HGCA

PROJECT REPORT No. 20

GROWING BARLEY FOR MALTING - A REVIEW

SEPTEMBER 1989

PRICE £1.50

HGCA PROJECT REPORT No. 20

Growing barley for malting - a review

by

N. L. CARRECK and D. G. CHRISTIAN

This report is a literature review which was completed in the first year of a project of three years' duration entitled 'N uptake of barley related to malting quality'. The work, which commenced in November 1987, is being supported by a grant of £54,329 to Rothamsted Experimental Station by the Home-Grown Cereals Authority (Project No. 0025/1/87).

H-G.C.A. PROJECT 0025/1/87

GROWING BARLEY FOR MALTING - A REVIEW

N.L. Carreck & D.G. Christian
AFRC Institute of Arable Crops Research, Rothamsted Experimental Station,
Harpenden, Herts., AL5 2JQ.

January 1988 (Revised September 1989).

INTRODUCTION

The problem of cereal overproduction within the E.E.C. in recent years has increased interest in the production of high quality, rather than high yielding crops. Quality crops such as milling wheat and malting barley are not yet in surplus, and command premiums which help to compensate for the slightly lower yields which they usually produce.

Malting barley has traditionally been regarded as a low input crop in Britain, being grown mainly on the poorer land with minimal inputs of fertiliser and pesticides. For this reason there has been a lack of research into the agronomic factors needed to produce high quality malting barley.

In this paper we set out the requirements for malting grade barley, and discuss the major agronomic factors necessary for its production.

THE MARKET FOR MALTING BARLEY

Great Britain is one of the largest producers of barley within the E.E.C., and in terms of output, lags only marginally behind France (Table 1). Yields obtained in Britain are among the highest of major barley producers, reflecting the intensive nature of British barley production.

Table 1.

Major barley producers - Mean production 1985-88.

Country	Area 000ha	Production 000t	Yield tha^{-1}
France	2,061	10,508	5.1
Spain	4,291	10,009	2.3
United Kingdom	1,898	9,412	5.0
W. Germany	1,896	9,306	4.9
Denmark	1,077	5,024	4.7
EUR. 12	12,501	49,123	3.9

(C.E.C., 1989)

As a percentage of E.E.C. production, Britain's contribution has remained fairly stable in recent years at 17%. The area grown has however declined from 2,401 ha in 1968 to 1,878 ha in 1988 (C.E.C., 1989). Over this period, the proportion of winter barley has increased from 5% in 1968, to 53% in 1987 (H-G.C.A., 1987).

Use by British maltsters has declined in recent years from 1,933,000 t in 1981/2 to 1,650,000 t in 1986/7, reflecting reduced beer consumption, and hence the proportion of British barley used for malting has declined from 17.5% in 1983/4 to 12% in 1986/7 (H-G.C.A., 1987).

The export market however, is potentially large, and there is considerable scope for expansion, particularly to West Germany and Belgium. The former has the largest beer production in Europe, and with its requirement for malting barley far in excess of domestic production, it imports 800,000 t each year, one third of its requirement. Other markets for malting barley outside the E.E.C., such as Japan and South America, are also capable of considerable further exploitation. It is estimated that approximately 40% of U.K. production of malting barley is now exported (Nix, 1986). Imports of malting barley to Britain have varied from 11% in 1985/6 to 4% in 1986/7 (H-G.C.A., 1987).

The demand for quality malting barley is shown by the considerable premiums paid, for example, a price of £146 t^{-1} for malting barley, as against £100 t^{-1} for feed barley (Big Farm Weekly, 31/8/89).

MALTING BARLEY PRODUCTION IN GREAT BRITAIN

Barley sold for malting remains a relatively small proportion of total barley production, and seed certification figures show that the majority of the increase in recent years of winter barley grown has been of feed varieties, which together account for nearly 40% of all barley sown in Britain. Interest in dual purpose varieties which are high yielding with malting potential, such as Plaisant and Magie, has however meant that the proportion of malt produced from winter varieties has also increased.

Table 2.

U.K. barley planting survey 1989.

