THE UNIVERSITY OF ADELAIDE
FACULTY OF AGRICULTURAL SCIENCE

A STUDY OF GENOTYPIC DIFFERENCES IN THE MALTING QUALITY OF BARLEY

by

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Thesis submitted for the degree of Doctor of Philosophy
in
Plant Breeding

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January, 1972.

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SUMMARY

The investigations reported in this thesis, had as their objective the development of an understanding of genotypic differences in the grain and malt quality of two row barleys, an understanding that was considered essential to the success of a hybridization and selection programme. This work is part of a continuing barley improvement programme serving the cereal belt of South Australia.

The study included a consideration of the genotypic differences in several aspects of malting quality. Since the study differed from previous investigations in being carried out in a winter rainfall, Mediterranean-type climate a consideration of the environmental effects on quality was of particular interest. The interaction of environment and genotype was investigated by conducting experiments over several sites and seasons. An analysis based on Finlay and Wilkinson's (1963) 'adaptation analysis' provided considerable information on genotypic differences in response to environmental change with regard to yield and the quality characters measured. Multivariate analysis was used in an attempt to elucidate the factors influencing grain and malt quality, and to provide a discrimination between genotypes which might provide a guide to parental selection for hybridization. A further aspect of the study was an investigation of the interaction of genotype and the malting additive gibberellic acid (GA_3) in order to determine whether, in the light of the commercial use of this substance, there was environmental and genotypic variation in sensitivity to GA_3 which should be considered in an improvement programme.

The chief environmental influence on yield in the different sites and years was found to be seasonal rainfall, whilst rainfall during three spring months had a considerable effect on grain nitrogen content. Since the latter was all important in determining aspects of malting quality the environment had its main influence on grain quality through grain nitrogen content. Conversely, varietal differences in malting quality were mainly evident as variation in the insoluble carbohydrate content. The property of high extractability appeared to be confined to a small specialised group of varieties. Much of the interaction of environment and genotype was caused by differences in varietal maturity. Thus varietal performance depended on the frequency with which the life cycle could be completed before the onset of the moisture stresses of late spring, which are experienced with differing severity each year. Patterns of interaction between environment and genotype were evident in all quality characters measured including response to GA_3.

As a result of the findings in this study and the conclusions drawn it is suggested that in South Australia a breeding programme for improved malting barleys must utilize varietal material from North Africa, in particular varieties from Egypt. This material is outstanding for its adaptability and performance under a winter rainfall climate although it has the disadvantage of low extractability and enzyme potential. It was evident that the desirable combination of agronomic performance and acceptable quality can only be obtained from complex crosses or selection and recrossing.

STATEMENT OF ORIGINALITY

This thesis contains no material which has been accepted for the award of any degree or diploma in any University. Neither, to the best of my knowledge and belief does this thesis contain any material previously published or written by another person, except when due reference is made in the test.

ACKNOWLEDGMENTS

The investigations reported in this thesis were carried out as part of the continuing programme for barley improvement in South Australia financed by the Barley Improvement Trust Fund.

It is a pleasure to acknowledge the help and guidance of my supervisors; the late Professor L.H. May; Dr. K.W. Finlay now of CIMMYT; Professor L.G. Paleg whose original encouragement lead to the initiation of the project; Dr. R. Knight for advice and criticism, especially during the preparation of the thesis.

I am also appreciative of advice, particularly in the biometrical and computing fields, from Dr. D.A. Ratkowsky, Miss S. Chambers, R. Lamacraft and D. Messent.

My thanks are also due to; M. Howe, J. Chigwidden and J. Lewis for technical assistance in seeding and harvesting; G. Golding and A. Sirmais who prepared the micro-malts and carried out many of the malt analyses; Dr. A. Jennings in whose analytical laboratory the grain and wort nitrogens were determined; Miss A. Trumble who drew the graphs; B. Palk for the photography; Mrs. S. Parker who prepared the typescript.

Finally I am deeply grateful for constant support from my wife, Gwyneth, without whose patience this thesis could never have been written.

INTRODUCTION

The first step in any crop improvement programme is an assessment of the variability available in the total gene pool of the crop. Such a study provides information on the range of variability in particular characters and, if carried further, an understanding of the interrelations of characters and their pattern of inheritance. With this information available, suitable parents can be chosen for hybridization and efficient selection practised among their progeny to isolate genotypes with high expressions of the characters.

It has long been recognized that certain types of barley were more suitable than others for malting and brewing. Barley varieties, acceptable to the commercial processor, were selected on a subjective basis, from natural or segregating populations before a great deal was known about the physiology of malting and hence of the character malting quality. With increasing research into the malting and brewing processes and the adoption of more objective methods by the industries concerned a more closely specified raw material is required, and the task of producing improved varieties becomes more exacting. It is important therefore, to gain a more detailed understanding of genotypic differences in malting quality.

