:

- i) in spring crops to control prevalent weeds,
- ii) in winter crops to control spring germinating broad-leaved weeds and others for which autumn treatment was considered unnecessary or impracticable,
- iii) in winter crops to control wild-oat or blackgrass that have either been inadequately controlled by autumn treatment or have germinated since.

3.5.3.2 Importance of decision to grower

Spring herbicides can help cereals achieve maximum yield potential but are often not warranted on the basis of expected yield increase.

Treatment reduces seed return and build-up of the buried weed seed bank.

Treatment eases harvesting and maintains grain quality and purity.

3.5.3.3 Influences on decision

a) Agronomic

- Crop inspection allows accurate determination of weed populations and makes the decision on herbicide use and selection easier than in the autumn.
- Time of drilling in either autumn or spring influences the weed flora and numbers.

b) Physiological

- The prevalence and relative competitive ability of weeds compared to the crop must be assessed.
- The timing of weed control must precede the period when the main competitive effect will be exerted.
- Crop tolerance of herbicides varies with its stages of development.
- Seed production and population dynamics of the weed species must be assessed.
- A weed's size affects its susceptibility to herbicides.
- Herbicides have optimum temperatures for activity.

3.5.4 Physiological research needed

3.5.4.1 Weed thresholds

Research is under way into the relationships between different weed species, their numbers and yield loss to determine competitive indices. The future need is for identification and quantification of the factors that regulate the timing of weed germination, the early growth and development of the weed seedling and its subsequent growth pattern through the season, when alone and in the crop, with a view to producing models that predict the effects of competition and the reaction of the crop to specific weeds and associated measures for their control. Such an approach would aim to accommodate the uncertainties of summer weather through closely describing the differences in response of the weed from that of the crop to changes in temperature and moisture. Confidence in calculated competitiveness would increase as the season progresses.

3.5.4.2 Low cost strategies for weed control

It is probable that herbicides can be used at reduced rates to restrict weed competition and maintain yield whilst reducing the prospect of damage to the crop and to the environment. The minimum frequency of application and levels of control required to maintain yield at economic levels over years whilst not increasing the weed seed burden need to be ascertained.

In circumstances where environmental efficiency is more important than maximum yield, less emphasis need be placed upon a complete weed kill in cereal crops than on a long-term strategy to prevent weed build-up. This will require a detailed understanding of weed population dynamics and the influence of reduced inputs and changes in cropping practices.

The Authority currently funds some work looking into the dynamics of broad-leaved weeds in mixed populations and, because of the far-reaching importance of the objective, it is appropriate for funding from the European Community. The Authority should therefore look to designing its support so that such funds can be attracted.

3.5.4.3 Weed-seed dormancy

The seeds of certain weed species, e.g. wild oat, can remain dormant after shedding and so contribute to a long term seedbank in the soil. Control of such weeds requires continuous herbicidal use over successive years and any failure to prevent seed return reinforces the seed bank. Weed control with conventional herbicides would be much easier if dormancy could be broken and first-shed seed encouraged to germinate immediately. The Authority currently funds some work on dormancy in Brome species but there is a need for more work on dormancy mechanisms to identify chemicals that might be used to stimulate immediate germination.

3.5.4.4 Crop tolerance

Although herbicides are crucial to the continuance of cereal cropping in the UK, the influence of weather before, at and after herbicide application on the crop is inadequately understood. It is not uncommon, both in spring and autumn cereals, for there to be visible effects of herbicides on the appearance (e.g. leaf size and colour) of crops for which they are recommended. There has been little recent work to quantify the detrimental effects of herbicides on modern cereal genotypes in the crop situation. There is a need for an exploratory exercise assessing effects at stages, seen with a physiological perspective, to be most important in the accumulation of cereal yield.

3.5.4.5 Herbicide resistance in weeds

The Authority currently funds work investigating the genetics of resistance of blackgrass to the substituted urea herbicides and whether resistance is responsible when there is poor performance of autumn applications. There is a need to ensure that the development of resistance to other chemicals will also be recognised in good time.

3.5.4.6 Fate of herbicide residues

Recent experiences with unexpected resistance of the sulphonyl urea herbicides and the appearance of traces of herbicides in drainage waters very soon after herbicide application has highlighted the need to understand better the relationship of soil-acting herbicides to soil temperature, water movement in the soil, adsorption on soil particles and organic matter, and metabolism by soil organisms. The industry has a vital interest in promoting such work with both the manufacturers and government.

3.5.4.7 The principles underlying spray application techniques

Little guidance is available on principles governing uptake and activity of herbicides. The Authority currently funds work comparing different designs of sprayer but there is a need to marry this knowledge with concepts of the preferred area of deposition of the spray, the proportion of the weed that must be sprayed and the optimum concentration of the spray according to the condition of weather, the target and the crop.

3.6 DISEASE CONTROL

3.6.1 General

Diseases, caused either by viruses or fungi, are recognised as major causes of yield loss in cereals whether attacking root (take-all in wheat), stem (eyespot, sharp eyespot, Fusarium spp.) or leaf and ear (Septoria spp., Fusarium spp., mildew, rusts).

◇ Varieties resistant to most of the important diseases are available and this genetic resistance can be exploited especially where potential yield and grain quality are equal to those of the best susceptible varieties to which fungicide has been applied.

◇ Most leaf and stem diseases can be controlled by pesticide applications, though for some diseases, e.g. eyespot, control is only partial. Yield benefits of 0.6-0.9 t/ha are commonly obtained in response to 2 or 3 spray programmes and are likely to be economic in over 50% of cases. There is no commercially available fungicide to control take-all and control relies on crop rotation and husbandry techniques.

◇ Introduction, development and spread of most diseases are favoured by:

a) early sowing of winter crops (though this increases the potential yield). Mildews and rusts survive on volunteers, and crops which emerge before these volunteers are killed are particularly at risk

b) warm autumn weather

c) excessive N uptake which softens tissues

◇ Diseases cause loss of green tissue and/or physiological effects as a result of toxins which affect plant metabolism. Fungal infections of the leaf usually reduce the efficiency of use of light energy and result in loss of photosynthesising tissue with an associated increase in the rate of water loss and senescence.

◇ Increases in respiration rate associated with diseases result in a reduction in the movement of assimilates from infected leaves (e.g. Rhynchosporium in barley) and may lead to increased import of assimilates to those leaves. This reduces the level of assimilates available to roots and the developing grain and tends to depress tillering and rate of leaf appearance.

◇ The use of crop developmental stages according to standard keys to identify recommended timings for fungicide application is well recognised and applied by growers.

◇ In some situations control of disease at early stem extension increases plant growth rates when the number of fertile tillers/plant and number of grains/ear are being formed, thereby preventing reduction in the number of grains produced per unit field area.

◇ It is important to maintain the health of the three leaves (including the flag leaf) nearest to the ear for as long as possible thereby affecting the 'grain size' component of yield.

◇ There are three main strategies for the use of fungicides to control leaf and stem diseases in cereals:

a) Disease risk assessment (regular crop monitoring and treatment applied only where there is risk of the disease becoming severe and when the crop is not too far advanced developmentally to almost eliminate the chance of a response) is time consuming, but most environmentally sensitive.

b) Routine prophylactic (preventative treatments applied at certain predetermined growth stages) is simply managed, but inflexible, likely to be least cost effective and most detrimental to the environment.

c) Managed disease control (some routine treatments applied where the risk of the disease is consistently high with sufficient monitoring to detect unexpected outbreaks) is relatively easily managed and is reasonably environmentally acceptable.

◇ Fungicides are most effective when applied early in the course of an epidemic. Delaying treatment until damage has occurred cannot restore lost photosynthetic potential.

3.6.2 Root diseases

3.6.2.1 Normal practice

Maintain take-all decline where this has been established in long run cereal rotations.

On second and subsequent wheat crops which are at risk from take-all, apply early nitrogen.

Where take-all is regularly severe, avoid second and subsequent wheat crops.

3.6.2.2 Importance of decision to grower

No control is available and experience shows that root diseases such as take-all can cause serious yield loss (up to 50%) and a high proportion of small grains.

3.6.2.3 Influences on decision

a) Agronomic

— Constraints on the cultivation and marketing of alternative crops dictate that two or three take-all prone cereals will often be grown in sequence.

b) Physiological

— Advantages of better rooting and greater yields must be balanced against increased seedling infection of earlier sown crops.

— Root disease causes an interruption in water and mineral translocation. Infection can be mitigated by ensuring good conditions for root function: firm but not compacted seedbeds, adequate nitrogen supply in early spring, with late February application, if necessary.

3.6.3 Stem-base diseases

3.6.3.1 Normal practice

Resistant varieties should be used if suitable for growers' requirements. Otherwise, apply fungicide, prochloraz, between GS 30-37 when infection threshold is exceeded.

3.6.3.2 Importance of decision to grower

Eyespot was the most serious disease occurring in winter wheat in 1987 causing losses of 2.4% (£29m). Yield losses average 0.58 t/ha nationally.

Fungicide application may also increase specific weight.

3.6.3.3 Influences on decision

a) Agronomic

- Resistance of eyespot to benzimidazole fungicides is now almost total.
- Eyespot is less damaging on winter barley than on winter wheat. Varietal resistance varies in winter wheat.
- By careful fungicide choice and spray timing in relation to crop development control of eyespot and leaf diseases may become complementary.

b) Physiological

- Damage is related to the extent that vascular tissue is impaired.
- Severe eyespot increases lodging risk.

3.6.4 Leaf and ear diseases

3.6.4.1 Normal practice

Grow a resistant variety if one exists with the potential for required yield and quality.

Spray according to risk assessment, routine or managed disease control programmes.

3.6.4.2 Importance of decision to grower

Effective disease control is essential for production of high yields and quality. Experimental results indicate that yield losses averaging about 0.5 t/ha are prevented by routine application of fungicide at flag leaf emergence. Treatment at this stage is likely to be cost-effective in about 70% of crops.

Grain specific weight is reliably improved if foliar and ear diseases are controlled.

3.6.4.3 Influences on decision

a) Agronomic

- Monitoring is time-consuming and thus expensive, resulting in more frequent use of routine treatments.
- Variation in varietal resistances to disease is important.
- Protectant fungicides need to be applied before infection occurs whereas those with eradicant properties can be used after infection.
- Several disease-causing fungi are developing resistance to fungicides. Programmes must be designed to minimise selection pressure.

b) Physiological

- Thick crops have a microclimate conducive to most leaf diseases. Crops which tiller profusely in moist, fertile conditions tend to be most at risk.
- Soft tissues with high N content are more sensitive to many diseases. Excessive nitrogen is thus best avoided.
- The greater yield potential of early sown crops may be jeopardised by high disease risk. Mildews and rusts easily transfer from surviving volunteers, and aphids migrating after emergence of early drillings infect plants with Barley Yellow Dwarf Virus (BYDV).
- Crops with adequate moisture reserves are more likely to benefit from late fungicides applied to protect leaves and ears during grain fill.
- The efficacy of disease control measures can be improved by an understanding of the contribution of different organs to yield. Flag leaf protection may influence duration of grain fill and thus grain size. In general, infection of lower leaves is less important than diseases on upper leaves or floral tissue.

3.6.5 Physiological research needed

3.6.5.1 Direct effects of fungicides on crop growth

Some fungicides are known to influence crop physiology through direct effects on, for example, cytokinins. Others may scorch leaves. Effects of both the fungicides and scorch on yield are difficult to measure because the scorch is unpredictable and effects are confounded with the positive yield effects resulting from disease suppression. Effects are unlikely to be purely cosmetic since the leaves most vital to yield are often those most affected. Knowledge of the effects on plant tissues which may lead to scorch would allow improved choice of product in relation to spray conditions to more closely achieve potential.

Carefully structured experiments should be conducted to assess the effects of fungicides in the absence of disease through changes in rate of products and application to disease free crops (e.g. late sown first cereals). This work could possibly be combined with that studying scorch effects of foliar nitrogen applications (see Section 3.4.10.4).

3.6.5.2 Monitoring of growth and development in relation to disease and fungicide performance

A series of experiments (part H-GCA funded) has shown good relationships between disease incidence, growth stage and yield loss. Disease incidence during different phases of development is being studied by use of sequential spray timings. In order to more confidently interpret the relationships, it is important to know the course of both growth and development by recording growth stage, and also dry matter accumulation at each site. These and other similar data can then be used to modify our understanding of events leading to yield loss through disease. Future experiments designed to compare disease effects at different stages of development should be accompanied by crop sampling for dry matter and nitrogen accumulation, examining partitioning between principal crop components.

3.6.5.3 Estimating consequences of damage by disease

Disease organisms differ in their effects. Most impose a respiratory load on infected tissue, creating additional sinks for assimilates. However, effects may also include masking and damage of green tissue, production of toxins to alter metabolic processes, impairment of vascular function either locally or systematically, or restriction of root exploration. These may result in secondary effects on leaf expansion and light interception. There is little knowledge of the relative differences between diseases on nitrogen physiology or carbohydrate assimilation for leaf, stem base, ear or root diseases or the effect of root and stem base diseases on transpiration and nutrient flow. There is evidence, for instance in barley, that foliar diseases limit the relocation of nitrogen from senescing leaves to developing grain. Experiments testing disease control measures would be improved by reference to a systematic description of disease effects in relation to the biological activity of fungicides. This would enable estimates of treatment benefits to be made in relation to disease control, crop developmental phase and potential for growth.

A programme of research should be conducted to set out a quantitative description of interactions between growth and disease, so that fungicide selection and treatment timing can be better planned to reduce unnecessary applications and reduce costs. This suggestion is developed for foliar diseases in Section 4.4.4.

3.6.5.4 Predicting appearance of yield-forming leaves

Results from recent experiments suggest that leaf 3 should be protected from diseases from its emergence, possibly by coinciding this with a spray for eyespot control timed at GS 32-33. The eradicant and protectant properties of some azole fungicides may therefore remove the need to control eyespot at GS 31, eradicate early *Septoria* and protect existing leaf area. With an incubation period for *S. tritici* of 25-30 days on the top three leaves, it is possible that only one further fungicide application would be required to provide season long protection. A broad-spectrum fungicide typically costs £20/ha and so a large potential saving in input cost is possible.

The subroutine which describes development in the AFRC Wheat Model should be extended, so that not only are node stages and anthesis described, but also emergence of the final three leaves, the ear and progress through the grain filling period can be predicted.

3.7 PLANT GROWTH REGULATION

3.7.1 General

Plant growth and development are controlled internally by the interaction of several types of natural hormone defined here as compounds synthesised in small quantities within the plant which influence processes away from the site of origin.

- Plant growth and development can be modified by inhibiting or enhancing plant responses to the endogenous hormones using applications of exogenous plant growth regulators (PGRs).

- Applied at given rates and timings, PGRs can achieve specific alterations — either stimulation or retardation — in leaf or stem expansion. They thus are capable of giving higher yield, easier harvesting and improved quality, all with the potential for increased financial return.

- Physiological studies have identified modifications to plant development processes resulting from PGR application, including a delay in the start of stem extension, reduced length of lower internodes and an increase in stem thickness, all resulting in improved crop resistance to lodging. However, autumn and early spring applications of PGRs, usually at low rates, have increased the growth of upper internodes thus reducing resistance to lodging. Physiology has also identified roles for the use of PGRs in the potential control of tiller production and survival, in spikelet survival, in delaying leaf senescence and reducing leaf erectness thereby increasing light absorption, and in modifying the growth of root systems.

- The most significant role for PGRs involves lodging control. Treatment can shorten and strengthen stems and delay onset of lodging or reduce the degree of lodging.

- Lodging results from a failure in the soil-shoot-air complex. Many interrelated attributes within this complex confer on a crop its propensity to lodge:

  a) strength of the soil surface, which is highly dependent on moisture content, and also texture.

b) rooting pattern and structural integrity, which can be affected by diseases and pests.

c) crown depth, which depends on sowing depth and seed treatment with Baytan.

d) stem thickness and health, particularly of the lower internodes, which can be affected by nitrogen nutrition, diseases and many other husbandry factors.

e) stem length and weight distribution which affect the moment on the stem base. Rain can increase this by wetting the shoots, or by its physical downward force.

f) resistance of the crop canopy to air movement which is affected by structure and disposition of tillers, leaves and ears.

g) wind speeds which depend on weather and field exposure.

Growth regulation can thus only have partial influence over lodging events.

◇ Several chemicals have so far been developed commercially for lodging control in cereal production:

a) Chlormequat (e.g. Cycocel) was initially developed for lodging control in wheat and is less effective in controlling lodging in barley. It is now also used for the manipulation of tillering in both barley and wheat production systems.

b) Ethephon (e.g. Cerone) was developed for more effective control of lodging in barley.

c) Ethephon with mepiquat chloride (e.g. Terpal) was developed for better control of lodging than achieved with ethephon alone.

d) Ethephon with chlormequat (e.g. Upgrade) allows chlormequat to be applied to winter wheat more effectively at later growth stages.

◇ In wheat, chlormequat is the most effective chemical to prevent lodging, whilst in barley, it is the ethylene generating products.

◇ The second recently identified role of PGRs involves growth manipulation. In this respect, the manipulation of tiller production and survival to increase the number of grains/unit area has received most physiological attention. This approach relies upon a temporary retardation in the growth of the larger shoots within the plant which increases the competitive ability of the smaller tillers permitting more to survive. Thus, ear number at harvest is increased, usually resulting in a small increase in grain number per unit area and in yield.

◇ Chlormequat can be applied to manipulate tiller survival in both wheat and barley.

◇ In addition to the synthetic growth regulators, two other types of hormone preparation are available commercially and, though not widely used on cereals, are advocated for the manipulation of growth:

(a) Seaweed extracts (e.g. Seamac 600, SM3) are understood to contain cytokinins.

(b) Gibberellins (e.g. Berelex)

3.7.2 PGRs for lodging control

3.7.2.1 Normal practice

Chlormequat to control lodging is applied as a single or split application between GS 30 and GS 31 to about 40% of winter cereals. Ethephon products may also be used (alone or in sequence with chlormequat) to give control of lodging and are applied between GS 32-49 on winter barley and GS 32-45 on winter wheat.

3.7.2.2 Importance of decision to grower

The decision to use PGRs can be vital as lodging can reduce yield by 0.5-1 t/ha and delay harvest, and grain quality is impaired after lodging, through grain discoloration, or germinating grain and associated high alpha amylase levels. As PGRs are relatively cheap (from £5.00/ha), they can be applied as an insurance measure to guard against lodging.