Winter:	Magie	12.5%
	Halcyon	6.2%
	Pipkin	4.3%
	Maris Otter	2.7%
Spring:	Triumph	11.2%
	Blenheim	8.5%
	Carmague	5.5%
	Natasha	3.3%
	Doublet	3.0%
	Atem	2.8%
	Golden Promise	1.9%
Other varieties and feed		38.1%

(H-G.C.A., 1989)

The major malting barley growing areas are located towards the east of the country, in East Anglia, the East Midlands, the South East, and the lowlands of Scotland, where much of the malt produced is used in the malt whisky industry.

Traditionally, winter barley has been regarded as a flexible crop. It is most often grown after cereals, either in a continuous cereals situation, or in rotation with a break crop such as oilseed rape. On chalky soils it is sometimes grown as a first crop after sugar beet. It is normally only rarely grown as a first cereal after a break, because the high residual fertility is most suited to a high yielding winter wheat, and also due to barley's greater lodging risk in high fertility situations.

MALTING QUALITY

Malting quality in barley can be regarded as a combination of a large number of different characteristics, which were listed by Sturgess and Knell (1978) as:-

1. Germinative capacity.
2. Nitrogen concentration,
3. Starch composition.
4. Enzyme activity.
5. Skin thickness.
6. Beta-glucan content.
7. Grain size and thousand grain weight.
8. Uniformity.
9. Variety.

Most of these factors are of a biochemical nature, more controlled by genetic rather than husbandry factors, and thus the choice of a recommended malting barley variety will ensure that the majority of these criteria are satisfied.

The starch contained within the endosperm of the grain consists of two compounds, amylose and amylopectin. During the malting process, these are broken down by the diastatic emzymes known as alpha and beta amylase. Diastatic power depends on the activity of both these enzymes, as they work together during amylopectin degradation. Beta amylase is present in ungerminated grain, whilst alpha amylase is manufactured only during the early stages of germination (Atanda & Miflin, 1970; Sturgess & Knell, 1978). Malting barley normally has a high diastatic power, this being especially important in the production of grain whisky (Hayter & Riggs, 1973). Alpha amylase activity is mainly determined by variety, but may be altered to some extent by environmental factors (Gothard, 1974).

QUALITY CHRACTERISTICS WITHIN THE FARMER'S CONTROL

Having chosen his variety, the quality characteristics which are input related and are therefore largely within the farmer's control, are limited to the following:-

Grain nitrogen concentration

The nitrogen concentration of the grain (%N) is used as a guide to crude protein content, as given by %N x 6.25. For malting barley %N should be below 1.8%, preferably below 1.6%. High protein contents lead to haze and instability problems in the finished beer, and also reduce the percentage of fermentable extract. For every 0.1% increase in the grain nitrogen content, the fermentable extract yield is reduced by 1%. This will affect the amount of malt required to produce a given amount of beer.

When a grain is viewed in cross section, a white, "mealy" appearance indicates that it possesses a high starch to protein ratio, and is therefore suitable for malting, whilst a grey, "flinty" appearance indicates a high protein content, with starch grains unavailable, and is therefore unsuitable for malting.

Nitrogen content is measured by Kjeldahl digestion, which is slow but very accurate, or by more rapid near infra red reflectance techniques which are widely used by grain merchants.

Germination

Samples must have better than 95% germination, preferably close to 100%. This is usually rapidly tested by staining for specific enzyme activity with Tetrazolium for 15 minutes (Bishop, 1957). There are other tests available, but these are time consuming, and are not normally used commercially by grain merchants.

Grain size and appearance

Maltsters prefer barley with large, plump, uniform grains, as this is an indicator of even germination. Ideally, over 75% of the grain should pass over a 2.8 mm sieve. The usual U.K. specification is that 95% must pass over a 2.2 mm sieve, whilst export specifications require 90% to be over 2.5 mm.

Grains with thin skins are preferred, as this enables steeping to take place rapidly, but excessively thin skins may cause splitting in the ear, especially in wet conditions, leading to fungal infection and poor germination.

Finally, grain for malting should be free from mould, taint, smell, and insect or mechanical damage.

THE SOURCE OF ASSIMILATES FOR GRAIN FILLING

As with all cereals, when discussing the effects of agronomic inputs, it is important to distinguish between potential and actual yields, and between growth and development. The potential yield is the maximum possible yield obtainable by a given variety in a given location. The actual yield obtained will depend on the aerial and soil environment, and the effects of pests and diseases. Husbandry inputs will hopefully reduce the difference between the potential and the actual yields.