With an established crop the first stages in an improvement programme might involve selection within local land races and hybridization, with subsequent selection, between local types. Within such material the variation in characters, including quality factors, is likely to be narrow and the potential for improvement small. In consequence, selection for quality might be restricted to maintaining

an accepted standard. As the programme advances exotic material will be introduced to improve yield, straw strength, disease resistance, etc. Such introductions may or may not provide improved quality but they will widen the range of types in segregating populations so that a greater emphasis has to be placed on selection to maintain or improve quality.

This sequence of events has been apparent in barley breeding programmes in the United Kingdom and in North Western Europe since about 1900. However, where barley has not long been established as a crop, as in Canada and Australia, the range of locally adapted and accepted material has been confined to chance introductions. In these countries, barley improvement has had to start with programmes of introduction and assessment. These have revealed the range of genotypic differences in the crop as a whole.

In Canada this phase was undertaken during the 1920's and 1930's. The earliest work by the Canada Malting Co. and T.J. Harrison at the Manitoba Agricultural College (the University of Manitoba) in Winnipeg led in 1929 to the adoption of the variety O.A.C. 21 as the standard for malting quality in the Manchurian type of spring six row barleys grown in Canada. O.A.C. 21 was selected from old Mandscheuri barley by C.A. Zavitch at the Ontario Agricultural College and released to farmers in 1910. The European varieties did not grow fast enough to crop well under the short season high latitude conditions of Canada (USA Technical Bulletin No. 1224). Although at this stage important studies were being undertaken on differences in varietal malting quality they were centred in Europe and concerned low protein two row barleys. In Canada the varieties grown and used

commercially were high protein six row types. As a consequence, in 1934, the National Research Council in Canada established a group under J.A. Anderson to carry out further work on variability in malting quality to provide guide lines to plant breeders wishing to improve the Canadian crop. The initial studies included:

(i) an evaluation for quality of a wide range of varieties likely to be used as parents in breeding programmes;

(ii) the calculation of interrelationships between barley and malt properties and, as a result

(iii) the development of prediction tests for malting quality and the application of these to the selection of segregating populations. (Meredith, 1967).

This work led to the publication of a series of 14 papers under the general title of "Varietal differences in Barleys and Malts" which have become a classic in their field.

These investigations have been instrumental in the steady improvement in malting quality of Canadian barley varieties from O.A.C. 21 through Montcalm, Portland and Conquest to the latest releases. All of which are the product of close co-operation between plant breeders and cereal chemists.

In southern Australia the slow growing European varieties perform reasonably well under the winter rainfall-summer drought conditions. However, their late maturity results in poor crops when spring rainfall is sparse. In consequence, before 1900 barley was a chancy crop with unreliable quality. The malting and brewing industries were content to import barley and malt from overseas and they became accustomed

to using European type malts processed from two row barleys.

After the Federation of Australia although tariffs were imposed on the import of barley and malt the local barley crop was not soundly established until the advent of Prior's Chevalier in 1904. This variety, a farmer's selection, is of unknown origin although akin to the European Chevaliers in plant and grain characters. Its success was largely the result of early maturity enabling it to avoid the moisture stresses of late spring. It's consistent production of good quality grain ensured its acceptance by farmers and the malting and brewing industries (Sparrow and Doolette, 1971).

The advent of Prior's Chevalier provided the industries with a local supply of raw material of a type to which they were accustomed. There was no need for a change from tradition as had been necessary in Canada. In consequence, Prior has persisted in Australian agriculture until the present day. As a result barley improvement programmes have been slow to develop and no major programmes were initiated until 1956. Some barley breeding was carried out from the 1930's but this was generally a sideline to wheat breeding and was not pursued with any great vigour. A few varieties were produced but only one of importance survives, Research, which is largely confined to southern Victoria.

From about 1940 the spread of pasture legumes in the cereal growing areas of southern Australia brought about a steady increase in soil fertility and increased grain yields. But in barley this also led to an increased nitrogen content in the grain and a reduction in grain quality. A post-war expansion of barley growing meant that

crops were grown in areas of lower rainfall which rarely produced samples of malting quality, further accentuating the decline in quality of the crop.

This factor was a major stimulus to the inauguration of the Barley Improvement Scheme in 1956. This scheme, which sponsors research in South Australia and Victoria, is financed by all sections of the industry and the Commonwealth Government. One outcome was the establishment, at the Waite Agricultural Research Institute in Adelaide, of a fundamental programme of barley improvement.

This programme began with the collection of a diverse range of varieties and their field testing in the South Australian cereal areas. One outcome of the investigation was the development of a procedure to analyse genotypic differences in yield and their interaction with variations in environment. Seasonal and site variability is a major factor in crop performance in southern Australia so that an assessment of genotype-environment interaction was found to be essential. The analysis makes use of the mean yield of a set of varieties at any one site to provide a measure of that particular environment. Whilst variety-environment regressions describe each individual's performance (Finlay and Wilkinson, 1963).