3.7.2.3 Influences on decision

a) Agronomic

- Crops on soils of high N index on exposed sites or in regions with high summer rainfall are at high risk from lodging.
- Winter barley is generally poorer at standing than winter wheat.
- Varieties differ in inherent standing ability. Testing agencies give scores for varieties for standing power and shortness of straw.
- Early sowing increases stem length in wheat and markedly increases the risk of lodging but decreases stem length in barley.
- Early application of N increases straw length making crops more prone to lodging.
- Whilst PGRs have no direct fungicidal action, the stronger stems resulting from their use may permit the crop to tolerate higher levels of stem base diseases without lodging.

b) Physiological

- Early lodging disrupts light penetration of the canopy and reduces grain filling, often resulting in a poor grain specific weight. Late lodging delays ripening by retaining moisture in the canopy, encouraging moulds, sprouting (hence high alpha-amylase development) and low HFN.
- Effects of growth retardants on stem structure can be anticipated because the tissues affected are those where cell expansion occurs following the time of application.

3.7.3 PGRs for growth manipulation

3.7.3.1 Normal practice

PGR applications specifically for this purpose are rarely made in practice. With winter barley and taller varieties of winter wheat a lower rate of chlormequat than is used for lodging control is sometimes applied towards the end of the tillering phase (GS 30).

3.7.3.2 Importance of decision to grower

Applying PGRs is a possible way of extracting slightly more yield out of an already established high yielding system. In the absence of lodging winter barley and winter wheat (other than semi-dwarf varieties) show a small (1-3%) yield response to applications of chlormequat. Yield depressions can occur in low-yielding circumstances or where a crop is unlikely to be able to produce sufficient assimilate to fill extra grains leading to a reduction in grain size and quality.

3.7.3.3 Influences on decision

a) Agronomic

- Application can be made with a fungicide or herbicide tank mix thus reducing the cost of application. This is useful when the optimum application times for PGRs, fungicides and herbicides coincide at GS 30-31 which has been shown to be a beneficial time for both lodging control and crop manipulation with chlormequat. However, tank mixing chlormequat can reduce the efficacy of some herbicides for cleavers control.
- Since chlormequat also controls lodging and lodging is difficult to anticipate, responses to growth manipulation encourage general use of chlormequat as a dual-purpose application at the start of stem extension.
- Applications to the crop at early stages of development in the autumn have proved unlikely to maintain any potential advantage through to grain yield.

b) Physiological

- Modifications to the number of grains/unit area will only be translated into grain yield increases if extra assimilate production/translocation is possible to adequately fill the extra grains. Thus crops most likely to respond to tiller manipulation are those grown in high yielding environments, e.g. freedom from drought stress.

- Timing of application in relation to crop growth stage is important, e.g. tillering is unlikely to be manipulated if the PGR is applied outside the tillering phase, i.e. before the emergence of tillers or after the start of tiller death.
- There is a tendency for crops treated with chlormequat but which do not lodge to have smaller grains than untreated, unlodged crops due to compensation for the increase in grain number. Effects on specific weight are marginal.

3.7.4 Physiological research needed

3.7.4.1 Prediction of lodging

Many growers use PGRs as an insurance measure to guard against lodging. This practice could be made more cost effective with a means of predicting early in the season the need for anti-lodging treatment. This requires detailed definition of the effect of agronomic practices on stem structural failure in the soil-root-shoot-air complex during the lodging event. This research proposal is more fully developed in Section 4.4.5.

3.7.4.2 Varietal interaction with PGRs

Some varieties, e.g. Triumph spring barley, respond unfavourably to PGRs in some stress situations. It is necessary to identify varietal characteristics which relate to sensitivity of varieties in conditions of stress and in the absence of lodging. This would help to avoid economic and other undesirable effects of insurance spraying.

Also, experiments have indicated yield losses from chlormequat on semi-dwarf wheats in the absence of lodging. There is a need to examine the potential to predict, from a knowledge of patterns of growth and development, the varieties which are most likely to show positive responses to PGRs in terms of increases in grain number/ear or ear number/plant.

3.7.4.3 Identification of responsive systems for growth manipulation

The usefulness of chlormequat-based PGRs for yield increases through tiller manipulation is dependent upon the relationship between grain number/unit area and grain yield, i.e. the stability of grain weight. The identification of cereal production systems where this relationship holds true will identify systems which are likely to benefit from tiller manipulation through chlormequat.

3.7.4.4 Increasing grain size by stimulating cell division

The potential size of the grain appears to be set during the first phase of grain growth when cell number is being determined. Although actual cell size is realised later, cell expansion during the second phase does not seem to be sufficiently elastic to compensate for any earlier restriction in cell numbers. It is often seen that, when there is no obvious external limiting factor, grains do not grow beyond a certain size. However, it also seems that when disease or drought intervene and there is a risk of grain shrivelling, translocation of assimilate stored in the stem can provide a buffer from which the grain is filled.

The hormones most likely to affect cell division are the cytokinins, and application of cytokinins has, on occasion, increased yield. It is possible that, if limits on potential size can be removed, stem reserves could be remobilised even when conditions after flowering were favourable for photosynthesis.

3.7.4.5 Why grains stop importing assimilate

Leaf life may be prolonged with fungicides, growth regulators or nutrients but grain growth can stop whilst leaves are still green. Possible causes of growth cessation are: displacement of grain moisture by starch, loss of control of grain moisture status, or vascular blockage according to some developmental trigger. Observations of these characters through grain development could indicate routes for their control.

3.7.4.6 PGRs to improve winter hardiness

PGR treatments to improve winter hardiness could allow the autumn sowing of high quality spring wheats and malting barley varieties. PGRs might also improve the survival of cold-sensitive winter oat varieties.

3.8 CONTROL OF QUALITY

3.8.1 General

The definition of quality, i.e. the degree of excellence, of grain for any market depends on the requirements for that specific market. Therefore, there are many different kinds of grain quality. All sectors of the cereal market have certain basic standards which the grain must meet and which vary considerably between various end-users. A test for the standard may vary from visual examination to sophisticated chemical analysis.

- No market will wish to accept grain which has been affected by insects in store, has moulds (possibly resulting in the production of mycotoxins) or contains noxious impurities, such as ergot or droppings. Even for the feed market, failure to reach a reasonable standard will result in a lower price.
- Grain attributes, which are required in various markets involve appearance, moisture content, specific weight, varietal purity, seed vigour, seed germination, protein quantity and composition, endosperm texture, flour yield and colour, water absorption capacity and enzyme activity.
- Some of these attributes are genetically controlled (e.g. endosperm texture), others relate mainly to the husbandry of the growing crop (e.g. grain N content) and still others to post-harvest management of the grain (e.g. germination, enzyme activity).
- Moisture content is one of the most readily manipulated quality characters. Drying with ambient air poses no direct risk to quality (although indirect microbiological deterioration is a serious hazard) but drying with excessive heat is known to reduce quality (discoloration, seed death, loss of vigour, protein denaturation and reduced lysine availability) with effects also dependent on initial moisture content. Dehumidifying, using dried ambient air, has become more popular recently, but little information is available on its effects on quality.
- Short-term storage (up to 15 months) is the norm for both growers and processors, though Intervention has resulted in much longer storage

periods. Storage at high moisture and high temperature increases grain respiration leading to heating, loss of both water and dry matter and reduces seed vigour and viability.

◇ Short-term storage under correct conditions can be advantageous in that, for wheat, protein chemistry is altered leading to better baking quality (an effect exploited by millers through grain carry-over from one season to the next) while, for barley, dormancy is broken due to after-ripening effects, giving a more evenly germinating sample for maltsters.

3.8.2 Seed

For the seed market, the grain lot must be of high germination, free from weed seeds and true to type.

◇ There is currently a lack of standardisation of vigour tests for cereal seed but, as vigour is less important in cereals than in other crops because of the considerable plasticity of crop structure and consequent compensatory ability, a reliable vigour test may not be a priority aim.

◇ The Tetrazolium test to estimate germination capacity, though widely used, is not completely reliable with heat-damaged grain. The production of a reliable rapid test which could be used at maltings/seed plant intake would be extremely valuable.

◇ Specific weight is widely used as a criterion for grain purchase but, except where the density of grain is important in minimising transport costs, e.g. when exporting, there is little justification for its use. For malting barley, % screenings is more reliable than specific weight as a measure of malt extract. For wheat, specific weight does not correlate with either flour quantity (i.e. extraction) or flour quality and, although it may indicate flour extraction potential in a single variety, across varieties it shows little relationship.

◇ Specific weight may be improved through the removal of low density grains in a gravity table separator. The remaining higher density grains may have high protein content and higher Hagberg Falling Number (HFN) with greater viability and seed vigour. It remains to be proven whether or not high HFN grain separated in this manner is capable of improving loaf quality.

3.8.3 Feeding

Barley, the traditional animal cereal feed grain, has been complemented in recent years by wheat, which is lower in fibre, has a higher energy content and usually a higher protein content. Trade in grain is not affected by feeding quality so currently, very low priority is given to breeding programmes aimed at higher quality feeding varieties.

- The two major industrial uses for grain are for malting (barley) and bread and biscuit making (wheat).

3.8.4 Malting

Maltsters require good malting barley varieties, sound grain of good uniform size with high viability and with low protein content.

- Good malting varieties take up water readily, germinate rapidly and evenly and produce high levels of hydrolytic enzymes. Varieties of different malting characteristics are used to meet the range of consumer specifications.

- During early germination, the physical structure of the endosperm is quickly and uniformly modified by the breakdown of cell walls and the protein matrix, thus liberating the starch granules. Slow germination and slow endosperm modification lead to high levels of cell wall (gums) remaining in the malt and possible haze in the beer. When uneven germination occurs, some grains are over-modified resulting in loss of fermentable carbohydrates due to root growth while others are under-modified, so that starch grains are not fully extracted.

- There is a clear correlation between grain N and amount of malt extract, low grain N giving more fermentable extract. A low nitrogen content within the range 1.5 to 1.65% is required. Higher nitrogen barley lots are more difficult to malt, often taking up water more slowly and usually yielding less fermentable carbohydrates.

- The grain must be fully ripe before harvesting, as unripe grains may be non-viable or more dormant and less vigorous than fully mature grains. Certain varieties such as Triumph and Doublet are prone to dormancy, especially when grown in cool conditions such as pertain in Scotland and northern England in certain years.

◇ Malting performance is assessed by the yield of hot water extract obtained in micro-malting tests which simulate the commercial process.

3.8.5 Bread-making

Hard wheats are required for bread-making. When hard wheats are milled the bran is easily separated from the endosperm giving high extraction rates of coarse, white flour which flows readily in bulk and which is capable of higher water adsorption in the production of dough. Soft wheats have much lower extraction rates and the flour has a higher bran contamination. The flour is composed of fine irregularly-shaped particles which flow poorly, are difficult to sieve and have a lower water adsorption capacity.

◇ The ability to yield a high flour extraction is a varietal characteristic and cannot be influenced by husbandry or environment.

◇ Wheat flour is used for bread-making because it gives a viscoelastic dough when wetted. Doughs may be either strong or weak, depending on the quantity and quality of protein. Stronger doughs exhibit elasticity due to the presence of much good quality gluten protein, whereas weak doughs are deficient in gluten but often show extensibility imparted by gliadin proteins.

◇ The strong flours used in bread-making develop an extensive viscoelastic matrix during dough formation which retains the gas produced by fermentation and, after baking, gives a large well-aerated loaf.

◇ The protein content required in the wheat may vary from 11% to 15%. There is a relationship between protein content and loaf quality, but this relationship appears to be less good for bread baked by the widely used Chorleywood process, which can cope with lower protein wheat (11%), than by the long fermentation method. The relationship has also sometimes been shown to break down where protein differences have been introduced by differential fertiliser application to the crop.

- A simple measure of protein quality may be obtained by washing the starch from a sieved wheat wholemeal sample leaving the gluten to be assessed subjectively for gluten strength. However, the sodium dodecyl sulphate (sedimentation test) which uses a wholemeal sample, provides a measure for both protein content and quality. Across varieties, it is superior to protein content (analysed by Kjeldahl or Near-infra-red reflectance) in indicating loaf volume. A good SDS is >60; SDS <50 is unlikely to give good bread.

- It is frequently stated that protein quality is dependent on genotype but not environment. Protein quality is strongly inherited but that the environment is not involved is clearly not correct. Crops suffering from either sulphur deficiency or severe aphid infestation are known to have reduced protein quality, and there can also be a negative interaction on protein quality with late urea and fungicide sprays.

- The starch in the flours is degraded to sugars (glucose and maltose) by the enzyme alpha-amylase which occurs in different amounts in different flours. The sugars liberated combine with some amino acids during baking, thereby sequestrating the nutritionally important amino acid lysine, and cause a stickiness in the crumb in the loaves which are then difficult to slice mechanically. The level of alpha-amylase is measured as the Hagberg Falling Number (HFN), which is an indicator of the conversion from starch to sugar. HFNs in excess of 220 are required by the industry, low HFNs being the major limitation to reliable use of home-grown grain for bread-making.

- All grain lots contain some endogenous alpha-amylase. There appear to be four stages of grain development at which the enzyme can form:

  (a) Green alpha-amylase — formed soon after anthesis but disappears when the grain moisture content has dropped to about 50%. This amylase does not appear to contribute to low HFN in harvested grain.

  (b) Pre maturity alpha-amylase — between about 40% and 20% grain moisture alpha-amylase can form in slow drying conditions in the absence of sprouting.

(c) Pre dormancy sprouting — the enzyme can form in wet weather before the onset of dormancy.

(d) Post dormancy sprouting — following dormancy, alpha-amylase can form in wet weather as grain germinates.

◇ There is genetic variation for pre maturity alpha-amylase activity, alpha-amylase activity due to sprouting and post dormancy enzyme formation, the two characters being inherited independently. Thus, varieties differ in alpha-amylase content where there is no sprouting activity, and if growing for quality wheat, varieties with low alpha-amylase and good resistance to sprouting should be chosen.

◇ There is a tendency for alpha-amylase levels to reach a minimum during ripening and thence to increase. In consequence there is an optimum date at which the grain should be harvested. Crops for bread-making are normally favoured by early harvest but the uncertain influences of variety and weather on alpha-amylase are such that changes are best followed by monitoring.

◇ The main problems with analysis for HFN are the variability that exists in the test results and the expense of the analysing instrument, which limits wider use by grain producers as a marketing aid (as equally does the expense of % protein measurements). The variability may largely be a sampling problem, since the distribution of alpha-amylase in low HFN samples is highly asymmetric, i.e. a few grains in a sample may have developed high alpha-amylase activity. A cheaper instrument for measuring HFN exists but its capabilities are not adequately proven.

◇ It is difficult to produce a set of specifications which a grain lot must meet for the various markets for bread-making, because some millers specialise in certain types of bread that have particular requirements and because lots may be blended with high quality imported wheat. Millers purchasing for bread-making usually require a specific weight above 76 kg/hl, a protein level of 11% (at 14% grain moisture content) and a HFN in excess of 220.

◇ Home grown wheat varieties now provide most of the flours for mass produced white bread in the UK but are often supplemented with gluten or imported high protein flour. General purpose bread flours usually contain only 30-40% UK wheat varieties, the strongest flours being made from North American grain.

- There is a need for flour colour to be unaffected by ripening diseases such as Cladosporium which darkens the flour.

3.8.6 Biscuit making

For biscuit making, flours are made from soft-milling wheats and have the reverse characteristics to those required for bread-making, i.e. they have low elasticity but high extensibility. Extensibility ensures that the various biscuit shapes cut from the sheets of dough remain in shape after cutting.

- As is done in many countries, elasticity of a flour may be reduced to the required level by adding a reducing agent, such as sodium metabisulphite, so the type of wheat used is not critical.

- Wheats with protein levels below 10% are preferred, thereby reducing the adverse effects of gluten. The low water adsorption capacity of soft wheats lessens the chances of cracking during cooling after baking. A wide range of alpha-amylase activities can be tolerated in flours for biscuit making.

3.8.7 Physiological research needed

3.8.7.1 Controlling grain quality

Grain formation lasts a short time in which not only size but the 'content' of grain is finally fixed. The crop manager's role in this is currently conceived as a passive acceptance of a course of key events over which he can no longer exert much control and of which the implications are obscure until harvest. Improving intelligence on grain quality is discussed in Section 4.4.6. However, other sections of this report cite many instances where quality may be controlled.

There are means available not only to control late leaf and ear disease (as explained in Section 3.6.5.3) and aphid infestations, but to provide nitrogen (Section 3.4.10) and sulphur for protein formation (Section

3.8.7.4b), provide naturally derived cytokinins, and increase or inhibit gibberellin levels (Section 3.7.4), which in turn may alter cell division, cell expansion, enzyme activities and leaf longevity. There is thus some scope to intervene in grain formation, given an ability to correctly assess the implications of observations and action at each stage.

3.8.7.2 Observing and defining grain development

The foundation of any sound intervention in grain growth is the accurate recognition of developmental events. Current definitions of grain development ("growth stages") are subjective (viz: watery, milky, or cheesy ripe), and are not related to physiologically distinct events. A revision of these definitions is needed which aims to tie observable characters to progress through the phases of cell division, cell expansion, deposition of storage materials, and dehydration.

3.8.7.3 Malting

a) Heritable components of malting quality For malting the level of N accumulation in the grain and the ability of the barley lot to germinate evenly and vigorously are vital. Research is needed to elucidate the differences at the biochemical and physiological level between good and bad varieties, identifying the proteins and other characteristics which confer good malting quality and on the factors that influence dormancy so that a balance can be struck in varieties between the level of dormancy desirable to protect grain from pre-germination in wet harvests and that of prolonged and stubborn dormancy.

b) Quick germination tests Germination testing by both seed merchants and maltsters could be improved by the development of a reliable, rapid test which could be used at maltings/seed plant intake. The Tetrazolium test is widely used but is not completely reliable especially with heat-damaged grain.

c) Predicting dormancy Work carried out to predict dormancy has not achieved forecasts of adequate accuracy. A more detailed set of case histories should be assembled as a base against which to test explanations of differences in dormancy, particularly that found in barleys produced further north in the United Kingdom where dormancy appears to be associated with overcast, sunless summers and possibly with slow rate of grain development.

3.8.7.4 Protein

a) Measurement of protein on the farm Although NIR is likely to remain the method on which most trade in grain is based the superiority of the SDS test over protein content in indicating baking performance of a flour and the rapidity and cheap equipment with which the test can be made means that there is some scope for the method to be developed to assist on-farm management of grain through tests made possibly before as well as after harvest, allowing best treatment during harvest, drying and storage to be given to the best quality grain.

b) Monitoring the development of sulphur deficiencies With the progressive desulphurisation of flue gas from power stations wheat crops should be regularly monitored for sulphur deficiency by testing samples in the H-GCA quality survey for % S and N:S ratio. Deficient areas should then be verified by inclusion of sulphur treatments in wheat experiments with an appropriate geographical distribution. This should enable the industry to pre-empt by applying sulphur, the expected deterioration in protein quality of deficient crops because of inadequate formation of the sulphur-containing proteins important in conferring elasticity on wheat dough.

c) Favouring proteins of nutritional value Changes in grain growth can bring changes in grain composition as well as in size. Proteins laid down during the first, cell division, phase of grain filling have better nutritional value than the storage proteins laid down during the second, cell expansion, phase. It is possible that deposition of grain nitrogen could be increased during the first phase at the expense of storage proteins laid down later so that feeding value (or baking quality) could be improved.

d) Deposition of 'elastic' proteins With the recent identification of specific wheat proteins which confer elastic properties on the dough there follows a need to trace the deposition of these proteins through the course of grain development so that inferences can be drawn (and tested) of ways, through husbandry as well as breeding, of optimising the content of these proteins in grain grown for breadmaking.