The development, or morphological stage of the plant is largely determined by temperature expressed as accumulated day degrees, whilst the growth, or increase in biomass of the plant is largely determined by the amount of solar radiation absorbed by the foliage. Husbandry inputs which lengthen the growing season, reduce limiting factors, or affect radiation absorption will therefore have profound effects upon the final yield.

With malting barley, yield and %N are the most important factors with which the farmer is concerned. The period of grain filling is therefore critical, as the financial return obtained from the crop is determined by the actual amounts of carbohydrate and protein in the grain, and the relationship between them.

In several experiments, nitrogen content of the ear has been measured as the crop proceeds to maturity. Brewer and Poehlman (1968), and Pomeranz *et al* (1971), found that %N increased towards maturity, whilst Knowles and Watkin (1931), Mclean (1933), and Harris and MacWilliam (1957), found it to steadily fall towards harvest. Brenchley (1912), and Ellen and Speirtz (1980) found it to fall for one month after anthesis (flowering), and then to rise again.

All authors do agree however, that the total nitrogen content, on a dry weight basis, will continue to rise towards maturity. The existence of such wide variation in measured values for %N means that in order to explain them, it is important to follow the source-sink relationships of the assimilates during the grain fill period. The stems and leaves are generally regarded as the source of assimilate, whilst the growing ears are regarded as the sink.

Carbohydrate

Much work, mainly using ^{14}C tracer studies, was done in the 1960s and 1970s, to establish the relative contributions of the various photosynthetic organs of the plant, towards the final carbohydrate content of the cereal grain. Carbohydrate is transported within the plant as sugars, and then stored as starch.

Estimates for the contributions of the various organs vary, but authors agree that the contribution of pre-anthesis photosynthesis is normally small, between 12% and 20% of carbohydrate (Lupton, 1969; Thorne, 1974). Its relative contribution to yield may however increase due to stress from drought (Bidinger *et al*, 1977), low fertility (Gallagher *et al*, 1975), or disease (Scott and Dennis-Jones, 1976).

The majority of carbohydrate is therefore normally derived from photosynthesis after anthesis. Estimates of the contribution from the ear itself vary from 26% to 100%, but it is generally agreed to be about 40-45% under normal conditions (Porter *et al*, 1950; Watson *et al*, 1958; Thorne, 1963; Biscoe *et al*, 1973; Thorne, 1974), of which the awns contribute between 10% and 35% (Porter *et al*, 1950; Watson *et al*, 1958; Biscoe *et al*, 1973).

The remainder of the assimilate is supplied by the leaves and stem of the plant, mainly the flag leaf and sheath (Watson *et al*, 1958; Lupton, 1969; Biscoe *et al*, 1973), although up to 15% of carbohydrate may be derived from parts of the plant below the flag leaf node under certain circumstances (Watson *et al*, 1958). Lupton (1966), showed that assimilate translocated from the flag leaf moved almost entirely to the grain, whilst this was less true of assimilate from the lower leaves.

Protein

Less work has been done on the movement of nitrogenous compounds to the grain during grain fill. This is surprising, in view of the fact that the carbohydrate is stored in the endosperm in the form of starch granules within a matrix of storage protein, mainly hordein, and therefore a shortage of nitrogenous compounds might be expected to restrict the sink capacity for carbohydrate of the developing grain. The majority of studies of nitrogen partitioning have been carried out only on wheat, but it is assumed that the patterns of nitrogen movement within the barley plant will be broadly similar.

Nitrogen uptake and assimilation is a complex process (Huffaker & Rains, 1978), but broadly speaking, all amino acids within the plant are derived from ammonium ions produced by the reduction of nitrate taken up from the soil, using nitrate and nitrite reductase. These ammonium ions then combine with the products of photosynthesis to form amino acids, from which the various proteins in the plant are then made.