This initial work was confined largely to yield, but it soon became apparent that an understanding of genotypic differences in grain and malt quality would be essential to the development of a successful hybridization and selection programme. The present study covers this phase of work and includes a consideration of genotypic differences in several aspects of malting quality, genotype-environment

interaction in these quality factors, and an investigation of the interaction of genotype and the malting additive gibberellic acid.

There is no satisfactory, all inclusive definition of malting quality. Different attributes of quality are considered by the different sectors of industry concerned. Malting quality is a highly complex character and one which is dependent upon the end product of the action and interaction of a hormone - enzyme - substrate complex. The process normally involves germination but is modified by the maltster to provide a supply of fermentable sugars and yeast metabolites for the brewer. The whole process is also dependent upon a time-temperature relationship which alters the amount and composition of the end product.

In the past the industries have developed certain empirical measures of malt quality. These measurements deal with some aspects of the end products of the commercial processes. The same measurements can be made on micro-malts; the measures of quality used in the present study have been those accepted as standard by the malting and brewing industries. Although empirical, these measurements have been of value in the appraisal of quality in the commercial product and in the breeders' selections. The use of more detailed measurement of the type and amount of carbohydrates and amino-acids involved has still to be developed.

Genotype-environment interaction is an important consideration in plant improvement, particularly so under the highly variable seasonal rainfall in southern Australia. A new crop variety has to provide good consistency of performance with regard to both yield and quality.

Varieties that give highly variable results in both characters are undesirable because of their unreliability. Genotypic differences in adaptability to differences in seasonal rainfall patterns have been demonstrated for grain yield but it was considered important to determine whether grain quality was affected in the same manner.

During the past decade the malting industry in Australia has made considerable use of the malting additive gibberellic acid. This chemical, which is similar in structure and action to the naturally occuring gibberellins, stimulates the malting process so that the modification of the endosperm occurs more rapidly. It results in a saving in production time and/or an increase in extractable material in the malt. Only small amounts of the chemical are required (e.g. 0.25 ppm of the original weight of the barley) and it is simple to treat barley for malting on a commercial scale. The treatment has proved particularly attractive to the Australian industry for two reasons. In the first place, an increased extraction has been a counter-balance to the declining quality of Australian barley already mentioned. And secondly, the continuing dependence on Prior has been offset by the potential for increased extract. Both factors are likely to be superseded by the advent of new varieties. But, in the process of producing these varieties it was important to know whether there was a genotypic variation in sensitivity to gibberellic acid which should be considered in the improvement programme.

Malting quality is a complex character and there are no criteria universally accepted as measures of quality. The same is true of quality in wheat: 'the concept of quality is as broad as the multitude of potential users for the wheat and as wide as the vast array of

testing procedures bequeathed to us by two generations of cereal chemists'. (Wrigley and Moss, 1969). The authors add that 'any property of wheat grain capable of being measured and ranked can be regarded as an aspect of its quality. These properties of the grain have significance as they relate to the suitability of the grain for its ultimate use'. A similar situation holds for barley and malt quality. This situation is further confused by the nature of the testing procedures which although standardised and designed to aid process control are generally only broad measurements of the chemical and enzymatic constituents of barley and malt. In addition three different systems of standardisation are used; a uniform and internationally recognised system has yet to be agreed upon whilst standard methods of determining specific chemical constituents and discrete enzyme activities in barley, malt and wort still await development.

Genotypic differences in malting quality have to be considered against this background. It is also apparent that there are two main approaches to malting quality, one of the commercial processor, the other of the scientist.

Maltsters and brewers are concerned with the economics of their processes and require the best material of the best variety available. Of over riding importance in their consideration is a barley and a malt that will provide fermentable sugars as cheaply as possible. Thus to the processor good quality tends to mean a high yield (or extract) of these materials in the mash tun. Other factors are taken into consideration. These include a balanced content of soluble

nitrogen compounds to provide sufficient yeast metabolites without adversely affecting the stability of the beer, whilst the use of cheaper starchy adjuncts in the mash has necessitated an interest in amylase enzymes in the malt. The maltster is therefore interested in material which will provide high yields of extract and which will modify rapidly during malting thus reducing costs. Such material is obtainable only from a small number of varieties. Hence the maltster is primarily interested in the influence of the environment on a few varieties and the quality of those varieties and the malting methods which will most efficiently produce malt of high extractability from the same material.

The plant breeder trying to improve agronomic characters and grain yield as well as the quality characters of the crop must concern himself with the full range of germ plasm. He is interested in understanding and defining the complex character malting quality, and in the processes involved in turing barley into malt. He has to consider the whole spectrum of variation in the species, to provide a basic understanding of the genotypic differences and genetic control of the various aspects of quality, as a starting point for an improvement programme. He will also be interested in the effect of environment on quality and the interaction of genotype and environment.