3.8.7.5 Alpha-amylase

Review article No. 2 published by the H-GCA on "Hagberg Falling Number and Breadmaking Quality" included recommendations for research on husbandry (p.57), breeding (p.76) and biochemistry (p.86). The Group endorses these recommendations. The following are intended as supplementary proposals:

a) Rapid tests for alpha-amylase Although Hagberg Falling Number is widely used, rapid and easy to conduct it uses expensive equipment, is subject to considerable variability and does not relate directly to the alpha-amylase levels in grain. Other instruments for measuring HFN have been devised. The capabilities of these methods and rapid alpha-amylase tests should be tested for reliability and suitability for use in assisting on-farm management as well as in trade.

b) Origins of high amylase grain The observation through use of the gravity separator of an association between low density and high amylase levels in wheat grain provides a useful opportunity to trace the development and origins of the relatively few high amylase grains within a crop which eventually displays a poor HFN. Whether these grains are from lodged stems, disadvantaged florets, precocious tillers, affected by aphid feeding or caused otherwise should be explored through 'mapping' of grain densities within the crop's structure. Identification of the origins of high amylase grains within a crop would assist in devising sampling schemes for amylase prediction, choosing criteria for selection in breeding programmes, and formulating explanations of how weather influences the amylase level at harvest.

3.8.7.6 Control of grain shrivelling

The phenomenon of retranslocated stem reserves has not been satisfactorily explored. Risk of grain shrivelling may well be related to a ratio between a stem's content of sugars and its ear weight or number of set grains. These may be easily observed. A large reserve per grain where risk of disease and drought are low may indicate the scope for fertilising, protecting, and perhaps stimulating grain growth.

Such observations together with some analysis of reserves remaining in stems at harvest may give a closer explanation of treatment effects on the course of grain filling in field experiments more generally. This approach may be particularly valuable in areas, such as fenlands, where grain shrivelling is a common problem and practices are needed which more regularly achieve crops at flowering with a structure which will enable post-flowering photosynthesis and retranslocation to comfortably fill the grain.

3.8.7.7 Specific weight

Specific weight (grain bulk density) is widely used as a criterion for grain purchase, but except where the density of grain is important in minimising transport costs, e.g. export, there is little justification for its use. For malting barley, % screenings is more reliable than specific weight as a measure of malt extract. For wheat, specific weight may indicate flour extraction in a single value for a variety, but across varieties shows little relationship. Since a single specific weight (usually 76 kg/hl) is the trading minimum for all bread-making wheat varieties, there is little argument for its retention other than as a criterion for market manipulation by Intervention purchase.

Another, less important, problem with specific weight is that it varies with moisture content, and a correction factor is frequently used for wheat to adjust to a common moisture content. Unfortunately, this relationship differs between varieties, but no account is taken of this when the correction is used. A further difficulty with this correction is that the relationship is only linear over a narrow moisture range.

FMBRA are carrying out research into alternative methods of assessing flour extraction. Intensification of this research would be of great benefit to all involved in wheat trading if it led to the eventual relinquishment of specific weight.

Cleaning clearly improves quality by removal of admixture but can also often increase specific weight. There are reputed to be instances, however, where **addition** of smaller particles of admixture can increase specific weight, presumably by filling the voids between grains. As long as the total admixture is less than the buyer's requirement then this practice will lead to enhanced **apparent** quality.

There is a need for a thorough analysis of the relationship between grain size distribution and bulk density. This would depend on an ability to perform detailed particle size analysis and should have the objectives of:

a) stipulating how the procedure for specific weight should be tightened so that added impurities do not cause improvements and define moisture correction methods and specific weight thresholds according to variety so that flour extraction is better predicted.

b) recommending cleaning procedures (e.g. screen sizes) which will optimise specific weight and % screenings according to the characteristics of the uncleaned grain.

c) identifying any analytical methods which better predict malt extraction in barley and intensifying development of image analysis techniques for predicting flour extraction in wheat.

3.8.7.8 Seed for sowing

a) Seed quality for substandard seedbeds

It is not unusual for some fields on a farm to be sown in 'compromise conditions' in order to avoid deteriorating weather and to achieve sufficient early growth (cf autumn 1987). A satisfactory standardised method for determining vigour of cereal seeds, as has successfully achieved commercial adoption for other crops, is needed so that establishment in poor conditions can be maximised.

b) Effect of nutrition and climate on seed ripening

Conditions during ripening are known to affect alpha-amylase activity and dormancy of harvested grain. In other crops e.g. sugar beet, cold temperatures during seed ripening are found to affect development of the daughter crop. There is evidence that ripening differences particularly as they affect nitrogen content and grain size, may alter seed quality or development of the daughter crop. There is scope for investigating this subject further.

3.9 TAILORING HUSBANDRY TO SITE AND SEASON

3.9.1 General

In the earlier sections of this chapter the influences of physiological knowledge on cropping decisions have deliberately been considered in relation to aspects of husbandry taken in isolation. It is of course recognised that the response to husbandry factors change from season to season and site to site in degree and even, on occasion, in direction. Can the physiologist help to tailor husbandry to suit particular sites and seasons? The challenge is in two stages: first to determine the potential for each site in a particular season and second to identify the factor that inhibits the achievement of potential in each case. Progress in this area might bring benefits not only to the individual grower but to the industry as a whole through improved ability to forecast yield and, possibly, reduced year to year variation in national yield.

3.9.2 Potential vs achieved yields

There have been several well substantiated cases of individual fields producing of the order of 12 tonnes/ha. A measure of potential can be obtained in a systematic way from multifactorial experiments where different levels of the main yield limiting factors (place in the rotation, sowing date, N amount and timing, irrigation, crop protection programmes) are tested in combination. The best treatment yield can be taken as a measure of potential. The most comprehensive multifactor experiments in the UK were at Rothamsted and yield maxima for winter wheat and winter barley are presented in Table 1 together with measures of 'good' and 'average' performance. The Experimental Husbandry Farms of ADAS embrace the range of farming systems, soils (Table 2) and climate operating for wheat and barley grown in England and Wales and their yields can be taken as reflecting achievement with good husbandry. The differential between good husbandry and potential of 2-3 t/ha may be an overestimate for it is known (although by no means fully explained) that yields from experimental plots exceed those from whole fields by the order of 10%. Average performance, from MAFF census data, is about 0.5 t/ha below 'good practice' for wheat but 1.0 t/ha less for winter barley. This may be a reflection that barley is grown more on the less specialised cereal-growing farms so receives less attention to detail. Also, compared with wheat, barley is generally grown at less favoured points in the rotation and more widely on the less fertile soils; data from Rothamsted indicate that its potential is about 1 t/ha less than wheat. On the evidence of Table 1 there is clear scope, with existing knowledge and techniques, for achievement with both crops to come closer to potential.

3.9.3 Season and site

Average yields of winter wheat from the EHFs (Table 3) reveal that 1984 was the highest yielding year at 7 of the 8 sites (the exception was Gleadthorpe) and that Rosemaund was the highest yielding site in 9 of the 10 years (the exception was 1989) with Gleadthorpe consistently low yielding. Were there any features of the weather experienced in 1983-84 that might account for the high yields? Of the three ways that weather influences cropping (opportunities for cultivation, influences on pest and disease incidence and direct effects on growth) the 1983-84 season was certainly not unfavourable for the first and second but on the evidence of weather data from Sutton Bonington (Table 6) the most unusual aspect was a combination of temperatures below average from May until July with radiation above average from June until August.

Unravelling the cause of yield variation due to weather is more complicated for cereals than for vegetative crops such as sugar beet (where the record yields in 1982 could be confidently and directly attributed to a period of unusually high temperatures in May and June that advanced the closure of the leaf canopy by three weeks compared to the norm, thereby substantially enhancing the amount of radiant energy absorbed by the leaf canopy). While sugar beet grows for as long as the weather allows, cereals mature and die for genetic and physiological reasons well before the end of the growing season. Moreover, the components of grain yield are not determined concurrently; grain number is determined by flowering and grain size thereafter. Leaf production is complete at flowering and temperature has a marked effect on senescence. In addition to high temperatures hastening leaf senescence and thereby shortening the main growth phase of cereals, they directly shorten the interval between developmental stages. The warmer the temperature, the shorter the growth period and a simple analysis indicates that cereal yields would be expected to decrease with increasing mean temperature for the period May until July. In England and Wales, mean cereal yields do show a trend of decreasing by about 5% per increase of 1°C mean temperature from May until July.

Results from sowing date experiments and those done at different latitudes show that the longer the period of each developmental stage (early sowing, higher latitudes, cool temperatures, adequate water supply), the longer the period for the interception of radiation and the higher will be the potential yield. Cereal crops in 1984 evidently benefited from the combination of cool, bright conditions.

Many in the industry were pleasantly surprised by the yields in 1989. Although December–March were exceptionally mild and May was warm, April and June were cooler than average. The exceptional feature was the prolonged high radiation, consistently over 10% above average, from May through to August. Evidently the combination of the wet April and average June rainfall was sufficient to exploit the remarkable potential for growth.

While it is possible now to give pointers to the origin of seasonal effects there is scope to do much more. Development and reinforcement of our ability to assess crop performance during growth is an obvious target as suggested in Section 4.4.7.

Why are wheat yields from Rosemaund consistently high? Again there must be lack of precision in the answer but pointers can be given. The soil is deep and water retentive and root systems are extensive and look healthy. Indications from studies of crop development at the EHFs are that wheat at Rosemaund has a longer growing season than in the Eastern Counties; it reaches the terminal spikelet stage a few days earlier, yet senesces a few days later. Comparisons of growth point to a high total biomass at the end of the season and more growth from flowering onwards. It seems likely that the failure of Rosemaund to be the top yielding site in 1989 originated in the very dry April which led to even greater soil moisture deficits than in 1976 and rapid senescence by early July.

In England the norm is for winter wheat crops to require some 300 mm of water to transpire at the potential rate and thus achieve potential yield. At Rosemaund wheat will usually comfortably obtain this from soil reserves and rainfall that averages 200 mm from April until the end of July. This also normally applies at Rothamsted, Terrington, Boxworth and Drayton. The Bunter Sand at Gleadthorpe is the clear exception and consistent low yields (poorest in all years other than 1985) reflect the low soil water holding capacity.

Yields of winter barley were generally good in 1984 (Table 4) but it was not the best year at every site; 1983 was better at High Mowthorpe and Boxworth. While the causes of this effect are not known it is possible to throw some light on why Rosemaund is not so clearly top yielding for winter barley as for winter wheat. Despite every effort to choose the best standing varieties and make judicious use of growth regulators, winter barley lodges in some years and it is in these that its yield is not the best.

Spring barley yields (Table 5) are lighter but apparently more stable than the winter cereals. No year was consistently best. As with other cereals Rosemaund's yields were generally good whilst Terrington's were generally poor.

3.9.4 The nature of yield variation

More extensive data available for winter wheat show that in the same season, there is a large variation in yield, even within the same locality. Examination of grain yields from individual fields growing winter wheat shows that the greatest proportion of the fields gives the mean yield, with an equal proportion greater and smaller than the average. With a mean yield of 5.5 t/ha and coefficient of variation of 18-24% only 1 in 10,000 fields yields over 10 t/ha. It is interesting that the variation in yield from the 'ICI 10 Tonne Club' is almost as great as the national average, even though yields average 2 t/ha more. Surprisingly, there is no evidence that higher inputs, and in all probability a better all round standard of husbandry, decrease yield variation. In the ICI data, there is no evidence that at the upper end of the yield scale a biological limit, that is extremely difficult to achieve, is being approached. Such a 'normal' distribution is usually a sign that many factors are contributing at a similar level and independently to the control of yield, rather than a few overriding ones. It seems that there is a small chance of all the factors inherent in the site, and all management decisions, being just right. Attempts to associate different features of sites and cropping with yield level have not indicated clearly dominant factors. Soil series was the factor accounting for most variation, but then only 18-19%. There was a tendency for yield of 10 t/ha to be obtained on the 21 out of 92 soil series that contained more loess than average.

3.9.5 Controlling yield at different sites

When controlled experiments have been made on a range of soils, it has usually proved possible, with careful agronomy, to achieve yields of 10 t/ha with first wheats after a break crop. In the comprehensive set of multifactorial experiments on winter wheat made on clay loam at Rothamsted and sandy soil at Woburn, several major yield restrictions were found. The effect of growing as a second cereal, rather than the first after potatoes or oats, caused the greatest difference in yield at nearly 3 t/ha, around 30%. Their take-all damaged root systems meant that second wheats benefited more from early nitrogen.

With irrigation and effective crop protection, yields in 1981 were as good on the light, sandy Woburn soil as those at Rothamsted. Treatment effects were greater at Woburn, e.g. late sown crops yielded poorly at Woburn unless given early (March) nitrogen; winter leaching moved more N deep in the profile and therefore out of the rooting range on the sand. Nitrate content of the sap in the stems revealed the limiting level at Woburn from March onwards whereas this was not reached at Rothamsted until early April.

In summary, it appears that the potential yield of winter wheat grown in the UK is currently 12-14 t/ha grain at 85% dry matter. With census results showing a mean yield of 6.1 t/ha in 1988 and a range from 2 to 14 t/ha, there would seem a great deal of scope to increase yield without improvements in genetic potential. Evidence from recent years suggests that the upward trend in national average yield so marked in the '50s, '60s and '70s is not being maintained in the '80s. Variety improvement demonstrably continues through recommendation of new varieties in place of varieties becoming outclassed. However, there has been no major advance in husbandry in the '80s equivalent to the progress made through better weed control and soil fertility in the '50s and '60s and in cultivations, disease control, lodging control and thus nitrogen nutrition which took place in the '70s.

Of the remaining major obstacles to full achievement of crop potential in cereals, some are well recognised, such as control of root disease, particularly take-all in wheat, virus control, particularly BYDV, control of grass weeds, control of lodging, particularly in winter barley, and provision of a well programmed moisture supply. Other obstacles may well exist as major restrictions on achievement, but go as yet unrecognised. There is thus still ample scope for new techniques to bring yield improvements in the 1990s. However, it is unquestionable that, even with existing techniques, achievement could often come closer to potential.

Table 1 Seasonal differences in cereal yields as shown by the MAFF census for the UK (average husbandry), EHF field yields (see Tables 3 and 4; good husbandry) and Rothamsted multifactorial experiments ('potential')

	WINTER WHEAT			WINTER BARLEY		
	MAFF census mean	EHF field mean	Rotham[d] expts. max	MAFF census mean	EHF field mean	Rotham[d] expts. max
1980	5.9	6.5	7.1	4.5+	5.8	-
1981	5.8	6.4	10.7	4.4+	5.3	7.8
1982	6.2	6.4	9.1	4.9+	5.6	8.7
1983	6.4	7.2	10.6	4.7+	6.3	8.5
1984	7.7	8.6	11.8	6.2	7.4	11.4
1985	6.3	6.8	9.1*	5.5	6.6	9.5
1986	6.9	7.4	10.7*	5.7	6.7	8.4
1987	6.0	6.7	8.1*	5.5	6.6	7.6
1988	6.1	6.8	7.3*	5.2	6.2	7.0
Mean	6.4	7.0	9.8		6.3	8.6

+ winter _and_ spring barley

* data for Avalon in variety trial without multifactorial treatments

Table 2 Experimental husbandry farms of the Agricultural Development and Advisory Service

Arthur Rickwood EHF Mepal, Ely, Cambs.	76 ha fen farm. Black fen peats over clay or sand. Main enterprises: potatoes, cereals, sugar beet, field vegetables such as carrots, celery and onions.
Boxworth EHF Boxworth, Cambs.	346 ha heavy land farm on chalky Boulder Clay. Main enterprises: intensive cereals, some break crops.
Bridgets EHF Martyr Worthy, Winchester Hants.	428 ha chalkland farm. Main enterprises: cereals, some break crops, large dairy herd (250 cows plus followers).
Drayton EHF Stratford-on-Avon, Warwicks.	182 ha farm on very heavy Lias clay. Main enterprises: intensive winter cereals, field beans and grain utilised in finishing dairy-bred beef or through prolific intensive sheep flock
Gleadthorpe EHF Meden Vale, Mansfield, Notts.	200 ha sandland farm. Main enterprises: cereals, potatoes, sugar beet. Some grass, utilised through dairy-bred beef. Only EHF poultry unit with laying hens and table poultry.
High Mowthorpe EHF Duggleby, Malton, Yorks.	437 ha wold farm on silty clay loams over chalk. Main enterprises: cereals, fed to suckler herd or through sheep. Dairy-bred cattle also finished.
Rosemaund EHF Preston Wynne, Hereford.	176 ha farm on silty clay loams over old crop. Main enterprises: cereals and cattle. Hop enterprises.
Terrington EHF Terrington St Clement Kings Lynn.	120 ha, silty loam over alluvium. Main enterprises: cereals, potatoes, sugar beet; some minor cash crops. Over 100 sows; progeny taken through to bacon.