Unlike grain carbohydrate, which is mainly produced after anthesis, it seems likely that under normal conditions, the majority of amino acids for grain formation are translocated from other parts of the plant, and are therefore derived from nitrogen absorbed before anthesis. Early work by Knowles and Watkin (1931), showed that 25% of the nitrogen present at final harvest is already present seven weeks before ear emergence, at Growth Stage (G.S.) 32 (Zadoks *et al*, 1974), whilst by anthesis, G.S. 61, the plant contains 83% of its final nitrogen (Austin *et al*, 1977). Spratt and Gasser (1970), concluded that 75% of nitrogen was taken up before anthesis, and the remaining 25% during grain formation. The proportion translocated seems dependent on the weather, and the nutrient status of the soil. Gregory *et al* (1981), stated that the crop may, or may not, continue to take up nitrogen after anthesis, depending on weather conditions, whilst Boatwright and Haas (1961), concluded that if sufficient nitrogen was available before ear emergence, then little or none would be absorbed from the soil between anthesis and maturity. If however, nitrogen supply was limiting, then uptake would continue until maturity.

Study of the degree to which nitrogen is translocated or absorbed following anthesis is important for two reasons; firstly because it will control the sink capacity of the grain, the cell number in the endosperm being regulated by the supply of assimilates during the first two weeks after anthesis (Brocklehurst, 1977), and secondly because the majority of translocated nitrogen comes from the leaves (Boatwright and Haas, 1961). Since the majority of the nitrogen in the leaves is contained within the chloroplasts, its removal will result in a reduction in photosynthesis, with a consequent reduction in carbohydrate available for grain fill (Gregory *et al*, 1979; Gregory *et al*, 1981). This will result in grains of poor size and weight, with a high nitrogen content.

This explains why crops suffering from sudden stress during the growing season, either from drought or nitrogen deficiency, will tend to produce poor yields of high nitrogen grain.

THE EFFECT OF HUSBANDRY FACTORS ON QUALITY

Soil type

Soil type is an important factor, due to its effect upon moisture holding capacity and nutrient availability. An ideal soil for malting barley production will be well drained, but not prone to drought. Soils over chalk, or a sandy clay loam have traditionally been regarded as most suitable.

Heavy soils may delay drilling, and tend to produce grain samples with high nitrogen content due to reduced leaching resulting in large quantities of available nitrogen late in the season during grain fill. This is not however, a fault of the soil *per se*, and more careful nitrogen application, perhaps at a reduced rate, or earlier in the spring, will probably overcome this problem to some extent. Heavy soils certainly seem to have an advantage in dry years, due to their high water retaining capacity, which prolongs the grain fill period.

Sandy soils often suffer from excessive drought susceptibility, causing premature senescence and shrivelled grain with a high nitrogen content. In areas where summer rainfall is reliable however, sandy soils can grow acceptable malting barley crops. The effect of increased leaching may lead to nitrogen shortage late in the season, so fertiliser applications should be amended accordingly.

Barley is tolerant to most soil types, but those with a pH of below 6.0 should be avoided, since they may contain acid patches which will be damaging to the plant. It is safer to use soils with a pH of 6.5 or greater.

Malting barley should not be grown on soils with a high residual nitrogen, such as after clover leys, peas or beans, or fodder roots, or on rich organic soils, as grain with a high protein content will result due to mineralisation of nitrogen in the later stages of grain growth. It is probable that under certain circumstances however, a moderate amount of residual nitrogen late in the season may be an advantage, as it may prevent premature senescence (Gregory *et al*, 1981).

Cultivations

Malting barley is usually grown after cereals, often with minimum cultivation. Techniques such as shallow ploughing or direct drilling are ideal. Methods such as deep ploughing which may lead to increased mineralisation and release of nitrogen late in the season should be avoided prior to a malting barley crop as they may result in grain with a high nitrogen content.

Compaction of the soil will cause loss of yield and high nitrogen grain due to poor plant growth and poor grain fill. Techniques which may increase problems of weeds or diseases should also be avoided.

Variety

Since many of the quality characteristics of malting barley are controlled by genotype, choice of variety is probably the most important factor in growing the crop. Varieties should be selected from the Recommended List (N.I.A.B., 1989), and from those preferred by the Institute of Brewing:-

Table 3.

<u>1989/90 - Preferred Barley Varieties: England and Wales.</u>

Winter:	Maris Otter	
	Halcyon	
	Pipkin	
	*Finesse	(* Provisional)
	*Waveney	
	*Puffin	
	*Melusine	
Spring:	Triumph	
	Natasha	
	Doublet	
	Corniche	
	Blenheim	
	*Prisma	

(I.O.B., 1989)

It should be noted that the use of a malting variety, whilst providing the potential for a good malting sample, is not a guarantee of malting quality actually being achieved, because of the large range of other factors which can affect quality.