LITERATURE REVIEW

1. Historical

It has long been appreciated that the nitrogenous constituents of barley grain influence the yield of extract and the properties of malt, wort, and beer. It was accepted, although not proven, that malt quality measured as extract was negatively associated with the nitrogen content of the grain. It was noted that barleys with high nitrogen content were difficult to grow on the malting floor, giving vigorous germination without corresponding modification (Hopkins and Krause, 1937). Also it was realized that the nitrogenous compounds in wort and beer were derived from those in barley, that these compounds were essential for yeast metabolism and that there was a positive association between barley nitrogen, wort nitrogen and diastatic activity of the malt. Hulton (1922) in a review of literature listed the factors believed to cause high grain nitrogen and the effects of this on barley quality, but points out that 'entire unanimity of opinion can hardly be claimed for any one of them'.

From about 1900 the barley breeders in Europe and North America, although chiefly concerned with improving the agronomic characters of the crop, were also interested in the occurrence of varietal differences in malting quality. For example, Beaven, who was also a maltster, reported (1902) on the investigation of quality in English, European and other imported barleys, both two and six row. He also investigated the effects on quality of seed rate and fertilizer application. The early breeders were limited in the improvement they could achieve in malting quality because of their lack of

understanding of factors underlying varietal differences in malting quality and the inadequate criteria they used, often only a subjective visual assessment. Because of its objectivity and applicability to numerous small samples the measurement of grain nitrogen content was widely adopted by plant breeders as a measure of potential malting quality (Hunter, 1926). Biffen (1906) was able to suggest that 'results obtained so far justify the belief that if high and low nitrogen may be taken as tests for barley quality then good and bad segregate from one another as sharply as could be wished'.

Unfortunately at that time the differential effects of environment and variety on grain quality were not appreciated. Commercial criteria used to assess the relative merits of one or two varieties were of limited value when differentiating between many varieties. It has been shown many times since that grain nitrogen is strongly influenced by the environment, it has a low heritability, and although it is indicative of quality potential within a variety it is far less reliable as a measure of differences between varieties.

2. Experiments under the Institute of Brewing Research Scheme, 1922-31.

A comprehensive study of barley quality carried out in Britain over the period 1922-31 was reviewed by Russell and Bishop (1933). The investigations included (1) the influence of soil, season, manuring and variety on the quality of barley grain, (2) the relation between the chemical composition of the barley, the extract yield of the malt and the composition of the resultant wort, (3) the relation between the composition of the extract from the malt and the properties of the beer produced from it.

Many trials were grown in the different barley areas of Britain and hundreds of samples malted and analysed. The range in soils and manurial treatments was kept wide so that the grain samples covered the range from unsuitable to suitable for malting. The authors point out that none of the effects and relations demonstrated could have been deduced without extreme non-malting samples and they realised that samples, suitable for malting, occupy only a small part of the spectrum of barley quality. Much of the work was conducted with the then current varieties Plumage-Archer and Spratt-Archer, but the qualities of other varieties at the National Institute of Agricultural Botany were also investigated. These varieties were 15-20 two row types, mostly derived from hybridization among British varieties and included little germ plasm from Europe. Thus the Binder x Gull material from Scandinavia, which has since been used in barley breeding throughout the world, and two row varieties from other areas were not investigated. Some diverse six row varieties were analysed, including samples from California, Canada and India, at that time imported for use in British brewing. There were, however, obvious limitations to the range of the material investigated. Notwithstanding, subsequent work has confirmed the major findings, as follows:

1. There is a close inverse relation between grain nitrogen content and malt extract, and an increase in nitrogen is associated with a decrease in extract (Bishop, 1930b, 1930c). For six varieties studied the effect of nitrogen content on extract was substantially the same although the level of extract and hence the value of the regression constant 'a' was different for each variety (Bishop and Day, 1933).

2. The chief factors influencing the nitrogen content of barley grain are soil and season acting through the amount and timing of nitrate uptake and the amount of carbohydrate synthesized and translocated to the developing grain. Up to a certain level, soil nitrate supply promotes crop growth and yield without increasing grain nitrogen content. Larger amounts of soil nitrate or late applications increase the nitrogen content of the crop, both plants and grain (Russell and Bishop, 1933).

3. The varieties tested appeared to absorb similar amounts of nitrate but differed in their capacity to synthesize and translocate carbohydrate. Thus the higher yielding varieties produced grain of lower nitrogen content than lower yielding varieties grown under similar conditions. The actual levels of yield and grain nitrogen content depended on the conditions of growth (Bishop, 1930a; Russell and Bishop, 1933).

4. The amounts of the individual protein fractions (Osborne's classification, 1895) in the grain are dependent on the total nitrogen content. With increasing grain nitrogen the proportion of hordein increases, the proportion of salt soluble nitrogen decreases and that of glutelin remains constant. Bishop (1928) termed this phenomenon 'protein regularity' and was also able to show (Bishop, 1930a) that different varieties had similar regularities but at the same grain nitrogen content the level of each protein fraction was

characteristic of a particular variety. These differences were more marked among the six row (more diverse) than the two row varieties.