Table 3 Average field yields of winter wheat (t/ha) from experimental husbandry farms (EHFs) in England (see Table 2 for farm descriptions)

Year	Drayton	Boxworth	Terrington	Rosemaund	Bridgets	High Mowthorpe	Gleadthorpe	Arthur Rickwood	Mean
1980	5.6	7.0	6.3	8.7	6.4	4.8	-	6.5	6.5
1981	5.8	6.8	6.6	7.7	6.9	5.7	-	5.3	6.4
1982	6.5	6.1	5.1	7.3	7.7	6.1	-	6.3	6.4
1983	6.6	7.3	7.3	7.8	7.6	7.8	6.3	6.7	7.2
1984	7.6	8.6	9.5	10.4	9.2	8.5	6.1	8.5	8.6
1985	6.6	7.1	7.2	8.6	6.4	7.0	6.5	5.2	6.8
1986	7.5	7.0	7.8	8.6	7.7	7.3	6.5	6.5	7.4
1987	6.4	6.1	6.9	7.4	7.3	6.9	6.7	6.2	6.7
1988	6.4	6.5	8.0	8.7	5.8	7.7	5.8	5.8	6.8
1989	6.5	7.6	8.5	6.9	8.5	7.1	5.6	6.9	7.2
Mean	6.6	7.0	7.3	8.2	7.4	6.9	6.2	6.4	7.0

Table 4 Average field yields of winter barley (t/ha) from experimental husbandry farms (EHFs) in England (see Table 2 for details)

Year	Boxworth	Bridgets	Terrington	Rosemaund	High Mowthorpe	Gleadthorpe	Arthur Rickwood	Mean
1980	6.8	5.6	5.3	7.3	4.6	6.3	4.4	5.8
1981	6.1	5.5	4.6	5.6	6.2	5.1	3.8	5.3
1982	6.8	5.2	5.2	6.3	6.2	4.9	4.6	5.6
1983	8.1	6.7	5.5	6.7	7.2	5.8	4.3	6.3
1984	6.9	7.8	7.6	10.5	7.1	5.7	6.4	7.4
1985	6.9	8.1	-	8.2	6.0	5.9	4.7	6.6
1986	6.7	7.1	-	7.5	6.7	5.7	-	6.7
1987	7.8	6.6	-	6.7	5.9	5.8	-	6.6
1988	4.8	5.9	5.8	7.4	7.0	6.0	-	6.2
1989	-	7.5	7.0	7.6	7.0	5.2	-	6.9
Mean	6.8	6.6	5.9	7.4	6.4	5.6	4.7	6.3

Table 5 Average field yields of spring barley (t/ha) from experimental husbandry farms (EHFs) in England (see Table 2 for details)

Year	Bridgets	Drayton	Terrington	Rosemaund	High Mowthorpe	Gleadthorpe	Mean
1980	5.6	-	5.8	5.1	4.9	5.1	5.3
1981	5.0	-	5.1	5.7	5.3	6.0	5.4
1982	6.1	4.7	5.1	5.6	5.2	4.6	5.2
1983	6.1	3.5	4.8	5.4	6.1	5.3	5.2
1984	6.1	4.8	4.8	5.6	6.3	4.7	5.4
1985	5.9	4.6	5.1	6.6	5.5	5.9	5.6
1986	5.3	4.7	5.6	6.3	5.7	5.1	5.5
1987	4.7	4.9	4.7	-	6.0	5.3	5.1
1988	5.0	4.5	4.7	5.5	4.8	5.0	4.9
1989	5.1	4.0	4.2	3.3	4.1	5.9	4.4
Mean	5.5	4.5	5.0	5.5	5.4	5.3	5.2

Table 6 Weather at Sutton Bonington in 1983/84 and 1988/89 compared with the long term average

	Monthly Rainfall mm			Mean Daily Radiation MJ/m^2			Mean Temperature °C		
	Long term	83/84	88/89	Long term	83/84	88/89	Long term	83/84	88/89
Oct	51	41	55	5.5	6.1	5.6	10.3	10.5	10.5
Nov	58	38	30	2.8	2.3	3.3	5.7	7.6	4.7
Dec	53	52	20	1.7	2.0	1.7	5.1	5.4	7.2
Jan	50	84	28	2.2	2.8	2.4	3.3	3.5	6.1
Feb	41	45	47	4.1	2.1	5.3	3.0	3.1	5.9
Mar	45	58	46	7.0	2.1	7.8	3.8	4.5	7.7
Apr	40	7	105	10.9	14.7	9.5	7.0	7.7	6.2
May	49	60	17	14.8	14.1	19.4	12.8	9.7	12.7
Jun	48	75	53	16.5	17.9	19.5	14.9	14.4	14.1
Jul	50	24	35	15.4	18.6	18.2	17.1	16.3	17.7
Aug	60	62	47	12.8	14.7	16.6	15.7	17.3	16.6

3.10 BREEDING

3.10.1 General

An improved understanding of the growth and development of cereals has provided a basis for breeders' selection criteria and thus aided the breeding of better varieties. Research in recent years, concerned with understanding genetic variation in responses to photoperiod, temperature and light intensity in terms of affected processes such as photosynthesis, respiration, tillering, leaf expansion and shoot apex development, has resulted in improved definition of the ideal wheat and barley plants (ideotypes) for modern agricultural conditions. As physiological knowledge increasingly complemented and underpinned empirical agronomic investigations to optimise the use of land and other resources to achieve maximum economic returns from cereal growers, breeders responded by producing varieties capable of exploiting the new environments, and their ability to do so has been aided by an insight into the underlying physiology involved.

Specific contributions of benefit from research on growth and development have been cited by world experts (listed in Appendix A and consulted by post) as including:

a) altered phenology to maximise benefits from early sowing. Winter wheat varieties must have a strong vernalisation requirement.

b) earlier flowering to reduce risk of drought and consequent yield loss. Earlier flowering also permits the late stages of ear development and grain filling to occur at lower (more favourable) temperatures and higher light intensities.

c) recognition that under high input conditions erect-leaved genotypes give improved yield.

d) assessment of the benefits and disbenefits from increased ear-bearing capacity.

e) characterisation of the side effects of the gibberellin-insensitive dwarfing genes in wheat.

f) recognition of the negative correlation between yield and percentage protein content of the grain and hence the need in wheat to improve protein yield if varieties more suitable for bread-making are to be produced.

g) use of harvest index as an early generation selection criterion.

h) development of techniques which can be used for biochemical tests for beneficial traits on small amounts of material early in the plant life cycle.

i) identification of beneficial grain protein components and methods of screening for them.

j) development of tests in controlled conditions to examine environmental responses such as drought tolerance.

k) identification of the most important genetic traits and biochemical processes involved in the baking quality of wheat and malting quality of barley.

3.10.2 Physiological targets for genetic improvement

The following are suggested as physiological or biochemical traits which can be identified as providing targets for genetic improvement of potential performance of cereal crops either by conventional breeding or genetic engineering.

3.10.2.1 Seedling vigour

a) High concentrations of seed protein are required to give rapid emergence and vigorous seedlings, whilst avoiding restriction of the potential yield of such seed per unit area.

b) Large seeds are necessary to give rapid seedling emergence, reduced vulnerability to deeper sowing and increased desiccation resistance during germination. Effects of producing large seed on proportions of grain constituents should be checked.

c) A large and vigorously growing first leaf is needed to obtain early light interception. This may not be simply related to seed size.

3.10.2.2 Root growth

a) The use of a larger proportion of plant assimilate for root growth to assist in lodging resistance and help prevent seedlings and plants becoming susceptible to drought. Effects on rapidity of depletion of soil water or reduction in shoot growth should be examined.

Continued root growth during ear development and grain growth could assure water and nitrogen supply at these critical times. There are likely to be benefits from altering root/shoot ratio within acceptable limits.

b) Good techniques are necessary to measure root distribution and growth in the field and to relate the reactions of roots to soil conditions, such as compaction and localised distribution of plant nutrients, both deficiencies and excesses. Techniques could be devised according to more fundamental studies of ion uptake and transport across membranes.

3.10.2.3 Frost hardiness

Very slow growth during cold spells, through photoperiod and temperature response, which could favour winterhardiness. That this might result in smaller plants, possibly with smaller ear primordia, needs to be examined.

3.10.2.4 Canopy structure

Maximum interception of light, through canopy structure adjustment and optimal distribution of leaves, to increase canopy photosynthetic rates in the main vegetative growth phase. The possibility that such a leaf arrangement may have reduced photosynthetic rates at grain fill when leaf area index is declining would need to be checked.

3.10.2.5 Dwarf habit

Introducing dwarf habit may confer resistance to lodging but may adversely affect crop microclimate and pattern of light interception. In dry conditions, dwarf plants cannot be sown as deeply as normal and their root systems may be less able to tap water at depth. Their changed hormonal relations may adversely affect floret and grain development.

3.10.2.6 Leaves

Fast initiation and longer duration of leaves to speed plant growth. Studies on rates and location of cell divisions in the leaf bases and on hormonal means of ensuring longer activity of green leaves are required. The effect of cell wall biochemistry in controlling leaf extension in conjunction with temperature should be examined.

3.10.2.7 Tillering

Genotypes with restricted tillering, especially absence of late tillering, to eliminate use by late tillers of water, minerals and assimilates to the potential advantage of early fertile tillers. The possibility of reducing the plant's ability to compensate for death of main shoot and early tillers needs to be investigated.

3.10.2.8 Stem growth

Reduced stem growth to permit better ear growth, resulting ultimately in increased yield and harvest index. As the stem and the inflorescence develop at the same time, they must often compete for assimilates. Effects of reduced stature through increased competition from weeds, poorer light utilisation if leaves are too close together, and possibly less capacity to store stem reserves need to be borne in mind.

3.10.2.9 Stem strength

High stem density (dry weight/unit length of stem) to confer resistance to lodging and provide a reserve of assimilates for grain filling. However, too great a withdrawal of material from the stem could lead to increased brackling and necking. The response of stem strength to lateral strains and the potential of plant growth regulators to affect strength need examination.

3.10.2.10 High rates of photosynthesis per unit leaf area

This may be achieved by one or combinations of several routes:

a) Low intracellular resistance to CO_2 uptake to increase both potential dry matter production and efficiency of water use. This may be accompanied by changes in leaf size and thickness which may affect any benefits.

b) Low photorespiration rate to be especially beneficial at high temperatures and in drought.

c) Low stomatal resistance and high stomatal frequency. This could give unacceptably high rates of water loss in dry conditions, only having potential in areas of ample water availability. That greater photosynthetic capacity has not yet been instrumental in increasing yields would suggest its association with some counter-productive effect, such as smaller cell or organ size or shorter duration of photosynthetic activity.

3.10.2.11 Respiration efficiency

Biochemical efficiency of energy production (as estimated, for example, by ADP/O ratios). Differences in genotypes would allow the possibility of selecting for respiration efficiency.

3.10.2.12 Nitrogen response

Genotypes more responsive to N fertiliser, giving larger plants more quickly, or genotypes capable of giving higher DM production per unit of N applied. There could be associated detrimental effects on level or type of grain protein. The capability to export N from leaves when their contribution to canopy photosynthesis is small could be important where soil nitrogen or water is limiting. A fuller understanding of the physiology and biochemistry of nitrogen metabolism and its control is required.

3.10.2.13 Nitrate

The ability to take up and reduce nitrate rapidly, and store nitrate and reduced nitrogen compounds for later use. Minimising loss of soil nitrogen through leaching or denitrification by rapid uptake and making nitrogen readily available at grain filling time (provided accumulation, especially at high levels of applied N, to toxic levels did not occur) should be studied.

3.10.2.14 Resistance to chemicals

Genotypes resistant to agrochemicals (especially herbicides and insecticides), salinity, toxic ions and pollutants. Ways of modifying and selecting such plants are required.

3.10.2.15 Water use

High cuticular resistance to water loss. By reducing transpiration rate, this would be especially useful in drought periods. Stomata, sensitive to water stress, but reopening quickly when the stress is removed. This should prevent irreversible damage in drought. Metabolic processes which are relatively insensitive to internal water stresses. Possessing such processes would be advantageous in drought conditions. Insensitivity to short periods of waterlogging especially during establishment.

3.10.2.16 Awns

Presence (and length) of awns. Awns can contribute substantially to the active photosynthetic surfaces late in the life of a crop and are very favourably positioned in relation to light and CO_2 supply, as well as being the closest source of assimilate for the growing grain. That they may compete with developing florets for assimilate, or may increase susceptibility to disease and lodging under humid conditions needs to be taken into account.

3.10.2.17 Dry matter production

Maximum biomass per unit area. If weight were concentrated in fertile tillers increased competitive ability against weeds, increased uptake of nitrogen and increased grain protein per hectare might result. Reduced efficiency of water use and increased lodging vulnerability might be counter effects. The cause of a claimed dry matter growth spurt at the time of floral initiation requires investigation, as does the relative duration of different phenological stages in terms of thermal time.

3.10.2.18 Floret number

Regulation of floret number, and floret and young grain abortion. This could assure correct grain numbers to match assimilate supply and increase grain size or alter grain composition.

3.10.2.19 Grain size

Control of the cessation of cell division. Potential grain size is a function of the number of cells and means of encouraging cell division should result in larger grain, assuming non-limiting supplies of carbon, mineral nutrients and water during the grain-filling period.

3.10.2.20 Storage proteins

Modification of the nutritive value of seed proteins. A clearer understanding of the regulation of storage protein synthesis should help plant breeders. High N uptake during grain filling and increased production of certain amino acids could be advantageous.

3.10.2.21 Sprouting in the ear

Resistance to help ensure that grain germination is not impaired and that grain for use in bread-making does not have a low HFN. There could be an increase in concomitant dormancy (a difficulty for maltsters) or an inhibition of germination following sowing.

3.10.3 Concluding remarks

Physiological investigation of these specific attributes, so as to better determine the advantages and disadvantages, and therefore their eventual potential for affecting cereal yield, needs to be made against a background as to what should be the foreseeable aims for cereal breeding in the current period of West European (but not world) grain surpluses.

Clearly, the more readily soluble problems have now been dealt with. The less tractable problems require a deeper and more varied attack which will depend on increased physiological understanding of the processes of growth and development and, with a view to expanding the comparatively narrow genetic base of many European cereal varieties, possibly a closer examination of the physiological and biochemical features of more primitive forms and wild relatives of the currently exploited cereal species.

3.11 BIOTECHNOLOGY

Biotechnology has been loosely defined as the use of living plants and animals in industry but has now been accepted as having the narrower definition of those techniques that rely on understanding function at the cellular and molecular levels. This section is concerned almost exclusively with molecular biology and its contributions to an understanding of form, function and productivity.

The traditional improvement of genetic material has been by conventional plant breeding techniques. In contrast, molecular biology now permits fundamental modifications to the genome to take place quickly by the identification of the genes which control economically important characteristics and their direct transfer between plants. Recent experience using chromosome fragments for genetic analysis of economic traits, suggests that the small-grained cereals will share in these scientific developments.

However, there are still major problems in getting this technology to work with cereals. Although a large number of crops including cereals can be regenerated from callus culture, it is not yet possible to regenerate cereals from protoplasts (cell contents excluding the wall). It is impossible, therefore, to apply the large scale screening methods developed for use with micro-organisms to identify resistance or tolerance to factors such as salinity. Even where this has been done with other crops, the tolerance has not always been stable, probably because tolerance to an undesirable factor in a mature plant is usually made up of a complex set of interrelated attributes, some of which cannot be expressed in protoplasts; for example rooting depth or cuticle thickness. Any major advance in the application of molecular biology to cereals must await the ability to regenerate plants from tissue culture.

Despite these problems, it is still possible to identify some opportunities for improvement of cereals using molecular biological techniques. These include the control of seed dormancy, prevention of preharvest sprouting and the manipulation of the quality of storage proteins in grain where current work is already showing promise. One major deficiency in home grown cereals is in the elastic properties of the glutenin protein complex. The higher molecular weight glutenin sub-units are known to have a major influence on dough strength and the molecular biology of this system is being intensively studied. This may lead to the identification and transfer of cloned sub-unit genes from appropriate land races and species into the wheat genome. It is also possible that herbicide resistant varieties, and varieties with improved disease and pest resistance, will be developed in cereals when the techniques become available. These would have the potential to reduce agrochemical inputs and could assist the current move towards methods of biological control of pests and diseases.

Although techniques are not yet available it is right that physiologists should now identify longer term objectives for biotechnologists. For example, the yield of any crop depends on the conversion of photosynthetic solar radiation to vegetable matter. At the present time, the conversion rate in all crops is 1.9-2.2 dry matter/MJ. The total amount of radiation intercepted can be changed by agronomically manipulating the structure of the leaf canopy and its longevity. A change in the conversion rate would seem to be an attractive alternate strategy to increase yields. It would, however, require a major change in the biophysics and biochemistry of photosynthesis. Work is in progress to investigate this possibility, but it is not clear that any change will automatically bring about a major improvement in crop productivity because the yield of the crop is dependent on a wide range of interrelated processes with a large degree of homeostasis. An example of this is the similar yields of C_3 and C_4 plants in the absence of environmental stress, even though the PEP carboxylase, the enzyme responsible for the initial capture of CO_2 in C_4 plants, is many times more efficient than Rubisco, the enzyme responsible in C_3 plants.

There are similar problems in trying to transfer the ability to fix nitrogen into cereals from legumes. The process is controlled by many genes affecting several physiological processes which have to act in sequence. The problems can therefore be infinitely greater than trying to obtain the expression of a single gene.

Considerations such as these indicate that the utilisation of transgenic organisms is several years away, given the need to develop the systems of gene transfer and plant regeneration and to evaluate the resultant material at all stages in this process. In order to evaluate germplasm availability and those attributes which it is feasible and commercially viable to transfer, and subsequently to test the transformed material, a detailed understanding of the processes which control crop growth and development will be necessary. In addition, conventional plant breeding will continue to be the final step in any programme involving molecular biology.

At present, the ability to transfer genes is progressing more rapidly than our understanding of the regulation of the various agronomic attributes. These include protein and oil contents, amino acid balance, tolerance to environmental stress, pathogens, pests and herbicides, vigour, yield and lodging. Current interest is focused on those factors such as resistance to certain viruses which are controlled by a single gene. Progress on other important agronomic characters such as vigour, yield and resistance to lodging require an understanding of complex physiological and biochemical events. Each component of yield and each characteristic of stem strength must be analysed and the genes associated with each of the key steps identified before the genetic engineers can modify the plant genome advantageously.

Chapter 4

A STRATEGY TO EXPLOIT PHYSIOLOGY IN THE FUTURE: RESEARCH PROPOSALS

4.1 PREAMBLE

Crop scientists have a vision: as with applied scientists of all kinds, it is that decisions in practice be made according to knowledge of the way things work. Practice through inference from crop processes demands much greater knowledge than practice according to 'tradition and experience'. Thus a concern for the way knowledge is shared and disseminated is central to the work of the committed physiologist.

The multiplicity of unknowns and uncertainties shown through the length of this review loudly denies the claim that physiology can now provide the basis for all decisions in the industry. However, that decisions are often made in ignorance of, and counter to, how crops are known to grow also cannot be denied. There is still much scope for extending the central role that physiology plays in formal education through to those producing crops, where the need for new knowledge is most sharp. The requirement is for a more active interplay between the colleges, universities and research institutions on the one hand and manufacturers, suppliers, representatives, advisers and growers on the other. At our present level of understanding, this must be the main way that physiology can benefit the industry. However, research and education can only alter the environment in which decisions are made: they cannot supply the decisions. Good decisions must be reasoned and made on a detailed scale. Thus, a well-educated crop manager must still repeatedly marshal, interpret and reinterpret his knowledge in the light of observations he makes. The emergence of artificial intelligence through development of computer software holds promise for assisting in this process in the future. With the immense obstacles in providing knowledge of sufficient precision and devising accessible technology, this approach will have to slowly prove itself in concert with existing, more conventional techniques. However, it is our contention that, with this aid, dependence on advance through reason should slowly outgrow dependence on advance by chance.

4.2 COMMUNICATING PHYSIOLOGICAL KNOWLEDGE THROUGH MODELLING

In seeking to assist progress in the industry it is important to know how the practitioner, be he in policy, production or trade now marshals his thoughts on crop production so that the crop scientist can plan for research to better feed those thoughts.