Sowing date

Much work has shown that early sowing of cereals such as barley will increase yield potential, mainly by bringing forward the period of maxiumum growth (Kirby, 1969; Evans and Hough, 1984; Kirby *et al*, 1985; Green and Ivins, 1985; Green *et al*, 1985(c); Widdowson *et al*, 1986). Green *et al* (1985)(b), concluded that as sowing is delayed, 0.3% of yield may be lost for each day after 22nd September for winter crops. The advantages given by early sowing only relate to potential yield however, and the longer period of crop growth thus obtained will mean that constraints such as diseases and pests will become more serious as sowing date is advanced.

Where earlier sowing has provided a high yield potential, high inputs of herbicides, fungicides and pesticides are justified so that this potential can be realised. Conversely, if potential is low, due to late sowing, high inputs are unlikely to produce an economic return.

Given adequate nutrition and weather, early sowings will produce vigorous plants with a good root system, a large leaf area, and a large number of grain sites, producing a high yield of grain with a low %N. Late sown crops, on the other hand, will have poorer root systems, and will produce lower yields with higher protein content. This is especially serious for spring sown crops, where the yield penalty may be as much as 50% for March sown crops in drought years (A.D.A.S., 1984).

Ideal sowing dates are: for winter crops, early to mid September, and spring crops should be sown as early as possible, from January onwards. It should also be noted that some varieties are more responsive to early sowing dates than others. Late maturing varieties such as Maris Otter may be very cold sensitive, and may produce excessively weak straw when sown early. Early maturing, stiff strawed varieties, such as Magie, will show a better response to early sowing.

Climate and weather

This is a factor over which the farmer has no control, but is the most important in determining whether or not malting quality will be achieved. The east coast of Britain provides good conditions for the production of barley, although other areas not noted for malting barley production are probably equally suitable. The cool summers of the lowlands of Scotland produce a long growing season and are thus ideal for the growing of quality spring barley.

Both waterlogging and drought will cause yield penalties and increase nitrogen percentage. Waterlogging prevents germination of seed, and leads to poor root growth, as well as causing the soil to warm only slowly in the spring. Drought early in the year causes tiller death and a reduction in ear number and grains per ear, which cannot be overcome by subsequent rainfall. Drought later in the season will lead to premature senescence, a shortened grain fill period, and shrivelled, small grains (Gallagher *et al*, 1976; Brocklehurst *et al*, 1978; Lawlor *et al*, 1981).

If irrigation is available, and not required for more responsive crops such as potatoes, its use on potential malting crops, especially on lighter soils is worthwhile, but as with all cereals, it is important to start early in the season for maximum response. Irrigation of barley will increase the risk of lodging, and hence is best used in conjunction with a growth regulator (Bailey, 1985).

Whilst increased solar radiation is loosely linked to increased grain production, the effects of temperature are more complex. Increased temperature seems to affect dry matter partitioning, and produce an increased rate of grain filling, but also shortens the period of anthesis and induces earlier leaf senescence (Thorne, 1974).

Fertiliser

Under ideal conditions, early applications of nitrogen fertiliser will increase vegetative growth and produce high yields with little effect on grain nitrogen percentage. The response obtained will depend on the weather, soil type, and variety. It seems important, as mentioned earlier, to ensure that a shortage of nitrogen does not occur during grain fill, or photosynthesis, and hence yield may be affected (Gregory *et al*, 1981). Excessive nitrogen late in the season will however increase grain protein content, without necessarily increasing yield. The amount and timing of nitrogen is therefore a question of balance.

The rate of nitrogen applied will depend on previous cropping and residual nitrogen, but it is best to allow approximately 23 kg N ha^{-1} for each tonne of expected yield. Each 25-30 kg N ha^{-1} will however increase grain nitrogen percentage on average by 0.1% (A.D.A.S., 1979; Lord and Vaughan, 1987).

An application of 125-150 kg N ha^{-1} will therefore be suitable for most situations following cereals. It is not advisable to attempt to decrease protein content by lowering the fertiliser input, as the yield penalty will be severe with no guarantee of actually achieving malting quality. A reduction of 25 kg N ha^{-1} may well reduce yield by 1 t ha^{-1}.