5. The nitrogen compounds of worts are closely related to those of the original barley although the actual percentage of wort nitrogen depends on the extent of modification of the malt. Grain with high levels of nitrogen contained more insoluble carbohydrates and had increased respiration and rootlet growth during malting and increased malt and wort nitrogen compounds (Bishop, 1929b, 1930b). High nitrogen barleys are more difficult to modify, both chemically and physically, because it was presumed increased protein not only replaced carbohydrate but also made that remaining less accessible to enzyme degradation. But, diastatic power increases with grain nitrogen level (Bishop, 1931); hence it follows that extract and diastatic power would be inversely related although this was not stated in these papers.

6. Grain size as measured by thousand grain weight shows characteristic varietal differences but is influenced by environmental factors. An increase in grain size is associated with an increase in extract, but there was no correlation between grain size and nitrogen content. By means of a multiple regression it was found possible to predict the extract of any sample of a known variety from its nitrogen and grain size (Bishop, 1930c; Bishop and

Day, 1933).

7. A regularity principle was found to apply to carbohydrate fractions of the grain. Each variety had a definite carbohydrate pattern, which was dependent upon total carbohydrate level. As pentosan and insoluble carbohydrate contents rose, so starch and extract decreased correspondingly (Bishop and Marx, 1934). A further prediction formula, termed 'restrictal general equation', involving insoluble carbohydrate and grain nitrogen was developed which was more accurate and had wider application than the other (Bishop, 1934).

Thus the scope of these investigations was considerable and they have become the foundation of all subsequent work on barley and malting quality. If they had limitations it was in distinguishing sufficiently between effects due to environment and to genotype. But in view of the small range of material used, and the small geographical area involved, this is not surprising.

3. Canadian investigations

The second major contribution to the understanding of malting quality was the Canadian investigations mentioned in the introduction (Anderson et al., 1941, and preceeding papers). The philosophy behind this work together with its basic findings have been summarized recently (Meredith et al., 1962). The Canadian work, which started in the late 1930's, was an extension of the British work, but dealt with a wider range of both varieties and environments. The objective of the work was to increase the likelihood of finding varietal differences

in malting quality characters by including varieties unacceptable for commercial malting but of potential use in breeding programmes. The wide range of environments and varieties were used to distinguish between the effects on quality of these two influences. Further, a study of the interrelations of barley and malt characters lead to the development of methods of predicting malt quality from barley analyses that could be utilised in selection programmes on hybrid material.

The investigations which were reported in a series of 14 papers under the general title 'Varietal differences in barleys and malts', were involved with 12 varieties grown at 12 stations in 1937. The 12 varieties consisted of; five six row rough awned types, including the standard commercial variety O.A.C. 21; five six row smooth awned types with the smooth awned variety Lion as a common parent; three two row varieties. Of the nine six row varieties all but two, Olli (Finland) and Peatland (Switzerland) were of the Manchurian type or with at least one parent of that type. Whilst the two row varieties all originated in N.W. Europe. Although the varietal material was more diverse than that studied in Britain it still represented only a limited sample of the world diversity of cultivated barleys. The 12 stations spanned Canada, from the Maritime Provinces to the Rocky Mountains, although there were none in Saskatchewan because of drought in that Province in 1937 (Anderson and Ayre, 1938). These stations covered an extremely broad range of soil types and climates and as a result the station mean grain nitrogens varied from 1.54% to 2.69% and other barley and malt quality characters varied accordingly. For each of the 144 samples 11 barley and seven malt properties were

analysed and the data used to study the relations among these properties at both the varietal and environmental level. A clear distinction was drawn between these two effects (inter- and intra-varietal), whilst the interaction of variety and environment was recognized. It is interesting, though, that in the analyses of variance of variety and station effects no interaction terms were included.

These Canadian studies confirmed the importance of grain nitrogen in influencing many aspects of grain and malt quality, (Table 1). They showed this was chiefly an environmental effect there being high within variety correlations between barley total nitrogen and most other characters whilst the only significant between variety correlation was with barley hordein nitrogen (Anderson, et al., 1941). They also confirmed Bishop's "protein regularity principle". It was evident that the environmental factors which govern total nitrogen also control the amounts of hordein and glutelin laid down whilst salt-soluble nitrogen although related to total nitrogen is particularly influenced by the metabolic processes in the grain during the final stages of ripening. Varietal differences were found for total nitrogen and each of the fractions, whilst the proportion of each fraction, at equal total nitrogen contents, was a varietal characteristic (Anderson and Ayre, 1938).