It is inevitable that differences in the growth of crops will be associated with their circumstances. All growers make such associations: for example that hot summers tend to give low yields, that cool conditions slow the spread of mildew, that wet seedbeds inhibit good establishment, that some spray formulations cause more scorch. Such 'rules of thumb' are often the only basis for future management decisions because an understanding of the underlying processes is not known or available to the operator. However, the thoughtful grower, as much as the researcher, strives to explain the growth he sees and in making associations or formulating explanations he produces what researchers have come to call a 'model'. As such, a model is an idea, often untested, rarely proven, not necessarily invoking cause, and in essence little different whether in the hands of grower or researcher. Despite this common approach, it is both undesirable and unfortunate that the research scientist has allowed 'modelling' to assume a mystique which has either alienated the practitioner or encouraged him to overestimate its practical value or potential for furthering crop science.

The practitioner knows that the frequency with which his complex environment requires him to make choices far exceeds his capacity to rationalise them. There has to be an undercurrent of decisions by rote: many practices are adopted not because they are understood, but because they have been found by experience to work. Further, many conscious decisions are still founded on this precept. Actions are often seen to have crucial implications in practice but lack any certain supporting science. Thus managers and their advisers can but resort to summarise empirical tests from which can be calculated a best practice, with a known probability but little explanation. The principal evidence governing current use of herbicides to control cleavers, nitrogen in early spring or fungicides at the first node stage takes just this form. Circumstances can be classed according to weather conditions, region, rotational position or soil type into those where a treatment will most likely work, but we still wait to work out why.

Meanwhile, the scientist distrusts the empirical approach and looks for rational explanations, which will recognise and accommodate the wealth of relevant observations, both published and personal that are now available to him and then unify them by forming chains of cause and effect.

The computer has emerged as the vital tool in this pursuit, with its almost unlimited capacity to calculate the consequences of multiple, interlinked associations, and researchers have used it with alacrity. Programs can easily be written to simulate many more processes than can concurrently be conceptualised in the mind. Researchers can thus explore the consequences of interlinking a broad range of thinking and can examine areas of ignorance for their importance by altering the assumptions that must be made, and looking at the extent of the changes that ensue. The AFRC Wheat Model is a good example of just such an approach.

However, it can be most misleading if assumptions are made about the accuracy and precision of such models. It must be recognised that the complexity which the computer allows tends to accentuate uncertainty of the outcome when imprecisions in the inputs or the equations become compounded by the calculations.

Model users can be further misled in thinking they can truly reflect plant mechanisms. Empirical models, as with 'rules of thumb', make no such claims, but all representations of plant processes must be empirical in parts. It is not relevant to include descriptions of metabolism or cellular behaviour in a model used to describe how weather affects grain yield, so broad assumptions are made of their effects.

One further aspect which contributes to the mystique of the model is the difficulty users encounter in following the consequences of changes in inputs or in equations: the 'black box' syndrome. It is thus most important that modellers do not allow misuse of models and users do not expect too much.

Within the complex models built to guide research, there can occur components in an appropriate form and of sufficient precision to find application in practice. For example, the development subroutines of the AFRC Wheat Model have already been developed to provide the 'growth stage' forecasts used by ADAS. The same model has been used as a basis of the report to the NERC on the probable consequences of changes in climate for cereals (and other crops) in the UK. However, the main value of computer models in explaining knowledge for the industry will only be realised if the side can come off the black box, so that the user can examine how processes are thought to work. This requirement demands enlightened programming if the model is at all complex, perhaps using pictorial and graphical techniques, but such methods must be found if computer models are to fulfil their promise to allow widespread links between observations and science by growers as well as in research.

4.3 TOPICS FOR FURTHER PHYSIOLOGICAL RESEARCH

In analysing the decision-taking process in Chapter 3 we have identified many topics as needing further physiologically based research. These are:

1. **Varietal choice** (Section 3.2.2, page 32)
   - a) Low input varieties
   - b) Varietal suitabilities
   - c) Characterisation of varieties
   - d) Varieties and sowing date
2. **Sowing** (Section 3.3.4, page 42)
   - a) Physiological obstacles to yield enhancement through heavy seedrates
   - b) Possible physiological disadvantages to very early sowing
   - c) Disassembling the influences of photoperiod and temperature on crops sown at different dates
3. **Nitrogen** (Section 3.4.10, page 54)
   - a) Maximising recovery of soil-applied N
   - b) Relationship between N requirement and yield
   - c) The least N that will optimise crop structure
   - d) Foliar application of N to maximise recovery and minimise soil residues
   - e) Timing of N applications to malting barley
   - f) Timing of N applications to wheat
4. **Weed control** (Section 3.5.4, page 62)
   - a) Weed thresholds
   - b) Low cost strategies for weed control
   - c) Weed-seed dormancy
   - d) Crop tolerance
   - e) Herbicide resistance in weeds
   - f) Fate of herbicide residues
   - g) The principles underlying spray application techniques
5. **Disease control** (Section 3.6.5, page 70)
   - a) Direct effects of fungicides on crop growth
   - b) Monitoring of growth and development in relation to disease and fungicide performance
   - c) Estimating consequences of damage by disease
   - d) Predicting appearance of yield-forming leaves

6. **Plant growth regulation** (Section 3.7.4, page 78)
   - a) Prediction of lodging
   - b) Varietal interaction with PGRs
   - c) Identification of responsive systems for growth manipulation
   - d) Increasing grain size by stimulating cell division
   - e) Why grains stop importing assimilate
   - f) PGRs to improve winterhardiness

7. **Control of quality** (Section 3.8.7, page 86)
   - a) Controlling grain quality
     - — Malting
       - i. Heritable components of malting quality
       - ii. Quick germination tests
       - iii. Predicting dormancy
     - — Protein
       - i. Measurement of protein on the farm
       - ii. Monitoring the development of sulphur deficiencies
       - iii. Favouring proteins of nutritional value
       - iv. Deposition of 'elastic' proteins
     - — Alpha-amylase
       - i. Rapid tests for alpha-amylase
       - ii. Origins of high amylase grain
     - — Specific weight
       - i. Control of grain shrivelling
       - ii. Improved procedures for measuring specific weight
       - iii. Cleaning grain to improve specific weight
       - iv. Analytical methods for predicting malt or flour extraction
     - — Seed for sowing
       - i. Seed quality for sub-standard seedbeds
       - ii. Effect of nutrition and climate on seed ripening
   - b) Observing and defining grain development

4.4 INTEGRATED RESEARCH PROPOSALS

In all proposals we advocate that concerted programmes be constructed so that communication is not just horizontal, amongst research workers, but vertical through the spectrum of grower-adviser-supplier-journalist-scientist, by forging specific partnerships which will hold a clear focus on problems in practice. There is a synergism to be harnessed through the guidance and data that commerce can provide for science and the technical awareness given in return.

Although proposals highlighted here have targets which may only be attainable long term, they also offer earlier prospects for practical improvements: in communications between researchers, discrimination in the use of fungicides, exploitation of candidate varieties, strategies for cereal nutrition, recognition of what makes cereals fail to stand, avoidance of shrivelling of grain, and anticipation of crop performance.

Before selecting these topics, we carefully considered other areas from Chapter 3, for example on producing seed for sowing, stimulating grain expansion or tailoring herbicide application more closely to crop condition but decided they were of lesser priority. For most cereal research we believe that this vertical approach should prove generally applicable and that it can counteract the inertia that has seemingly damped cereal improvement in recent years.

Some topics are more appropriate for extensive investigation by an individual, for instance the study of the origins of high amylase grain or of predicting dormancy. However, in many areas a multidisciplinary approach seems essential; seven such proposals are highlighted in our proposals below.

4.4.1 Physiological responses and varietal characterisation

4.4.1.1 Background

Judged by the popularity of varieties as components of trials programmes in their burgeoning local group activities growers have an intuitive instinct that varieties exist that are better tailored than others to their own conditions (Section 3.2.2.2). Although examples can be quoted where particular suitabilities of specific varieties have become evident following extensive cultivation it is rare for genotype/environmental interactions to be evident at the National Trials stage other than clear cut features such as disease susceptibilities.

In theory there should be some straightforward relationships between physiological responses and performance in the field; the necessity for a low vernalisation requirement if a variety is to be suitable for late sowing, the need for early ripening if it is to be grown at altitude or in the North, and the need for short stiff stems and resistance to shedding if grown on exposed sites. The specific reactions of varieties to certain herbicides and growth regulators should of course also be evident.

There are also other possible associations that are more subtle. It would seem likely that genotypes differ in their ability (a) to germinate and establish in less than ideal seedbed conditions. e.g. too dry, too wet, sowing too deeply, (b) to survive severe overwintering conditions particularly in relation to growth rate and growth habit, (c) to compensate for a gappy stand through their capacity to tiller, (d) to reach an acceptable yield where the crop is prone to drought possibly by economical use of water early, combined with early completion of grain growth before water supplies are exhausted, (e) to perform more consistently on certain fen soils because of their ability to store and mobilise stem reserves thus buffering against poor finishing conditions that occur frequently, (f) to thrive in highly fertile conditions because of standing ability and disposition of the leaf canopy (many small erect leaves), (g) to produce reasonable yields in the less fertile conditions of second and succeeding wheats because of rapid and sustained root growth.

All of these characteristics might be indicated by definable, reproducible tests on small amounts of plant material that would allow many genotypes to be screened, and confirmatory evidence could be obtained through multisite data available from existing trialling by the industry.

Were it possible to devise standard tests on the behaviour of seeds, seedlings or plants at particular growth stages that indicate field performance several benefits would arise:

a) Farmers would have earlier indications of how best to exploit the range of material made available to them.

b) Varietal testing organisations would have useful pointers to possible suitabilities for particular site and cultural conditions.

c) As breeders and variety testers were more aware of potential suitabilities less material might be rejected at an early trials stage.

d) Breeders would be appraised at an early stage of the likely "niching" abilities of lines to particular "slots" in the varied conditions for cereal growing in the UK.

4.4.1.2 Proposal

There are four stages in the project:

a) To formulate likely associations between plant physiological responses and crop performance in particular environments.

b) To develop simple tests (some in controlled conditions) to examine specific physiological responses of characters known to be heritable.

c) To test for these associations by grouping varieties according to responses in controlled conditions, then examining the performance of the different groups in conditions chosen to discriminate whether suitable indicators are borne out in formal field experiments, many of which may already have been conducted for other purposes.

d) To coordinate and disseminate the knowledge gained to all potential beneficiaries, e.g. physiological features that had proved valuable as indicators of performance might be recorded in the National List System to establish distinctness, uniformity and stability.

Table 7 provides a list, by no means exclusive, of characteristics that could be screened in definable, reproducible test conditions, not yet specified, but which should allow many genotypes to be examined. They are presented in broad time sequence and the star ratings denote the degree of confidence in the strength of associations between performance under test and performance in the field. In deploying this proposal there is scope for collaboration between breeders, physiologists, testing agencies and farming groups which record field yields.

Table 7 Physiological characteristics and suitabilities indicated

Physiological response in standard test	Suitability indicated
1. Dormancy^{xxx}	Long dormancy unsuitable for malting and early sowing
2. Vernalisation requirement^{xxx}	Short vernalisation requirement essential for late sowing The role of long vernalisation requirement in determining suitability for early sowing and ability to survive hard winters needs investigating
3. Rate of germination/seedling^{xx} emergence in standard tests	Ability to establish in a wide range of seedbed conditions
4. Response of seedlings to freeze and other^{xx} standard hardiness tests and inter-relationship with growth habit, stage of growth and chemical composition	Ability to survive hard winters
5. Rate of root growth and balance between^{x} shoot and root in the early stages	Suitability for lodging, drought prone and soil-borne disease prone (second wheat) situations
6. Tillering characteristics^{x}	Ability to compensate for gappy stands; suitability for soils where seedbeds are difficult to prepare and where early pest damage (wheat bulb fly, frit fly) likely
7. Development rate (time to reach double^{xx} ridge, terminal spikelet and anthesis)	Match development rate to length of growing season (determined either by likelihood of harvest conditions deteriorating or by crop running out of water)
8. Length, structure and composition^{xxx} (dry wt/unit length) of stems	Standing ability on exposed or highly fertile sites

(Continued . . . .

Physiological characteristics and suitabilities indicated (continued)

Physiological response in standard test	Suitability indicated
9. Shoot/root ratio and water use at early^{x} development stages	Suitability for drought-prone situations
10. Size and orientation of leaves^{x}	Suitability for fertile conditions
11. Weight of stem and amount of soluble^{x} carbohydrates	Consistent performance where probability of 'poor finishing' conditions
12. Nitrogen and soluble nitrate content^{x}	Ability to accommodate N (suitability for inherently infertile conditions and minimal fertiliser use)
13. Composition of proteins in the whole plant^{x}	Suitability for breadmaking
14. Reaction to growth regulators at^{xxx} specific growth stages	Matching variety and growth regulator
15. Response to fungicides^{xxx}	Suitability for low input system
16. Aphid colonisation^{xxx}	Suitability for low input system
17. Reaction to pesticides at^{xxx} specific growth stages	Pesticides to avoid

4.4.2 Matching cereals to a wider range of sowing dates

4.4.2.1 Background

During the past decade several developments have modified traditional attitudes to sowing date and heightened interest in the choice of species and variety in relation to sowing date.

The work to be done in autumn on intensive cereal growing farms has increased greatly. From 1976 to 1986 the area of winter wheat sown in the UK increased from 1.2 to 2.0 million hectares. Moreover the proportion of barley sown in autumn increased from 10% in 1971 to 40% now. Thus if the risk of yield penalties from late sowing were to be minimised an earlier start to sowing becomes essential. The increasing popularity of autumn sown oil seed rape and autumn sown barley clears more of the ground early and improvements in weed control now present opportunities to begin sowing in early September, even August. Traditionally winter barley is sown first because seed is available earlier and it is mainly grown on the lighter soils. Recently there has been increasing interest in very early sowing of wheat but performance has been inconsistent and generally disappointing.

Developments in relation to efforts to minimise leaching of nitrogen to aquifers and drainage to watercourses are likely to reinforce the need for clarification of the strengths and weaknesses of species and varieties for earlier sowing. Already farmers are to be encouraged to plant crops to 'mop-up' the nitrate that is released when warm soils are cultivated in late summer and rewetted following post-harvest rains. Although voluntary at present, there is the prospect that the practice will be the subject of future legislation.

In very recent years there has been an increasing tendency for growers to sow nominally 'spring' rather than 'winter' varieties when sowing has been delayed until the November-January period. Evidence from ADAS and plant breeders indicates that by this time yields of spring varieties are at least as great as for winter varieties, particularly for wheat grown on light soils. Attractions include a wider choice of varieties suitable for breadmaking, greater tolerance to further delay in sowing and possible savings in agrochemical requirements. Similar considerations apply to spring barley but its reputation for greater susceptibility to frost tends to delay until December its adoption as an alternative to winter barley. The ban on straw burning in 1992 will inevitably lead to a wider spread of sowing dates, particulary on heavy land, and debate will strengthen as to the relative merits of species, types and varieties over an extended series of sowing dates.

From first principles it might be expected that cereals would respond positively to earlier sowing. The following growth patterns could well result:

a) a more extensive root system with prolonged activity that will effectively mop-up nitrogen leading to a lower fertiliser N requirement,

b) earlier closure of the leaf canopy with increased radiation interception in September, April and May,

c) increased leaf persistence in the generally cooler conditions of early summer,

d) extended intervals of development with more radiation intercepted within each developmental period and consequent increases in the size of the yield component currently being determined,

e) a possible increased buffer against the vagaries of weather and disease incidence during grain filling by virtue of large reserves of retranslocatable material laid down in the stems during prolonged vegetative growth.

Whilst increasing the length of the growing season would normally be expected to increase plant productivity there are two factors which could certainly override this; if poor establishment and/or increased incidence of disease occurred with early sowings any potential advantage could be negated. These have clearly been the cause of adverse effects from early sowings in some experiments. In other experiments where no such effects occurred, however, there has been no advantage or a disadvantage from early September sowing.

Wheat and barley exhibit distinctive responses to earlier sowing. Wheat becomes taller and more vulnerable to lodging whilst barley grows shorter. One characteristic of wheat varieties that perform well when sown early is that they are short and have stiff straw. The use of growth regulators may be a crucial adjunct to eliciting a more consistent response from wheat to further advancing the growing season. So might genetic resistance to aphids, common and sharp eyespot and leaf diseases, particularly if pesticide usage is discouraged. For mopping up nitrogen a high root:shoot ratio may well be a desirable characteristic. There is some evidence that species (such as rye) and varieties which develop slowly and have a long vernalisation requirement (see proposal on varieties) are best suited to early sowing. Certainly the reverse would be expected to apply, i.e. rapid development would be an essential characteristic for success from late sowing. The relationship between stage of growth at the onset of winter and ability to survive needs to be clarified. On the one hand if early sown plants are too erect their leaves may be vulnerable to frost and vulnerable to damage of the apex; on the other, small late sown plants would probably be most vulnerable to heaving of the soil as it freezes and thaws.

As well as a detailed comparison of the response of winter wheat and winter barley to early sowing there is a need to elucidate precisely what sets a limit to how early nominally 'spring' varieties of wheat and barley can be successfully sown and how the performance of winter and spring types compares over a wide range of sowing dates.

4.4.2.2 Proposal

Recent reviews have highlighted the limitations of interpretation possible when information is restricted to a list of sowing dates, varieties and yields. The challenge is to find material whose developmental pattern is so prolonged that it keeps in step with the extra growth that comes from early sowing. To achieve this it is vital to follow the effects of sowing date on the developmental phases through which the crop passes before yield is determined. The investigation must allow

a) clear analysis of whether or not total biomass and grain yield of wheat and barley do increase consistently with length of growing season and if not where the system "goes wrong" (it would be necessary to include in the investigations a wide genetic base which might with advantage incorporate rye and triticale).

b) determination of what sets the limit to how soon the range of nominally winter and spring varieties of wheat and barley can be sown. There is a need to rank characters such as a long vernalisation requirement, slow development, resistance to lodging and disease in denoting suitability for early sowing. Is there an optimum stage of growth and development for the crop (a) to enter the winter, and (b) to recommence growth in spring?

The AFRC wheat model can be used to predict development of Avalon sown on a range of dates. When the behaviour of this variety can be predicted with confidence the need for modification and the basis for the modifications required to account for response patterns of contrasting varieties needs to be established. The stage beyond that is to model the responses to sowing date in terms of growth as well as development — the key to answering (a) above.

Supplementary investigations are required to establish whether by careful selection of variety and judicious use of growth regulators it is possible to override the response that results in early sown wheat and late sown barley becoming more susceptible to lodging. Moreover, with a substantial area of second and subsequent wheats it is necessary to ascertain how responsiveness to early sowing changes when root diseases, particularly take-all, are prevalent.

It is clear that this proposal would depend for its success on integrating commitments from soil scientists, plant breeders and plant pathologists as well as from agronomists and physiologists.