The correct timing of nitrogen is important to avoid either deficiency or excessive protein content, and also to avoid excessive leaching of fertiliser. Seedbed nitrogen is not recommended for winter sown crops as it is usually lost before the plant can use it. Spring nitrogen should be applied either as one application in early or mid March, or split with one third in late February/early March with the remainder before G.S. 30. For spring sown crops, the fertiliser should either all be applied to the seedbed, or split with one third in the seedbed, and the remainder before G.S. 30.

Growth regulators

As barley, especially with relatively high rates of nitrogen application is very susceptible to lodging, growth regulators offer great potential for improvements in yield due to reduced lodging. Results are somewhat conflicting, but Chlormequat (CCC), 2-Chloroethyl phosphonic acid ("Cerone"), or 2-Chloroethyl phosphonic acid and Mepiquat Chloride ("Terpal"), tend to reduce nitrogen percentage when yield is increased (Green *et al*, 1985(a); Garstang, 1987).

In dry years growth regulators could be harmful if the plant is unable to supply assimilate for this increased potential, resulting in shrivelled grain with a high nitrogen content. The low cost of growth regulators however, makes them worth using in many situations. Best results are probably obtained with the use of several together, such as CCC at G.S. 31, followed by Terpal at G.S. 37 (Garstang, 1987).

Pest and disease control

Advancing sowing date increases the potential yield, but all too often this is not realised. The problems of pests and diseases are more serious in a high potential crop, because the yield reductions which they cause become proportionally greater. The most serious constraints will vary, due to climate and past cropping, but may include; snow rot and mould, eyespot, take-all, Fusaria, powdery mildew, net blotch, leaf blotch, B.Y.D.V., cereal flies, and various ripening diseases.

Not all of these problems can be successfully controlled by chemical means, but in many trials, fungicides have produced significant yield increases, and improved grain quality. This is probably because fungal diseases reduce the effective leaf area, and may also interfere with the transport of nitrogen within the plant. It seems likely that late diseases will cause more profound effects on grain yield and quality then those early in the season, as an early disease attack, if checked, will usually be negated by the cereal's capacity for compensatory growth.

We can therefore conclude that since diseases are more damaging on early than late sown crops, an early sown crop with high potential must be accompanied by a systematic managed pest and disease control programme, if this potential is to be realised.

Harvesting

As mentioned earlier, the grain %N may rise, fall, or remain constant as maturation proceeds. This raises the question of the ideal time for harvesting. Traditionally barley tended to be harvested when dead ripe (Bishop, 1970; Briggs, 1978; Sturgess and Knell, 1978), but more recent advice tends towards early harvesting, which will undoubtedly result in a clean sample with even germination, whilst late harvesting will increase the risk of shedding and ear diseases (Bishop, 1970; Sturgess and Knell, 1978; A.D.A.S., 1984).

CONCLUSIONS

As the %N in the grain is the most important quality characteristic and the factor upon which the price paid for a crop is based, it is only by improving our understanding of the factors which affect it that we can improve the consistency of crops attaining the required standard.

Research work at Rothamsted Experimental Station sponsored by the Home-Grown Cereals Authority is curently examining the pattern of nitrogen uptake and translocation within the barley crop, how this can be changed by various husbandry factors, and how these changes can be related to the malting quality of the grain.

Details of this work, and the results obtained so far, can be found in the Annual Interim Reports of the project, entitled "N uptake by barley related to malting quality".

REFERENCES

A.D.A.S. (1984), *Malting Barley.* Booklet 2399. M.A.F.F.; London.

A.D.A.S. (1979), *Nitrogen for winter barley.* S.E. regional technical bulletin R/55/80/15. M.A.F.F.; Reading.

ATANDA, O.A., & MIFLIN, B.J. (1970), Factors affecting the production of alpha amylase in barley grains. *J. Inst. Brew.* 76 51-55.

AUSTIN, B., FORD, M.A., EDRICH, J.A., & BLACKWELL, R.D. (1977), The nitrogen economy of winter wheat. *J. Agric. Sci., Camb.* 88 159-167.

BAILEY, R.J. (1985), Irrigation of winter cereals. In *Gleadthorpe E.H.F. Annual Review, 1985.* pp. 14-22. M.A.F.F., Gleadthorpe.

BIDINGER, F., MUSGRAVE, R.B., & FISCHER, R.A. (1977), Contribution of stored pre anthesis assimilate to grain yield in wheat and barley. *Nature* 270 431-433.