Within varieties barley total nitrogen showed high inverse correlations with barley starch, barley extract (Ayre et al., 1940) and malt extract (Meredith and Anderson, 1938). It also showed high positive correlations with barley and malt diastatic activity

TABLE 1

Associations with grain nitrogen (Anderson et al., 1941)

Relation between	Intra-varietal	Inter-varietal
Grain nitrogen and,		
barley salt-soluble nitrogen	.851**	.238
barley hordein	.985**	.811**
barley glutelin	.926**	.369
barley starch	-.953**	-.399
barley extract	-.908**	-.401
barley diastatic activity	.976**	.199
malt extract	-.957**	-.381
malt diastatic activity	.962**	-.039
malt proteolytic activity	.854**	.070
wort nitrogen	.764**	.166

TABLE 2

Associations with barley salt-soluble nitrogen (Anderson et al., 1941)

Relation between	Intra-varietal	Inter-varietal
Barley salt-soluble nitrogen and,		
barley starch	-.801**	.018
barley extract	-.740**	.109
barley diastatic activity	.818**	.739**
steeping time	-.549	-.740**
malting loss	.427	.840**
malt extract	-.767**	.452
malt diastatic activity	.757**	.727**
malt alpha-amylase activity	.469	.727**
malt proteolytic activity	.578*	.874**
wort nitrogen	.610*	.887**

(Anderson et al., 1938) malt proteolytic activity (Ayre and Anderson, 1939) and wort nitrogen (Meredith and Anderson 1938; Anderson et al., 1939). Whilst less significant positive correlations were apparent with malting loss (Meredith and Anderson, 1938) and malt alpha-amylase activity (Sallans and Anderson, 1939).

Barley salt-soluble nitrogen showed both intra and inter-varietal associations with several characters (Table 2). Within varieties it was negatively correlated with those characters related to extractable material i.e. barley starch, barley extract and malt extract (Sallans and Anderson, 1940; Anderson et al., 1939). It was also positively associated, with enzymatic activities including barley diastase and malt diastase (Anderson et al., 1938) and at a lower level with malt proteolytic activity and wort nitrogen (Ayre and Anderson, 1939; Anderson et al., 1939). However, the within variety partial correlation coefficients independent of total nitrogen were not significant. In other words, the properties mentioned above are affected, to a greater or lesser extent, by the same environmental factors that influence total nitrogen content, which further highlights the importance of total nitrogen in malting quality (Anderson et al., 1941).

From the inter-varietal associations with salt-soluble nitrogen it was concluded that 'barley varieties high in salt-soluble nitrogen tend to be high in enzymatic activity, in wort nitrogen and malting loss and also tend to absorb water more rapidly in the steep'. Further partial correlations, independent of salt-soluble nitrogen, showed that fundamental relations existed between barley and malt diastatic activities, malting loss and proteolytic activity, malt alpha-amylase

activity and diastatic activity which were not entirely dependent on the genetic factors controlling salt-soluble nitrogen (Anderson et al., 1941).

The above differences between the inter and intra-varietal relations were concluded to 'result from the fact that whereas within varieties salt-soluble nitrogen is closely related to total nitrogen content, between varieties salt-soluble nitrogen is independent of total nitrogen content' (Anderson et al., 1939).

To provide methods of predicting malt performance from analysis of the original barley the Canadian workers investigated the relationships of several barley constituents to malt extract and other malt characters. Studies were made of barley starch, an enzymatic extract of barley and an insoluble residue left after chemical digestion, akin to the insoluble carbohydrate fraction (Bishop and Marx, 1934). It was found that very close intra and inter-varietal associations existed between starch content and barley extract (.96**; .98**) which were independent of total nitrogen content (Ayre et al., 1940). Since barley extract was more closely correlated, in both respects, to malt extract than was barley starch, it was suggested that the former could be adopted as a method of assessing the malting potential of hybrid lines (Sallans and Anderson, 1940). For the same reason barley starch is not discussed further in this review.

The important relations established for barley extract and barley insoluble residue are given in Table 3. Within varieties barley extract was highly correlated with several characters; positively with malt extract and steeping time, negatively with enzymatic

TABLE 3

Associations with barley extract and insoluble residue (Anderson et al., 1941)

Relation between	Intra-varietal	Inter-varietal
Barley extract and,		
barley starch	.961**	.983**
barley insoluble residue	-.420	-.969**
barley diastatic activity	-.861**	-.001
steeping time	.814**	-.313
malt extract	.973**	.914**
malt diastatic activity	-.871**	-.024
malt alpha-amylase activity	-.792**	.333
malt proteolytic activity	-.915**	.340
wort nitrogen	-.749**	.074
Barley insoluble residue and,		
barley starch	-.386	-.950**
steeping time	-.670*	.298
malt extract	-.329	-.913**

TABLE 4

Associations with barley diastatic activity (Anderson et al., 1941)

Relation between	Intra-varietal	Inter-varietal
Barley diastatic activity and,		
malt extract	-.918**	.288
malt diastatic activity	.978**	.904**
malt alpha-amylase activity	.589*	.750**
malt proteolytic activity	.841**	.634*
wort nitrogen	.771**	.735**

activities and wort nitrogen. Between varieties it was only highly correlated with insoluble residue and malt extract. This was the insoluble residue's only significant inter-varietal association whilst within varieties it showed a high negative correlation, independent of total nitrogen, with steeping time. In other words an increase in structural material, within any one variety, is accompanied by a more rapid absorption of water in the steep and conversely an increase in potentially extractable material results in a slower absorption (Sallans and Anderson, 1940).