4.4.3 Basing tactics for N use on the way N governs growth

4.4.3.1 Background

Cereals receive about 40% of the UK's fertiliser N. A large part of this N is indisputably not recovered by the crop. In addition to the financial loss this represents there is now the consequence that large tracts of cereal growing land in eastern England face compulsory restrictions on fertiliser use or even curtailment of cereal cropping.

A decade ago the change to provision of large N supplies for winter cereals was accompanied by new genotypes and greater use of more effective pesticides, especially fungicides. Now, with the modern counter concern that pesticide use should fall, there needs to be more frugal use of fertiliser N.

It is thus of considerable importance that opportunities are taken to have ready a constructive, industry-led response by sponsoring a programme of research, maximising N recovery by the crop (and so minimising the residues), ensuring that N use can be rationalised, and actively developing any appropriate new technologies. There are three essential background points:

a) Diminishing returns from nitrogen: Experiments examining effects on grain yield of increasing amounts of applied N always show that, although yield may have been more than doubled by fertiliser, the last tenth of the yield depended upon more than half of the N that was applied. The implication is of great inefficiency; certainly the value of the first part to be applied hugely outweighs the value of the last. Why should this be and need it be so?

b) The concept of 'requirement': Recommendation systems for applying N to cereals invariably presume the inefficiencies. They rely upon a concept of 'requirement' for the crop (to be balanced by supplies of nitrogen from both soil and fertiliser) of perhaps 30 kg N per tonne of expected yield. Yet each tonne will only contain 20 kg at most.

Perhaps 'requirement' is a notional property unfairly conferred upon the crop by scientists mainly concerned with balancing gross biological or chemical equilibria in soils. Certainly it ignores the dynamics of crop growth: that a succession of leaves initiate, expand, turn green, mature and die; that these are raised by successively extending stem sections to form a canopy upon which sunlight falls, through which it filters and by which, according to its changing strength as the sun reaches its zenith through the season, through the day and as the cloud patterns pass, the small (yet increasing) content of carbon dioxide in the air is turned to sugar, starch and cellulose. What role has nitrogen in this?

c) How N is thought to govern growth: Of the changes brought by an application of N to a cereal crop in spring, the most significant in the mind of the grower would commonly be its greener and more numerous shoots. On the other hand, the physiologist's concern in seeking to harvest as much of the incident light energy as possible is to maintain the presence of a just adequate canopy for as long as possible, and therefore to look for enough green matter to keep the ground in near darkness through to August. Undoubtedly the canopies formed by contemporary cereal crops receiving normal levels of nutrition are larger than needs be in May and June, and raise risks of lodging and disease. Then too, green area often fades to less than the crop area before the grain has fully filled, and thereby much intense mid-summer energy is not converted to yield. Is there scope to rectify the normal growth and persistence of a canopy to meet more closely the optimum for intercepting light? The paramount means of influencing this must be through the judicious supply of nitrogen. But by what stratagem should it be judged?

In April the total of nitrogen already in the crop, available from soil reserves or just applied as fertiliser, greatly exceeds that needed to form an adequate canopy in May; it would seem that fertiliser could be withheld with likely benefits to disease and lodging and without serious effect upon growth at that time. There is a case to examine later nitrogen supplies. A legitimate scenario for efficient use of N is that a small but healthy canopy should be encouraged to persist whilst the grain obtains its nitrogen elsewhere.

4.4.3.2 Proposals

The work would take three complementary tacks:

a) Description of optimum crop structure: Studies should be made of crops receiving one half and both halves of the normal N amount, tracing the origin of that small but important proportion of extra yield arising from application of the second half.

Leaf histories, with nitrogen status and photosynthetic performance in these crops should be used to delineate how their developing canopies can best be nurtured to accommodate the seasonal pattern of sunlight.

Note should be made of the leaf tissue conditions and canopy structures likely to minimise risks of fungal infection, but the main thrust should be to formulate effects of N on leaf, tiller and internode extension to arrive at the most frugal strategies for N application which achieve the necessary canopy progression.

b) Testing of new strategies for N application: Given adequate techniques, we raise the hypothesis that cereals can be fertilised more effectively if the aim is to optimise canopy development rather than to supply a 'requirement' guessed at an early stage.

The target would be early formation of a closed canopy, fully exploiting soil nitrogen reserves (perhaps by sowing early and basing supplementary fertiliser amounts on measured soil nitrate and ammonium), and then maintenance of the canopy for as long as possible (perhaps by regular feeding with nitrogen according to the monitored nitrogen status of the most vital leaves). At the experimental stage it is expected that leaves might best be maintained through a nitrogen solution provided by trickle irrigation to the roots (a technique which has been shown to give 100% recovery of applied N). The objective would be to provide the supporting strategy for developing new techniques for feeding leaves directly.

c) Direct nutrition with N for cereal leaves: The technical obstacles of providing, through leaf uptake, the entire shortfall between crop uptake of N for achievable yield (say 200 kg/ha) and N available from rainfall and soil organic matter (say 40 kg/ha) should not be underestimated. However, small amounts of urea N are commonly sprayed onto wheat to increase the protein concentration of the grain and recoveries of N from these sprays, and in the few cases where larger amounts have been tested, have often been equivalent to those of soil-applied N. It is thus quite probable that, by this means, a more flexible approach to cereal nutrition might be effected and that the N left in the soil at harvest could be reduced.

The existing sophisticated technologies of spray formulation and application have not been fully explored for nitrogen, but the requirements for minimising soil deposits, maximising canopy retention, controlling penetration through to metabolic tissue without causing leaf scorch, and providing for translocation to growing parts, do not appear insuperable. There would thus seem much scope for attention to be turned toward this aim.

A programme of both plant research and spray development should be combined using existing expertise to tackle each of the diverse components of the objective in a concerted way:

- plant biochemists should assess the route by which nitrogen is best assimilated by leaves in order to ensure that there are no deleterious effects, such as through changes in cell pH, and that the assimilated N is effectively translocated to responsive tissues.

- formulation chemists should assess N forms and spray additives which optimise penetration of the leaf, prevent volatile losses, and minimise leaf scorch.

- applications engineers should test techniques which cause retention on appropriate parts of cereal canopies of different ages, e.g. by comparing electrostatic, air assisted and more conventional sprays.

- soil scientists should assess not only the residues left from sprays at harvest but any indirect effects that sprays may have on N exudation by roots, inhibition of uptake of soil N, or longer term effects of soil N release for leaching or future crop uptake.

Because of the wide commercial and public interest involved in this proposal the Authority should look to support aspects which can provide a focus for extra funding from other sources, including Government, the European Commission and industry.

4.4.4 Estimating consequences of damage by disease

4.4.4.1 Background

The thrust of our proposals for tactical use of fungicides carries through from the logic which we applied to the use of nitrogen.

In the past, fungicide use has been seen as a means of protecting the crop so that, in new varieties which resist lodging, responses available from nitrogen applications could be exploited to the full. New attitudes to the use of nitrogen and fungicides now require that they be applied in a way that minimises any dependence upon them. We suggest that this is possible if attention is turned away from maintaining a crop environment free from disease or nutritional impediments toward creating a crop structure which is just adequate to realise the available potential for crop growth as dictated largely by sunlight.

We again suggest that the current pattern of canopy development may not be the most efficient. The creation of a large canopy in early summer at the expense of large quantities of nitrogen and with routine dependence on fungicidal protection might be bettered through creation of a more open canopy with a microclimate less conducive to disease and which would depend on smaller supplies of nitrogen.

Changing attitudes toward the management of crops now indicate that the effort needed to discriminate in applying chemicals will be seen as worthwhile when set against the stigma associated with their routine use. There is thus a need for a rationale on which disease management can be based so that decisions to use fungicides can be justified convincingly.

Philosophies underlying present strategies for the control of cereal diseases place most emphasis on probabilities of a response calculated from a large number of treatment tests, sometimes categorised according to factors such as region and rotation.

Spray decisions tend to favour broad-spectrum fungicides which may be applied at two or three predetermined growth stages. Choice of these stages has been based on disease epidemiology and factors affecting spore dispersal; until recently, less attention has been paid to the way diseases are expected to damage crop function.

We suggest that an attempt should be made to relate disease effects more closely to size and longevity of the final crop canopy. The aim should be to identify sizes and longevities which prove adequate and thus the extents to which a canopy can bear infections by each common pathogen without impairing grain formation. Use of a fungicide could then be justified and adopted by showing there to be a threat that the crop canopy would otherwise be inadequate in meeting the potential of the conditions in question.

4.4.4.2 Proposals

Success in improving strategies for the control of diseases depends on provision to growers of a clearer picture of the way that disease damage accrues. Our suggestions address five areas of current uncertainty.

a) Disease organisms differ in their effects. Most impose a respiratory load upon infected tissues, creating additional sinks for assimilates. However, effects may also include masking and damage of green tissues, production of toxins which alter metabolic processes, impairment of vascular function either locally or systematically, or restriction of root exploration. There is a need to type more closely the effects of diseases to allow more accurate estimation of their damaging effects. This would involve combined studies in laboratory and field for each major disease.

b) Results from recent experiments suggest that wheat should be protected against disease from the emergence of leaf 3, possibly uniting leaf disease and eyespot control. The eradicant and protectant properties of some azole fungicides may therefore remove the need to control eyespot at GS 31, eradicate early Septoria and protect existing leaf area. With an incubation period for S. tritici of 25-30 days on the top three leaves, it is possible that only one further fungicide application would be required to provide season-long protection. A broad-spectrum fungicide typically costs £20 per hectare and so a large potential saving in input costs is possible.

c) A series of experiments (part H-GCA funded) has shown close relationships between disease incidence, growth stage and yield loss. Disease incidence during different phases of development is being studied by use of sequential spray timings. In order to more confidently interpret the relationships, it is important to know the course of both growth and development by recording growth stage and also the pattern of dry matter accumulation at each site. These and similar data can then be used to modify our understanding of events leading to yield loss through disease.

d) With the possibility of rescheduling the provision of nitrogen applications to cereal crops there is a need to examine more closely whether restricted nutrition reduces the risk of disease. Existing H-GCA funded experiments may provide relevant pointers. However, there will be a need to design specific experiments which test a more general strategy for efficient management of cereal canopies.

e) Effective estimates of disease damage depend upon accurate knowledge of crop development. The subroutine that describes development in the AFRC Wheat Model has been extended (with MAFF funding) so that not only are node stages and anthesis described, but also the emergence of the final three leaves. There is scope to improve the precision of these predictions and there is a need to extend calculations further so that emergence of the ear and progress through the grain filling period can be predicted.

Integration of the information emerging from the above work depends upon combining the expertise of epidemiologists, physiologists and meteorologists and should attract a close interest from fungicide manufacturers.

4.4.5 Defining and confining lodging

4.4.5.1 Background

Lodging is a widespread, frequent and serious problem for cereal growers; it reduces yields, inhibits harvest and damages grain quality. It is a particular problem with winter barley. In field experiments consideration of the influence of various husbandry factors on cereal growth and yield highlights the extent to which lodging, or the lack of it, mediates the treatment effect, particularly with barley. Whether there is a yield response to early or late sowing, to increased seed rate, to nitrogen (particularly early N), to growth regulator or to crop protecting chemical is often directly related to the occurrence of lodging. This is equally true of site and seasonal effects. Were it possible to confine the risk of lodging, treatment, site and seasonal effects on both grain yield and quality would be more predictable.

Heavy yields will not be realised where a large number of grains are developing, if the point of anchorage of the stem in the soil weakens, or the bending momentum of the stem causes it to lean from near the base, or to break halfway up (brackling). Early lodging disrupts light penetration of the canopy, impairs grain filling leading to reduced specific weight and shrivelled grain. Late lodging delays ripening by retaining moisture in the canopy, encourages moulds, alpha-amylase development, thus low Hagberg Falling Number and sprouting.

It would be helpful to more closely define the principal contributors to risk in lodging-prone fields, for lodging-prone genotypes and as each season progresses, and to devise husbandry policies which can best counteract them.

4.4.5.2 Proposal

The aim should be to build upon the model system being developed with H-GCA funding in Northern Ireland, to describe the critical complex that results in structural failure, and thus explain the origin of lodging events.

Initial work should map boundary conditions of crop patches that are newly lodged and analyse the physical characteristics in the vicinity of the primary site of failure in the soil-root-shoot system. It is commonly overlooked that the point of failure is often within the top 2 cm of soil between the surface and the crown: in many crops the point where the stem has cut through wet soil is clearly evident. It is not known whether root breakage is involved and also whether the incidence of root diseases, take-all and Fusarium foot rot is related to poorer anchorage and an increased risk of lodging. Standard tests should be devised to check the strain at which the critical parameters reach points of failure.

There is potential in investigating the nature of the well-known 'tram-line' effect, in which plants adjacent to tram-lines remain standing while the remainder of the field goes flat. This will involve testing differences in the degree of compaction, surface drainage characteristics, row spacing and extent of abrasion close to the tramlines. Experiments should examine cultivation treatments that change the structure of the surface layer of soil and its speed of drying for their effects on proneness to lodging. Similarly, the nature of the effects of nitrogen and plant growth regulators on lodging require investigation. As well as weakening the stem, it may be that more nitrogen increases the elasticity of the roots. It is known that as sowing is delayed, wheat becomes shorter, but barley taller. The nature of this response in plant morphological terms, and the relationship to proneness to lodging, needs to be understood. For stem lodging, as opposed to root lodging, the relationship with the structure of the cell wall and any biochemical basis for weakness need to be established.

It will be necessary to define the consequences for plant function of the different forms of lodging through their effects on:

(a) radiation absorption
(b) the efficiency of conversion of absorbed radiation to biomass both in the short and longer term and
(c) leaf longevity.

The sporadic pattern of lodging events and the close scrutiny needed for their analysis will best be met by combining the efforts of growers or advisers on an extensive scale, agronomists using field experimentation, and physiologists for the intensive in-field analyses.

4.4.6 Forward estimates of grain quality

4.4.6.1 Background

Through its 'Cereals Quality Survey', the Authority currently supplies quick intelligence to the industry on the quality of grain soon after harvest. Not only does this provide the industry, through rapid publication of the findings in the Weekly Digest, supplemented later with a full report in the Marketing Notes, with invaluable information in support of its trading and exporting strategies but it is the best record of grain quality in the UK over the past 16 years.

The information is derived from over one thousand samples each of barley and wheat and is comprehensive in that both Regions and varieties can be compared for grain size, specific weight, sprouting, nitrogen (or protein) concentration, and (for wheat) Hagberg Falling Number.

It is clear that it is the availability of intelligence at an early date which puts the industry in the best position to gauge its strategy; however, competitor countries in the European Community and major forces in world markets have earlier harvests and can pre-empt any assessment of performance at harvest time here.

Before harvest, there certainly are pointers to the likely quality of the grain which has formed; although no formal mechanism exists to link quality of grain with conditions during its formation, there is much informal speculation based on crop appearance, patterns of sunshine and rainfall, soil dryness, and air temperatures.

Knowledge of grain physiology relates to this speculation; physiological principles are sufficiently well known to provide explanations, of a qualitative form, to associate hot weather in July with small grains, wet summer conditions with high nitrogen concentrations, bright, cool conditions with low nitrogen concentrations, or moist ripening weather with poor Hagberg Falling Numbers. Yet, how often have our pundits been surprised? Surely some room for improvement exists?

Physiologists could contribute further to cereal quality intelligence, using **existing**, and surprisingly precise, **quantitative** knowledge of the interrelated processes involved: retranslocation of nitrogen, carbon assimilation leading to deposition of carbohydrates, synthesis of important enzymes such as the amylases, and dehydration to harvestable dryness. The intent would be to describe these, through a combination of observations and calculations, in a way which assists and formalises the industry's forward estimates of quality.

4.4.6.2 Proposal

The suggestion is that a series of reference crops should be selected every year, and that physiological parameters are monitored on these so that calculations of quality characters can be made, and subsequently checked.

a) Observing the progress of grain formation: The grain characters of interest to users are determined at different times through the final phases of crop growth; the foundation for any forward estimate of quality must be an accurate assessment of the progress toward maturity.

The small variability in flowering date of cereals and the close link between grain development and air temperatures could be used now to publish national intelligence of progress through grain filling. Accuracy of such calculations should be checked initially and improved with a coordinated programme of observations, but the prospect is for a direct calculation of cessation of grain filling to be possible from temperature records.

b) Protein accumulation: Most of the nitrogen which will be harvested has been assimilated before grain growth starts. Observation and analysis can determine its extent; its concentration depends upon assimilation of carbohydrate later. Then, for the week or two before harvest the crop is simply drying out; concentration on a dry weight basis can thus be determined well in advance.

c) Determination of grain size: Grain numbers do not change perceptibly throughout the grains' filling phase. An early measurement can thus form the base from which their expansion can be assessed. At the same time, assessments can be made of the extent of stem reserves which may buffer grain growth against any later stress.

The filling of grains is crucially dependent on receipt of light energy by green tissue whilst they are growing. Though a green canopy can be assumed to be present at the start, it often senesces before grain growth stops. Such colour changes are sensitively monitored by aerial photography and satellite imagery, and light energy is continuously recorded at several sites, varying little over short distances. Extensive observations could thus be made of both light energy and its absorbing surface so that grain growth, and protein 'dilution', could be estimated.

d) Alpha amylase activity: Determination of Hagberg Falling Number in wheat perhaps presents physiologists with their biggest challenge here. However, amylase activity can simply be monitored, and phases of grain development for which wet weather has a marked effect are becoming more closely defined. A combination of these two assessments should improve upon subjective judgements used hitherto.

Suggestions in this proposal must draw on complementary contributions from grain traders for best ways of presenting the results, growers for the reference crops, meteorologists for weather records, agronomists for observations of crop state, and physiologists for the principles for calculating the results.

4.4.7 Assessment of crop productivity before harvest

4.4.7.1 Background

It would be of benefit to the cereal industry to have in operation a system for yield prediction similar to that now operated by crop physiologists for the UK sugar industry. On the basis of predictions made from late June onwards, plans are made for the organisation of the campaign and for storage and sales of the products. Because of the relatively simple growth pattern of sugar beet in the first year of its life, it has proved possible to predict national yields with useful accuracy from a simple model based on the effects of temperature on leaf growth and the relationship between yield and intercepted radiation. For cereals there is also a widespread commercial need to foresee each season probable patterns of trading, Intervention purchasing, storage and shipment of grain based on some assessment of current crop potential for both yield and quality.

Although for cereals total biomass production is also closely related to the amount of light energy absorbed by green tissue from sowing until harvest, it is as yet not possible to reliably predict grain yield. Formal yield prediction, according to physiological principles, is still forestalled by incomplete knowledge of how current observations should be weighed in trying to forecast the build-up of yield. The system is more complicated than for sugar beet. Cereals mature and die for genetic and physiological reasons well before the end of the growing season and the timing of the end of growth is particularly important. Moreover, the components of grain yield are not determined concurrently; grain number is fixed by flowering and grain size determined thereafter.