BISCOE, P.V., LITTLETON, E.J. & SCOTT, R.K. (1973), Stomatal control of gas exchange in baley awns. *Ann. Appl. Biol.* 57 355-364.

BISHOP, L.R. (1957), Ultra rapid method for measurement of the germinative capacity of barley grain. *J. Inst. Brew.* 63 516-520.

BISHOP, L.R. (1970), *Growing barley for British beer.* H-G.C.A. Technical note No. 14, London.

BOATWRIGHT, G.O. & HAAS, H.J. (1961), Development and composition of spring wheat as influenced by nitrogen and phosphorus nutrition. *Agron. J.* 53 33-36.

BRENCHLEY, W.E. (1912), The development of the grain of barley. *Ann. Bot.* 26 903-928.

BREWER, D.H. & POEHLMAN, J.M. (1968), Grain yield and kernal quality of winter barley (*H. vulgare* L.) harvested at different moisture levels. *Agronomy J.* 60 472-474.

BRIGGS, D.E. (1978), *Barley.* Chapman & Hall, London.

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

BROCKELHURST, O.A., MOSS, J.P. & WILLIAMS, W. (1978), Effects of irraiance and water supply on grain development in wheat. *Ann. Appl. Biol.* 90 265-276.

C.E.C., COMMISSION FOR THE ECONOMIC COMMUNITY (1989), *Eurostat - Crop production quarterly statistics.* C.E.C., Luxembourg.

ELLEN, J. & SPIERTZ, J.H.J. (1980), Effects of rate and timing of nitrogen dressings on grain yield formation in winter wheat. *Fert. Res.* 1 177-190.

EVANS, S.A. & HOUGH, H. (1984), The effects of several husbandry factors on the growth and yield of winter sown barley at four sites in each of three years. *J. Agric. Sci, Camb.* 103 555-560.

GARSTANG, J. (1987), The effect of plant growth regulators, nitrogen and variety on the production of malting barley in *Aspects of applied biology* 15 *Cereal Quality.*

GALLAGHER, J.N., BISCOE, P.V. & SCOTT, R.K. (1975), Barley and its environment. V. Stability of grain weight. *J. Appl. Ecol.* 12 319-336.

GALLAGHER, J.N., BISCOE, P.V. & SCOTT, R.K. (1976), Barley and its environment. VI. Growth and development in relation to yield. *J. Appl. Ecol.* 13 563-583.

GOTHARD, P.G. (1974), Screening of varieties for alpha amylase content. *J. Inst. Brew.* 80 387-390.

GREEN, C.F., DAWKINS, T.C.K. & HUNTER, B. (1985a), Influence of foliar applied CCC on radiation attenuation by winter barley canopies. *J. Agric. Sci., Camb.* 105 213-216.

GREEN, C.F., FURMSTON, D.T. & IVINS, J.D. (1985b), Time of sowing and the yield of winter barley. *J. Agric. Sci., Camb.* 104 405-411.

GREEN, C.F. & IVINS, J.D. (1985), Time of sowing and the yield of winter wheat. *J. Agric. Sci., Camb.* 104 383-393.

GREEN, C.F., PAULSON, G.A. & IVINS, J.D. (1985c), Time of sowing and the development of winter wheat. *J. Agric. Sci., Camb.* 105 217-221.

GREGORY, P.J., CRAWFORD, D.V., & MCGOWAN, M. (1979), Nutrient relations of winter wheat. I. Accumulation and distribution of Na, K, Ca, Mg, P, S, & N. *J. Agric. Sci., Camb.* 93 485-494.

GREGORY, P.J., MARSHALL, B. & BISCOE, P.V. (1981), Nutrient relations of winter wheat. III. Nitrogen uptake, photosynthesis of flag leaves, and translocation of nitrogen to grain. *J. Agric. Sci., Camb.* 96 539-547.

HARRIS, G. & MACWILLIAM, I.C. (1957), Carbohydrate in malting and brewing. IV. Changes in the carbohydrate composition of barley on ripening, and corresponding variations in nitrogenous constituents. *J. Inst. Brew.* 63 210-220.

HAYTER, A.M. & RIGGS, T.J. (1973), Environmental and varietal differences in diastatic power and four associated characteristics in spring barley. *J. Agric. Sci., Camb.* 80 297-302.