Within varieties total nitrogen besides being associated with the nitrogen fractions was associated with the extractable carbohydrates but not with the insoluble residue, an exception to the regularity principle also reported by Bishop (1934). Although the regularity of the nitrogen fractions to total nitrogen only holds within varieties (Anderson and Ayre, 1938) the regularity of carbohydrate fractions holds both within and between varieties (Ayre et al., 1940) and is also related to the yield of malt extract, again with the exception of insoluble residue within varieties (Sallans and Anderson, 1940). This was an additional reason for preferring barley extract in prediction rather than Bishop's 'restricted general equation' which incorporates total nitrogen and insoluble carbohydrate.

A further aspect of barley analysis studied was beta-amylase both that soluble in water (free) and after activation by papain (total). Total barley beta-amylase showed high associations, both within and between varieties (Table 4) with malt diastatic activity (Sallans and Anderson, 1938), malt alpha-amylase activity, malt proteolytic

activity (Sallans and Anderson, 1939) and wort nitrogen (Anderson et al., 1941). It also showed a negative intra-varietal correlation with malt extract (Sallans and Anderson, 1940). It's correlations with malt diastatic activity were discussed at some length by Sallans and Anderson (1938), who deduced that because of the high values obtained total barley beta-amylase is the most important single factor controlling the development of malt diastatic activity and that the contribution of alpha-amylase to the latter was probably small. These findings were in agreement with the hypothesis, first advanced by Hills and Bailey (1938) that the beta-amylase activity of malt can be predicted from a papain digest of the original barley. Between varieties the lack of complete correspondence between the two activities was suggested as due to varietal differences either in production of alpha-amylase or in response to the malting method used, which may have been unfavourable to the development of full enzyme potential in some varieties. Sallans and Anderson (1938) further suggested that the measurement of barley total beta-amylase would be a useful tool, not involving micro-malting, in the selection of hybrid lines with a potential for high malt diastatic activity. They also point out that according to Hopkins and Krause (1937) a high level of activity for one hydrolytic enzyme implies a high level in others, thus selection for one would be selection for all. This idea is supported in later papers of the Canadian series by the demonstration of strong correlations between barley beta-amylase and malt enzymatic activities, their close association with barley salt-soluble nitrogen, and positive correlations between the malt enzymes at both the environmental and genotypic level.

Another barley property, the number of hours required to steep grain to a moisture content of 44% showed some interesting associations with other properties (Table 5). Within varieties it was highly correlated with thousand grain weight, in other words, the environmental factors that increase grain size also result in a slower water uptake. Since steep time was also positively associated with barley and malt extract it seems likely that grain size, extractable material and water uptake rate are linked through a common association with the chemical structure of the endosperm (Anderson et al., 1941). In support of this, note the good correlation with barley starch ($r = .79^{**}$). Steep time was negatively associated with malt diastatic activity, malt alpha-amylase activity, malt proteolytic activity and wort nitrogen (Sallans and Anderson, 1940).

Between varieties all significant correlations with steep time were negative; these involved salt-soluble nitrogen, the enzymatic activities, malt extract and wort nitrogen (Sallans and Anderson 1940; Anderson et al., 1941). In other words rapid water uptake indicated a variety's potential for high values of all the important malting quality characters, with, in view of the size of the coefficients, particular reference to the enzymatic activities. It was for this reason that steep time was found to be of use in a multiple regression equation for the prediction of malt extract. In the equation barley extract was used to provide a measure of the potentially extractable material whilst barley salt soluble nitrogen and steep time measured the enzymatic potential (Sallans et al., 1941). It is also of interest that more recently Hartong and Kretschmer (1958, 1961) found

TABLE 5

Associations with steeping time (Anderson et al., 1941)

Relation between	Intra-varietal	Inter-varietal
Steeping time and,		
grain size	.756**	.289
barley starch	.793**	-.174
malt extract	.722**	-.589*
malt diastatic activity	-.661*	-.814**
malt alpha-amylase activity	-.881**	-.954**
malt proteolytic activity	-.704*	-.823**
wort nitrogen	-.783**	-.806**

TABLE 6

Associations with malting loss and malt extract (Anderson et al., 1941)

Relation between	Intra-varietal	Inter-varietal
Malting loss and,		
malt extract	-.704*	.688*
malt diastatic activity	.702*	.465
malt proteolytic activity	.701*	.915**
wort nitrogen	.343	.748**
Malt extract and,		
malt diastatic activity	-.931**	.325
malt alpha-amylase activity	-.728**	.592*
malt proteolytic activity	-.949**	.644*
wort nitrogen	-.716**	.431

that the 'water absorbing power' of a barley was positively correlated ($r = .80$) with evaluation of a malt based on the Hartong Index.