With the crucial influence on yield of weather patterns late in growth no prospect of precise predictions can be claimed. However, it would be possible to monitor a range of crop characters in a standard way and, at the very least, to compare the condition of the crop nationally with that in previous years according to current assessment of the characters' physiological importance. Indications early in the year could not claim or deserve any better credibility than more subjective judgements. However, the precision of predictions must improve as the season progresses, and in regularly explaining its workings a crop assessment exercise would serve the valuable end of widely demonstrating the important elements of current crop science as it evolves.

4.4.7.2 Proposal

The first stage is to examine existing unanalysed data from ADAS's Experimental Husbandry Farms and other centres on dry matter and nitrogen accumulation measured in February, April, May, June, July and August. Measurements were tied to different developmental phases and included observations on leaf area, tillering and ear weight. Thus the extent of site variation in growth can be defined and the relationship between nitrogen uptake by the whole crop and nitrogen accumulation in the grain examined. Tests should be made of the ability of the AFRC Wheat Model to account for the differences observed.

The second stage is to grow standard 'reference' crops throughout the cereal growing regions with similar husbandry and to monitor progress in relation to:

- rooting depth
- the extent of mineralisation of nitrogen and nitrogen distribution in the soil profile
- canopy expansion and light interception
- total dry matter and nitrogen accumulation
- carbohydrate accumulation in stems and
- grain growth and nitrogen in the grain.

Again, the aim is to define and test how far it is possible to explain the variation due to site and season. As missing links are identified, effort can be directed to explaining observations.

The third stage is to 'go public' when an expert group is convinced that useful observations can be made on the current pattern of yield accretion against the past norm and previous seasonal deviations. The exercise will begin with existing models but an important activity must be to refine these in the light of new observations. The aim is to derive a useful prediction partly of eventual performance, but in addition, to provide background information for matching husbandry decisions more closely to the way crop and soil are behaving.

Thus, again, we see value in harnessing the interests not only of crop scientists but of growers in providing the test bed of crops, journalists who will know how the underlying information can best catch the interest of industry, and traders who can gauge the importance of the result.

Finally,

we believe that, as an essential component of the vertically structured projects advocated in this chapter, there must be clear and obvious channels by which all those with common concerns can keep in touch with progress in the work which is sponsored by the Authority. Undoubtedly, vertical structuring will ensure good communication amongst the few immediately concerned, and major new findings and final conclusions will be published and gain mention in the farming press, but there is a need for the industry to be able to refer to the current state of understanding on a particular topic as and when relevant questions arise in practice.

Some awareness of its sponsored research is now being generated by a presence at national shows and conferences. However, the full two-way benefit of its current sponsorship will not come without a mechanism for wider dissemination of, and quick and easy access to, the detail of each project. In other spheres 'Perspectives Agricole' produced by ITCF and 'British Sugar Beet Review', the house journal of the home-grown sugar industry, provide examples of useful parallel initiatives.

The proposal for a new initiative for cereals is made here because of our great concern that, without it, cereal physiologists, whose work is naturally in the 'middle ground', will be thwarted in their commitment to link science with practice and so improve the scope for rational decisions in our industry.

◇-◇-◇-◇-◇-◇-◇

APPENDIX

The following scientists gave most helpful responses to the Working Group's enquiries regarding the world wide benefits derived from research on cereal physiology

1.	R.B. Austin	AFRC Institute of Plant Science Research Cambridge Laboratory, Maris Lane, Trumpington, Cambridge, England.
2.	J.P. Cooper	Former Director, Welsh Plant Breeding Station, Plas Gogerddan, Aberystwyth, Wales.
3.	R.A. Fischer	Director, Wheat Program, International Maize and Wheat Improvement Centre, DF, Mexico.
4.	R.M. Gifford	Division of Plant Industry, CSIRO, Canberra, Australia.
5.	E.J.M. Kirby	Department of Agronomy, The University of Western Australia, Nedlands, Perth, Western Australia.
6.	J.H.J. Spiertz	Research Station for Arable farming and Field Production of Vegetables, Lelystad, The Netherlands.
7.	W.R. Stern	Department of Agronomy, School of Agriculture, The University of Western Australia, Nedlands, Perth, Western Australia.

BIBLIOGRAPHY

2 FORM AND FUNCTION

2.1 Introduction

AUSTIN, R.B. and JONES, H.G. (1975) The Physiology of Wheat. Annual Report of the Plant Breeding Institute 1974, Cambridge, 20-73.

BISCOE, P.V. (1979) Basic cereal physiology and its application to wheat. In Course Papers: The Yield of Cereals, pp 7-19. Stoneleigh, National Agricultural Centre.

BISCOE, P.V. and GALLAGHER, J.N. (1977) Weather, dry matter production and yield. In Environmental Effects on Crop Productivity, eds J.J. Landsberg and C.V. Cutting. Academic Press, London, 75-100.

BISCOE, P.V., SCOTT, R.K. and MONTEITH, J.L. (1975) Barley and its environment. III. Carbon budget of the stand. J. Appl. Ecol., **12**, 269-293.

DAY, W. and ATKIN. R.K. (1985) Wheat Growth and Modelling. Plenum Press, New York.

EVANS, L.T. and WARDLAW, I.F. (1976) Aspects of the comparative physiology of grain yield in cereals. Advances in Agronomy, **28**, 301-359.

EVANS, L.T., WARDLAW, I.F. and FISCHER, R.A. (1975) Wheat. In Crop Physiology: some case histories. Ed. L.T. Evans, pp 101-149. Cambridge University Press, Cambridge.

FISCHER, R.A. (1983) Wheat. In Potential Productivity of Field Crops, pp 129-154. International Rice Research Institute, Los Banos, Phillipines.

FONSECA, S. and PATTERSON, F.L. (1968) Yield component heritabilities and interrelationships in winter wheat (T. aestivum L.). Crop Science, **8**, 614-617.

GALLAGHER, J.N. (1979) Barley, growth, development and yield. In Course Papers: The Yield of Cereals, pp 80-96. Stoneleigh, National Agricultural Centre.

GALLAGHER, J.N. and BISCOE, P.V. (1978a) Radiation absorption, growth and yield of cereals. J. Agric. Sci., Camb., **91**, 47-60.

GALLAGHER, J.N., BISCOE, P.V. and DENNIS-JONES. R. (1983) Environmental influences on the development, growth and yield of barley. In Barley : Production and Marketing. Agronomy Society of New Zealand, Special Publication No. 2, pp 21-50.

GALLAGHER, J.N., BISCOE, P.V. and SCOTT, R.K. (1976b) Barley and its environment. VI. Growth and development in relation to yield. J. Appl. Ecol., **13**, 563-593.

GALLAGHER, J.N., BISCOE, P.V., SCOTT, R.K. and DENNIS-JONES, R. (1977) Barley physiology and its relation to farming practice. The Yield of Cereals, Cereal Information and Demonstration Unit, Stoneleigh, 11-17.

HAY, K.M. and WALKER, A.J. (1989) An Introduction to the Physiology of Crop Yield. Copublishers Longman Scientific and Technical and John Wiley and Sons, New York, 292 pp.

JONES, J.L. and ALLEN, E.J. (1986) Development in barley (H. sativum). J. Agric. Sci., Camb., **107**, 187-213.

KIRBY, E.J.M. and APPLEYARD, M. (1981) Development of the cereal plant. Yield of Cereals, Cereal Information and Development Unit, Stoneleigh, 1-10.

KIRBY, E.J.M. and APPLEYARD, M. (1984) Cereal plant development and its relation to crop management. In Cereal Production (Ed. E.J. Gallagher), pp 161-173, Butterworth.

KIRBY, E.J.M. and APPLEYARD, M. (1987) Development and structure of the wheat plant. In Wheat Breeding and its Scientific Basis (Ed. F.G.H. Lupton).

LEGG, B.J., DAY, W., LAWLOR, D.W. and PARKINSON, K.J. (1979) The effects of drought on barley growth : models and measurements showing the relative importance of leaf area and photosynthetic rate. J. Agric. Sci., Camb., **92**, 703-716.

SCOTT, R.K. and DENNIS-JONES, R. (1976) The physiological background of barley. J. natn. Inst. agric. Bot., **14**, 182-187.

THORNE, G.N. (1966) Physiological aspects of grain yield in cereals. In The Growth of Cereals and Grasses, eds E.L. Milthorpe and J.D. Ivins. Butterworth, London.

WEIR, A.H. et al. (1984) A winter wheat crop simulation model without water or nutrient limitations. J. Agric. Sci., Camb., **102**, 371-382.

2.2 The growth of leaves

BAKER, C.K. (1979) The environmental control of development in winter wheat. Ph.D Thesis, University of Nottingham.

KIRBY, E.J.M., APPLEYARD, M. and FELLOWS, G. (1982) Effect of sowing date on the temperature response of leaf emergence and leaf size in barley. Plant, Cell and Environment, **5**, 477-484.

MONTEITH, J.L. and ELSTON, J. (1983) Performance and productivity of foliage in the field. In The Growth and Functioning of Leaves (Eds. J.E. Dale and F.L. Milthorpe), pp 499-518. London: Cambridge University Press.

PORTER, J.R. (1984) A model of canopy development in winter wheat.

RUSSELL, G. and ELLIS, R.P. (1988) The relationship between leaf canopy development and yield of barley. Ann. Appl. Biol., **113**, 357-374.

2.3 The growth of roots

BARRACLOUGH, P.B. and LEIGH, R.A. (1984) The growth and activity of winter wheat roots in the field; the effect of sowing date and soil type on root growth of high yielding crops. J. Agric. Sci., Camb., **103**, 59-74.

BARRACLOUGH, P.B. and WEIR, A.H. (1988) Effects of a compacted subsoil layer on root and shoot growth, water use and nutrient uptake of winter wheat. J. Agric. Sci., Camb., **110**, 207-216.

CANNELL, R.Q. (1981) Cereal root systems : factors affecting their growth and function. In Opportunities for Manipulation of Cereal Productivity. BPGRG Monograph No. 7 (Eds. A.F. Hawkins and B. Jeffcoat), 118-129.

LUPTON, F.G.H., OLIVER, R.H., ELLIS, F.B., BARNES, B.T., HOWSE, K.R., WELBANK, P.J. and TAYLOR, P.J. (1974) Root and shoot growth of semi-dwarf and taller winter wheats. Ann. Appl. Biol., **77**, 129-144.

WELBANK, P.J., GIBB, M.J., TAYLOR, P.J. and WILLIAMS, E.B. (1974) Root growth of cereal crops. Rothamsted Experimental Station Report for 1973, Part 2, 26-66.

2.4 Tillering

CANNELL, R.Q. (1969) The tillering pattern in barley varieties. I. Production, survival and contribution to yield by component tillers. J. Agric. Sci., Camb., **72**, 405-422.

GRANT, D. (1984) Growth and development of the winter barley crop. Ph.D Thesis, University of Edinburgh.

SHARIF, P. and DALE, J.E. (1980) Growth regulating substances and the growth of tiller buds in barley : effects of IAA and GA. J. Exp. Bot., **31** (124), 1191-1197.

SIMMONS, S.R., RASMUSSON, D.C. and WEIRSMA, J.V. (1982) Tillering in barley: genotype, row spacing and seeding rate effects. Crop Science, **22**, 801-805.

THORNE, G.N. and WOOD, D.W. (1988) Contributions of shoot categories to growth and yield of winter wheat. J. Agric. Sci., Camb., **111**, 285-294.

2.5 Ear development

COTTRELL, J.E. (1980) The effects of light and gibberellic acid on development of the mainstream apex of barley (Hordeum vulgare L.). Ph.D Thesis, University of Edinburgh.

FISCHER, R.A. (1985) Number of kernels in wheat crops and the influence of solar radiation and temperature. J. Agric. Sci., Camb., **105**, 447-461.

HUTLEY-BULL, F.D. and SCHWABE, W.W. (1982) Morphogenesis in the wheat apex as influenced by environment and plant growth regulators. In Opportunities for Manipulation of Cereal Productivity. BPGRG Monograph No. 7 (Eds. A.F. Hawkins and B. Jeffcoat), 159-166.

JENKINS, G., KIRBY, E.J.M. and ROFFEY, A.P. (1980) Selection for developmental response in winter barley. J. Agric. Sci., Camb., **87**, 591-598.

KIRBY, E.J.M. and ELLIS, R.P. (1980) A comparison of spring grown barley in England and Scotland. 1. Shoot apex development. J. Agric. Sci., Camb., **95**, 101-110.

RAWSON, H.M. (1970) Spikelet numbers : its control and relation to yield per ear. Aust. J. Biol. Sci., **23**, 1-15.

TRAVIS, K.Z. and DAY, W. (1988) Modelling the timing of the early development of winter wheat. Agriculture and Forest Meteorology, **44**, 67-79.

WHEELER, A.W. (1976) Some treatments affecting growth substances in developing wheat ears. Ann. Appl. Biol., **83**, 455-462.

2.7 Grain growth

BAYLES, R.A. (1977) Poorly filled grain in the cereal crop. I. The assessment of poor grain filling. Journal of the National Institute of Agricultural Botany, **14**, 232-240.

BAYLES, R.A., EVERS, A.D. and THORNE, G.N. (1978) The relationship of grain shrivelling to the milling and baking quality of three winter wheat cultivars grown with different rates of nitrogen fertiliser. J. Agric. Sci., Camb., **90**, 445-446.

BINGHAM, J. (1967) Investigations on the physiology of yield in winter wheat by comparisons of varieties and by artificial variation in grain number. J. Agric. Sci., Camb., **68**, 411-422.

BREMNER, P.M. (1972) The accumulation of dry matter and nitrogen by grains in different positions of the ear as influenced by shading and defoliation. Aust. J. Biol. Sci., **25**, 657-681.

BROCKLEHURST, P.A. (1977) Factors controlling grain weight in wheat. Nature, **266**, 348-349.

BROCKLEHURST, P.A., MOSS, R.P. and WILLIAMS, W. (1978) Effects of irradiance and water supply on grain development in wheat. Ann. Appl. Biol., **64**, 375-384.

FISCHER, R.A. and HILLERISLAMBERS, D. (1978) Effect of environment and cultivar on source limitation to grain weight in wheat. Aust. J. Agric. Res., **24**, 443-458.

GALLAGHER, J.N. and THORNE, G.N. (1978) The control of grain size in barley. Home Grown Cereals Authority, Progress Reports on Research and Development 1977-1978, pp 36-37.

GALLAGHER, J.N., BISCOE, P.V. and HUNTER, B. (1976a) Effects of drought on grain growth. Nature (London), **264**, 541-542.

GALLAGHER, J.N., BISCOE, P.V. and SCOTT, R.K. (1975) Barley and its environment. V. Stability at grain weight. J. Appl. Ecol., **13**, 319-336.

HANIF, M. and LANGER, R.H.M. (1972) The vascular supply of the spikelet in wheat (Triticum aestivum). Ann. Bot., **36**, 721-727.

JENNER, C.F. and RATHJEN, A.J. (1972) Limitations to the accumulation of starch in the developing wheat grain. Ann. Bot., **36**, 743-754.

KING, R.W. (1979) Ascorbic acid synthesis and metabolism in wheat ears. Aust. J. Plant Physiol., **6**, 99-108.

SPIERTZ, J.H.J. (1978) Weather and nitrogen effects on rate and duration of grain growth and on grain yield of wheat cultivars. Crop Physiology and Cereal Breeding. Proceedings of Eucarpia Workshop, Wageningen, 60-64.

2.8 Harvest index

DONALD, C.M. and HAMBLIN, J. (1976) The biological yield and harvest index of cereals as agronomic and plant breeding criteria. Advances in Agronomy, **28**, 361-405.

GALLAGHER, J.N. and BISCOE, P.V. (1978) Assimilate partitioning and high yields in cereals. In Opportunities for Chemical Plant Growth Regulation. BPGRG Monograph No. 1, 113-124.

GALLAGHER, J.N. and BISCOE, P.V. (1978b) A physiological analysis of cereal yield. II. Partitioning of dry matter. Agric. Prog., 51-70.

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

3 PHYSIOLOGY IN THE DECISION MAKING PROCESS

3.1 Introduction

HEARN, A.B. and de ROZA, G.D. (1985) A simple model for crop management applications for cotton (Gossypium hirsutum L.). Field Crops Research, **12**, 49-69.

PORTER, J.R. (1985) Models and mechanisms in the growth and development of wheat. Outlook on Agriculture, **14** (4), 190-196.

SYLVESTER-BRADLEY, R. (1982) Plant physiology in advisory work. Agricultural Progress, **57**, 13-18,

TENG, P.S. and GAUNT, R.E. (1980) Modelling systems of disease and yield loss in cereals. Agricultural Systems, **6**, 131-154.

3.2 Varietal choice

MYCROFT, H. (1983) Variability of yield in cereal variety x fungicide trials. J. Agric. Sci., Camb., **100**, 535-538.

SILVEY, V. (1986) The contribution of new varieties to cereal yields in England and Wales between 1947 and 1983. J. natn. Inst. agric. Bot., **17**, 155-168.

WOLFE, M.S. and BARRETT, J.A. (1981) The agricultural value of variety mixtures. In Barley Genetics IV, Proceedings of the Fourth Barley Genetics Symposium, Edinburgh, pp 435-440.

3.3 Sowing

CARVER, M.F.F. (1977) The influence of seed size on the performance of cereals in variety trials. J. Agric. Sci., Camb., **89**, 247-249.

CHATHAM, C.J. (1985) The growth, development and modification of barley seed crops. Ph.D Thesis, University of Nottingham.

CLARE, R.W., KAP DEWI, I. and MADGE, W.E.R. (1986) The effect of autumn nitrogen, insecticide and fungicide on winter wheat sown at two dates and with three levels of spring nitrogen. Proceedings 1986 Conferences Crop Protecting Conference: Pests and Diseases, **1**, 165-172.

ELLIS, R.P. and RUSSELL, G. (1984) Plant development and grain yield in spring and winter barley. J. Agric. Sci., Camb., **102**, 85-95.

FIELDER, A. (1988) Interactions between variety and sowing date for winter wheat and winter barley. HGCA review article. Agricultural Development and Advisory service, Reading.

HEGARTY, T.W. and ROYLE, S.M. (1978) Soil impedance as a factor reducing crop seedling emergence and its relation to soil conditions at sowing, and to applied water. Journal of Applied Ecology, **15**, 897-904.

KIRBY, E.J.M. (1969) The effect of sowing date and plant density on barley. Ann. Appl. Biol., **63**, 513-521.

KIRBY, E.J.M. (1976) Population and competition. J. natn. Inst. agric. Bot., **14**, 187-190.

KIRBY, E.J.M., APPLEYARD, M. and FELLOWS, G. (1985) Variation in development of wheat and barley in response to sowing date and variety. J. Agric. Sci., Camb., **104**, 385-396.

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD (1978) Sowing Cereals. Short term leaflet 94. ADAS.

WHITE, E.M. (1982) The effect of varying seed populations on the yields of two spring barley cultivars of contrasting seed size. Record of Agricultural Research (Department of Agriculture for Northern Ireland), **30**, 61-66.