HOME-GROWN CEREALS AUTHORITY (1987), *Cereal statistics.* H-G.C.A., London.

HOME-GROWN CEREALS AUTHORITY (1989), *The quality of wheat and barley from the 1987 harvest.* H-G.C.A., London.

HUFFAKER, R.C. & RAINS, D.W. (1978), Factors influencing nitrate acquisition by plants; assimilation and fate of reduced nitrogen. In *Nitrogen in the environment.* 2 *Soil-plant-nitrogen relationships.* Ed. Nielsen, D.R. & MacDonald, J.G. pp. 1-155. Academic Press; New York.

I.O.B., INSTITUTE OF BREWING (1989), *Malting Barley News* 10 I.O.B.; London.

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., APPLEYARD, M. & FELLOWES, G. (1985), Variations in development of wheat and barley in response to sowing date and variety. *J. Agric. Sci., Camb.* 104 383-396.

KNOWLES, F. & WATKIN, J.E. (1931), The assimilation and translocation of plant nutrients in wheat during growth. *J. Agric. Sci., Camb.* 21 612-637.

LAWLOR, D.W., DAY, W., JOHNSTON, A.E., LEGG, B.J. & PARKINSON, K.J. (1981), Growth of spring barley under drought. Crop development, photosynthesis, dry matter accumulation, and nutrient content. *J. Agric. Sci., Camb.* 96 167-186.

LORD, E.I. & VAUGHAN, J. (1987), Optimising nitrogen applications for the production of malting barley. In *Aspects of Applied Biology* 15 *Cereal Quality.*

LUPTON, F.G.H. (1966), Translocation of photosynthetic asimilates in wheat. *Ann. Appl. Biol.* 57 355-364.

LUPTON, F.G.H. (1969), Estimation of yield in wheat from measurements of photosynthesis and translocation in the field. *Ann. Appl. Biol.* 61 109-119.

MCLEAN, D.M. (1933), The effects of harvesting at different stages of maturity on the yield and chemical composition of barley. *Scientific Agriculture* 13 698-713.

N.I.A.B., National Institute of Agricultural Botany (1989), *Recommended varieties of cereals.* Farmers leaflet No. 8. N.I.A.B.; Cambridge.

NIX, J. (1986), *The farm management pocketbook.* University of London; Wye College.

POMERANZ, Y., STANDRIDGE, N.N. & SHANDS, H.L. (1971), Functional and biochemical changes in malting barley. I. Changes in malting and brewing characteristics. *Crop Sci.* 11 85-88.

PORTER, H.K., PAL, N. & MARTIN, R.V. (1950), Assimilation of carbon by the ear of barley and its relation to the accumulation of dry matter by the grain. *Ann. Bot.* 14 55-68.

SCOTT, R.K. & DENNIS-JONES, R. (1976), The physiological background of barley. *J. Nat. Inst. Agri. Bot.* 14 182-187.

SPRATT, E.D. & GASSER, J.K.R. (1970), Effects of fertiliser nitrogen and water supply on distribution of dry matter and nitrogen between the different parts of wheat. *Can. J. Pl. Sci.* 50 613-625.

STURGESS, L.M. & KNELL, C.J. (1978), *British malting barley - supply and demand.* H-G.C.A.; London.

THORNE, G.N. (1963), Varietal differences in photosynthesis of ears and leaves of barley. *Ann. Bot.* 27 155-174.

THORNE, G.N. (1974), Physiology of grain yield of wheat and barley. *Report of Rothamsted Experimental Station 1973, part 2,* 5-25.

WATSON, D.J., THORNE, G.N. & FRENCH, S.A.W. (1958), Physiological causes of differences in grain yield between varieties of barley. *Ann. Bot.* 22 321-352.

WIDDOWSON, F.V., DARBY, R.J., DEWAR, A.M., JENKYN, J.F., KERRY, B.R., LAWLOR, D.W., PLUMB, R.T., ROSS, G.J.S., SCOTT, G.C., TODD, A.D. & WOOD, D.W. (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 at Rothamsted in 1981 to 1983. *J. Agric. Sci., Camb.* 106 551-574.

ZADOKS, J.C., CHANG, T.T. & KONZAK, C.F. (1974), A decimal code for the growth stages of cereals. *Weed Res.* 14 415-421.