WIDDOWSON, F.V. et al. (1986) The effects of sowing date and other factors on growth, yield and nitrogen uptake, and on the incidence of pests and diseases, of winter barley from 1981 to 1983. J. Agric. Sci., Camb., **106**, 551-574.

WILLEY, R.W. and HOLLIDAY, R. (1971) Plant population and shading studies in barley. J. Agric. Sci., Camb., **77**, 445-452.

3.4 Nitrogen

BISCOE, P.V. and WILLINGTON, V.B.A. (1984) Cereal crop physiology — a key to accurate nitrogen timing. Marketable Yield of Cereals, Cereal Information and Development Unit, Stoneleigh, 67-74.

BLOOM, T.M., SYLVESTER-BRADLEY, R., VAIDYANATHAN, L.V. and MURRAY, A.W.A. (1988) Apparent recovery of fertiliser nitrogen by winter wheat. In Nitrogen Efficiency in Agricultural Soils and the Efficient Use of Fertiliser Nitrogen. CEC Seminar, Edinburgh. Eds. D. Jenkinson and K.A. Smith, pp 27-37. Elsevier, London.

CHALMERS, A.G. and LEECH, P.K. (1986) Fertiliser use on farm crops in England and Wales, 1985 (and preceding annual reports). MAFF, London (SS/CH/22).

DEPARTMENT OF THE ENVIRONMENT (1986) Nitrate in water. Pollution Paper No. 26. HMSO London, p 104.

GEORGE, B.J. (1984) Design and interpretation of nitrogen response experiments. In The Nitrogen Requirements of Cereals (MAFF/ADAS Reference Book 385), pp 133-148.

GRYLLS, J.P. and ARCHER, J.R. (1982) Response of winter barley to nitrogen. In The Nitrogen Requirement of Cereals. MAFF Reference Book 385, HMSO, London.

LORD, E.I. and VAUGHAN, J. (1987) Optimising nitrogen applications for the production of malting barley. Aspects of Applied Biology, **15**, 319-335.

NEUMANN, P.M. (1988) Plant Growth and Leaf-applied Chemicals. CRC Press Inc., Boca Raton, Florida.

SYLVESTER-BRADLEY, R., ADDISCOTT, T.M., VAIDYANATHAN, L.V., MURRAY, A.W.A. and WHITMORE, A.P. (1987) Nitrogen advice for cereals : present realities and future possibilities. Proceedings of the Fertiliser Society of London, Dec 1987, pp 1-36.

WHINGWIRI, E.E. and KEMP, D.R. (1980) Spikelet development and grain yields of the wheat ear in response to applied nitrogen. Australian Journal of Agricultural Research, **31**, 637-647.

WIDDOWSON, F.V., DARBY, R.J., DEWAR, A.M., JENKYN, J.F. and KERRY, B.R. (1986) The effects of sowing date and of six other factors, on growth, yield, nitrogen uptake, and on the incidence of pests and diseases of winter barley at Rothamsted 1981 to 1983. J. Agric. Sci., Camb., **106**, 551-575.

3.5 Weed control

MOSS, S.R. (1987) Competition between black-grass (Alopecurus myosuroides) and winter wheat. British Crop Protection Conference - Weeds, pp 367-374.

ORSON, J.H. (1988) The control of Galium aparine (cleavers) in winter cereals with herbicides: ADAS results, harvest years 1985 to 1987. Aspects of Applied Biology, **18**, 99-108.

ORSON, J.H. and MARSHALL, J. (1985) The control of annual broad-leaved weeds in winter cereals: autumn, spring or summer and spring applications compared. British Crop Protection Conference - Weeds, pp 715-722.

SLY, J.R.A. (1986) Survey Report 41, Review of Usage of Pesticides in Agriculture, Horticulture and Forestry in England and Wales 1980-1983. London; Ministry of Agriculture, Fisheries and Food.

ZIMDAHL, R.L. (1980) Weed-crop competition. International Plant Protection Center, Oregon State University, Corvallis, Oregon 97331, USA, 5-140.

3.6 Disease control

ANON (1986) Winter Wheat — Managed Disease Control. Ministry of Agriculture, Fisheries and Food, Advisory Leaflet No. P831, 6 pp. MAFF Publications, Lion House, Alnwick, NE66 2PF.

COOK, R.J. and JENKINS, J.E.E. (1988) Contribution and value of chemicals to disease control — Cereals. In Costs and Benefits of Disease Control (Ed. B. Clifford), Blackwell Scientific Publications, Oxford (in press).

COOK, R.J. and THOMAS, M.R. (1988) Influence of agronomic factors and fungicide programmes on yield of winter wheat in England and Wales, 1979-1987 (in press).

GREEN, C.F. and IVINS, D.J. (1984) Leaf infestation of take-all (Gaeumannomyces graminis var. tritici) on winter wheat (Triticum aestivum cv. Virtue): Yield, yield components and photosynthetic potential. Field Crops Research, **8**, 199-206.

KING, J.E. (1977) Surveys of diseases of winter wheat in England and Wales, 1970-1975. Plant Pathology, **26**, 8-20.

LARGE, E.C. and DOLING, D.A. (1962) The measurement of cereal mildew and its effect on yield. Plant Pathology, **11**, 47-57.

LAST, F.T. (1962) Analysis of the effects of Erysiphe graminis D.C. on the growth of barley. Ann. Bot., **26**, 279-289.

SCOTT, S.W. and GRIFFITHS, E. (1980) Effects of controlled epidemics of powdery mildew on grain yield of spring barley. Ann. Appl. Biol., **94**, 19-31.

THOMAS, M.R. and COOK, R.J. (1988) Likelihood of economic responses to fungicide programmes on winter wheat. Proceedings of the Second International Conference on Plant Diseases, Bordeaux, 1988 (in press).

THOMAS, M.R., COOK, R.J. and KING, J.E. (1988) Factors affecting development of Septoria tritici in winter wheat and its effect on yield. Plant Pathology (in press).

TYLDESLEY, J.B. and THOMPSON, N. (1980) Forecasting Septoria nodorum on winter wheat in England and Wales. Plant Pathology, **29**, 9-20.

WEBSTER, J.P.G. and COOK, R.J. (1986) Knowledge-based microcomputer systems for disease control in winter wheat. FBU Occasional Paper Number 13. Wye College, University of London.

ZADOKS, J.C. (1981) Epipre : a disease and pest management system for winter wheat developed in the Netherlands. Eppo Bulletin, **11** (3), 365-369.

3.7 Plant growth regulation

AUFHAMMER, W. (1981) Role of plant growth regulators in wheat yield. In Aspects and Prospects of Plant Growth Regulators. BPGRG Monograph No. 6 (Ed. B. Jeffcoat), 131-140.

AUSTIN, R.B. (1982) A combined genetic and chemical approach to increasing and stabilizing wheat yields. In Opportunities for Manipulation of Cereal Production. BPGRG Monograph No. 7 (Eds. A.F. Hawkins and B. Jeffcoat), 193-203.

BOOTHROYD, D. and CLARE, R.W. (1984) Growth regulator use on winter wheat and barley. Recent Developments in Cereal Production. proceedings of a Conference held at the University of Nottingham, 21-37.

CALDICOTT, J.J.B. (1978) Review of effects of cycocel on grain yield of winter wheat. Cyanamid of Great Britain Limited, Technical Review.

CALDICOTT, J.J.B. (1982) The uptake and translocation of chlormequat in wheat and barley. A review. Cyanamid of Great Britain Limited.

CALDICOTT, J.J.B. and LINDLEY, C.D. (1964) The use of CCC to prevent lodging in wheat. In Proceedings of the 7th British Weed Control Conference, 49-56.

CARTWRIGHT, P.M. and WADDINGTON, S.R. (1982) Growth regulators and grain yield in spring cereals. In Opportunities for Manipulation of Cereal Production. BPGRG Monograph No. 7 (Eds. A.F. Hawkins and B. Jeffcoat), 61-70.

CHILD, R.D., TREHARNE, K.J. and HOAD, G.V. (1983) Growth regulator potential for improvement of cereal yields. Factors Affecting the Accumulation of Exploitable Reserves in the Cereal Plant. MAFF Reference Book 222, HMSO. 14-26.

DE VOS, N.M., DILZ, K. and BRUINSMA, J. (1967) The effects of 2-chloroethyl-trimethyl ammonium chloride (CCC) on yield and lodging of wheat. Netherlands Journal of Agricultural Science, **15**, 50-62.

GRAHAM, J. (1983) Crop lodging in British wheats and barleys. Ph.D Thesis, University of Reading.

GREEN, C.F. (1987) The use of foliar applied, synthetic plant growth regulators on cereal crops with special reference to chlormequat. Report to MAFF Chief Scientist's Group.

GREEN, C.F. and DAWKINS, T.K.C. (1983) Response of winter sown cereals to chlorocholine chloride in the absence of lodging. Report of pilot trials, 1982-83 season, University of Nottingham.

HUMPHRIES, E.C. (1968) CCC and cereals. Field crop Abstracts, **21**, 91-97.

HUMPHRIES, E.C. and BOND, W. (1969) Experiments with CCC on wheat : effects of spacing, nitrogen and irrigation. Ann. Appl. Biol., **64**, 375-384.

JORDAN, V.W.L. and STINCHCOMBE, G.R. (1986) Interactions between fungicide, plant growth regulator, nitrogen fertiliser applications, foliar disease and yield of winter barley. Ann. Appl. Biol., **108**, 151-165.

KETTLEWELL, P.S., WHITLEY, ELERI A., MEREDITH, W.S. and SYLVESTER-BRADLEY, R. (1983) Effects of early applications of chlormequat on tillering and yield of wheat. J. Agric. Sci., Camb., **100**, 735-738.

KORANTENG, G.O. and MATTHEWS, S. (1982) Modification of the development of spring barley by early applications of CCC and GA and the subsequent effects on yield components and yield. In Chemical Manipulation of Growth and Development (Ed. J. McLaren), Butterworths, London, 343-358.

MATTHEWS, S. and THOMSON, W.J. (1984) Growth regulation : control of growth and development. Cereal Production (Ed. E.J. Gallagher), pp 259-266, Butterworth.

MAYR, H.H. AND PRESOLY, E. (1963) Untersuchungen an mit chlorcholinchlorid (CCC) behandellten weizenpflanzen. Anatomischomorphologisches ergebinisse. I. Mitteilung. Zeitschrift fur Acker und Pflanzenbau, **118,** 109-124.

NAYLOR, R.E.L., STOKES, D.T. and MATTHEWS, S. (1987) Chemical manipulation of growth and development in winter barley production systems. Field Crop Abstracts, **40** (5), 277-289.

NEEDHAM, P. (1973) The effects of chlormequat on yield and nitrogen response of wheat : a review. ADAS Closed Conference of Soil Scientists SS/C/39/AIC 10. July 1973.

WADDINGTON, S.R. and CARTWRIGHT, P. (1986) Modification of yield components and straw length in spring barley by the application of growth retardants prior to main shoot stem elongation. J. Agric. Sci., Camb., **107**, 367-375.

WILLIAMS, R.H. and CARTWRIGHT, P.M. (1979) The effect of applications of a synthetic cytokinin on shoot dominance and grain yield in spring barley. Poster given at the AAB Conference, 18 September 1979.

WOOLLEY, E.W. (1982) Performance of current growth regulators in cereals. In Opportunities for Manipulation of Cereal Productivity. BPGRG Monograph No. 7 (Eds. A.F. Hawkins and B. Jeffcoat), 44-50.

3.8 Control of quality

ANON (1984) Post-harvest losses in quality of food grains. FAO Food and Nutrition Paper 29. Food and Agriculture Organisation of the United Nations, Rome.

AUSTIN, R.B., MORGAN, C.L., FORD, M.A. and BLACKWELL, R.D. (1978) Photosynthesis, translocation and grain filling. Annual Report of the Plant Breeding Institute, Cambridge for 1977. pp 136-139.

BATHGATE, G.N. (1987) Quality requirements for malting. Aspects of Applied Biology **15,** Cereal Quality, 18-31.

DUFFUS, C.M. (1987) Cereal grain structure and development : relationship to the technological properties of the mature grain. Aspects of Applied Biology, **15**, 65-78.

FLINT, D., AYERS, G.S. and RIES, S.K. (1975) Synthesis of endosperm proteins in wheat seed during maturation. Plant Physiology, **56**, 381-384.

FORD, M. (1987) Quality requirements for milling and baking. Aspects of Applied Biology, **15** (Cereal Quality), 10-17.

GALE, M.D. and LENTON, J.R. (1987) Pre-harvest sprouting in wheat — a complex genetic and physiological problem affecting breadmaking quality of UK wheats. Aspects of Applied Biology, **15** (Cereal Quality), 115-124.

HOOK, S.C.W., SALMON, S.E. and STEWART, B.A. (1988) Effects of various nitrogen-fertilizer regimes on the milling and baking qualities of home-grown bread-making wheats. Report to the Priorities Board, Flour Milling and Baking Research Association.

HOOK, S.C.W., SALMON, S.E., GREENWELL, P. and EVERS, A.D. (1988) Gravity table separation in the production of milling and baking quality wheat from samples containing sprout-damaged grain. HGCA Research Report No. 1. Home-Grown Cereals Authority, London.

KETTLEWELL, P.S. (1989) Breadmaking quality in wheat. Agricultural Progress, **84**, 30-45.

MICHAEL, G. and SEILER-KELBITSCH, H. (1972) Cytokinin content and kernel size of barley grains as affected by environmental and genetic factors. Crop Science, **12**, 162-165.

RADLEY, M. (1978) Factors affecting grain enlargement in wheat. J. Exp. Bot., **29**, 919-934.

STEVENS, D.B., VAIDYANATHAN, L.V. and BALDWIN, J.H. (1988) Hagberg falling number and breadmaking quality. HGCA Research Report No. 2. Home-Grown Cereals Authority, London.

STEWART, B.A. and SALMON, S.E. (1988) Measures of the breadmaking quality of wheat. HGCA Research Report No. 3. Home-Grown Cereals Authority, London.

SWAIN, R.W. and MELVILLE, S.C. (1973) Shrivelled grain and poor finishing of cereals. ADAS QUarterly Review, **11**, 118-127.

SYLVESTER-BRADLEY, R. and FOLKES, B.F. (1976) Cereal grains : their protein components and nutritional quality. Science Progress, **63**, 241-263.

WHITEHOUSE, R.H.N. (1970) The prospects of breeding barley, wheat and oats to meet special requirements in human and animal nutrition. Proceedings of the Nutrition Society, **29**, 31-39.

WILKIN, D.R. and ROWLANDS, D.G. (1988) Biodeterioration of stored cereals. HGCA Research Report No. 3. Home-Grown Cereals Authority, London.

3.9 Tailoring husbandry to site and season

AUSTIN, R.B. (1978) Actual and potential yields of wheat and barley in the United Kingdom. ADAS Quarterly Review No. 29, 76-87.

CHURCH, D.M. and AUSTIN, R.B. (1983) Variability of wheat yields in England and Wales. J. Agric. Sci., Camb., **100**, 201-204.

ELLIS, R.P. and KIRBY, E.J.M. (1980) A comparison of spring grown barley in England and Scotland. 2. Yield and its components. J. Agric. Sci., Camb., **95**, 111-115.

KIRBY, E.J.M., PORTER, J.R., DAY, W., ADAM, J.S., APPLEYARD, M., AYLING, S., BAKER, C.K., BELFORD, R.K., BISCOE, P.V., CHAPMAN, A., FULLER, M.P., HAMPSON, J., HAY, R.K.M., MATHEWS, S., THOMPSON, W.J., WEIR, A.H., WILLINGTON, V.B.A and WOOD, D.W. (1987) An analysis of primordium initiation in Avalon winter wheat crops with different sowing dates at nine sites in England and Scotland. J. Agric. Sci., Camb., **109**, 123-134.

LUPTON, F.G.H. (1969) Estimation of yield in wheat from measurement of photosynthesis and translocation in the field. Ann. Appl. Biol., **71**, 363-374.

PREW et al. (1985) Some factors limiting the growth and yield of winter wheat and their variation in two seasons. J. Agric. Sci., Camb., **104**, 135-162.

TALBOT, M. (1984) Yield variability of crop varieties in the UK. J. Agric. Sci., Camb., **102**, 315-321.

THORNTON, P.K. and McGREGOR, M.J. (1988) The identification of optimum management regimes for agricultural crop enterprises. Outlook on Agriculture, **17** (4), 158-162.

TINKER, P.B. (1984) Site-specific yield potentials in relation to fertiliser use. 18th Coll. Int. Potash Institute Bern, 193-208.

TINKER, P.B. and WIDDOWSON, F.V. (1983) Maximising wheat yields and some causes of yield variation. Proceedings of the Fertiliser Society, **211**, 149-184.

3.10 Breeding

AUSTIN, R.B. (1980) Physiological limitations to cereal yields and ways of reducing them by breeding. In Opportunities of Increased Crop Yields, eds R.S. Hurd, P.V. Biscoe and C. Denis. Pitman, London, 3-20.

AUSTIN, R.B. (1988) A different ideotype for each environment? In Central Breeding Related to Integrated Cereal Production (Eds. M.L. Jorna and L.A.J. Slootmaker). Pudoc, Wageningen.

AUSTIN, R.B. (1989) Genetic variation in photosynthesis : a review. J. Agric. Sci., Camb., **112**, 287-294.

AUSTIN, R.B., BINGHAM, J., BLACKWELL, R.B., EVAN, L.T., FORD, M.A., MORGAN, C.L. and TAYLOR, M. (1980) Genetic improvements in winter wheat yields since 1900 and associated physiological changes. J. Agric. Sci., Camb., **94**, 675-689.

AUSTIN, R.B., FORD, M.A. and MORGAN, C.L. (1989) Genetic improvement in the yield of winter wheat : a further evaluation. J. Agric. Sci., Camb., **112**, 295-301.

BINGHAM, J. (1976) Basic cereal physiology and its application to wheat. J. natn. Inst. agric. Bot., **14**, 179-182.

ELLIS, R.P. (1986) Spring barley cultivars bred at the Scottish Crop Research Institute. Crop Research (Hort. Res.), **26**, 57-77.

EVANS, L.T. (1981) Yield improvement in wheat: empirical or analytical? In Wheat Science - Today and Tomorrow, eds L.T. Evans and W.J. Peacock. Cambridge University Press, pp 203-222.

HURD, E.A. (1962) Phenotype and drought tolerance in wheat. Agric. Meteorology, **14**, 39-55.

LUPTON, F.G.H. (1987) Wheat Breeding. Chapman and Hall, London.

McKENZIE, H. (1972) Adverse influence of awns on yield of wheat. Can. J. Plant Sci., **52**, 81-87.

3.11 Biotechnology

AUSTIN, R.B. et al. (1986) Molecular biology and crop improvement : a case study of wheat, oilseed rape and faba beans. Cambridge University Press.