Malting loss (Table 6) was, within varieties, correlated negatively with malt extract and positively with malt diastatic activity and malt proteolytic activity. Between varieties the correlations with malt extract, enzymatic activities and wort nitrogen were all positive but at varying degrees of significance (Anderson et al., 1941). It is apparent that, as might be expected, the development of the various malt properties is dependent on the growth of the embryo and the consequent loss of dry matter by respiration and rootlet growth.

Malt extract (Table 6) showed strong negative intra-varietal associations with the enzymatic activities (Sallans and Anderson, 1940) and wort nitrogen again demonstrating the inverse relation between extractable carbohydrates and the nitrogen compounds. Between varieties extract was positively correlated with the same malt characters but only the associations with proteolytic activity and alpha-amylase activity were significant. There was thus no evidence for inter-varietal regularities in composition between nitrogen compounds and extractable carbohydrates (Anderson et al., 1941).

The differentiation between the effects of the environment and the effects of different varieties on barley and malt properties was, as mentioned earlier, an important part of the Canadian study. This differentiation emphasised the contrast in approach to maling quality required by maltster and plant breeder respectively. As pointed out by Meredith et al., (1962) the maltster interested in selecting the

best samples of one variety grown over a range of environments needs to use 'a barley property that shows a close environmental relation with an important malt property, e.g. barley nitrogen and malt extract. On the other hand, the plant breeder who wishes to select the best lines from the progeny of one cross grown at the same station, must use paired properties that show a high genetic correlation, e.g. barley extract and malt extract'.

It was realised that the 12 varieties originally investigated, although diverse in type, still represented a limited sample of genotypes, and subsequent studies were extended to include 24 varieties at six stations. The subsequent work also involved several wort properties, including fermentability, viscosity and turbidity, to determine whether wort quality could be related to any malt properties (Meredith and Sallans, 1943; 1945). It was found that wort quality was dependent on the degree of modification of the malt, that is, the enzymatic degradation of the endosperm. Wort viscosity showed the highest associations with malt properties; salt-soluble nitrogen ($r = -.67^{**}$), malting loss ($r = -.81^{**}$), malt extract ($r = -.56^{**}$), diastatic activity ($r = -.52^{**}$) and wort nitrogen ($r = -.84^{**}$). It, therefore, assessed the changes that take place during malting better than any other measurement (Meredith and Sallans, 1945; Meredith et al., 1962).

In a further study (Meredith, 1949) wort viscosity was found to be even more closely related to the difference between barley extract and malt extract ($r = .90^{**}$). In other words 'wort viscosity reflected intractability of some material in the barley to enzymatic degradation during malting' (Meredith, 1958), a further aspect of modification.

Following this wort viscosity of green malts mashed at 70°C, which showed a wider varietal range than kilned malts mashed by the Congress procedure, was used by Bendelow (1959) to measure malt modification and 'maltability' in the selection of good quality lines from segregating populations.

The viscous principle of wort was isolated and found to be a non-starchy polysaccharide (Meredith, 1949). This lead the Canadian group to studies of barley and malt gums and cytolytic enzymes. Thus Bass and Meredith (1956) were able to demonstrate varietal differences in cytolytic activity, whilst Bass et al. (1957) investigated the relationship of this activity to other barley and malt properties. Between varieties, in a set of 15 six row barleys drawn from a fairly restricted population of Manchurian and Finnish types, cytolytic activity was correlated with malt extract ($r = .71^{**}$), index of protein modification ($r = .79^{**}$), cold water extract ($r = .88^{**}$), diastatic activity ($r = .87^{**}$) and alpha-amylase activity ($r = .85^{**}$). Whilst two gum fractions were correlated with neither cytolytic activity nor cold water extract (Bass and Meredith, 1959). In a more recent study of 12 two row varieties, from Australia, North-West Europe and the Mediterranean basin, Sparrow and Meredith (1969) also found a good correlation ($r = .77^{**}$) between cytolytic activity and malt extract when one anomalous variety was omitted from the calculation. They were also able to demonstrate varietal differences in gum content but concluded that 'cytolytic activity is almost certainly a more significant factor than gum content in determining malt extract'.

These studies have provided guides to selection procedures. The information on inter-varietal relations between barley and malt properties was used to develop a system of simple barley analyses applicable to the preliminary selection of hybrid lines for quality. Two barley properties received particular attention, papain activated barley diastatic activity and barley extract, which had shown highly significant inter-varietal relations with malt diastatic activity ($r = .90^{**}$) and malt extract ($r = .91^{**}$) respectively (Sallans and Anderson; 1938, 1940).

The Canadian workers have developed pilot malting equipment and have studied the interaction of variety with malting method. It was concluded that the differential effect of malting method on varieties is not as large as the differential effect of environment (Anderson and Meredith, 1938).

More recently studies have been carried out on chill haze and on the amylase and proteolytic enzyme systems of barley and malt (Meredith, 1967). But as pointed out by Anderson (1961) 'the principal interest in Canada has always been in finding out why some varieties are satisfactory for malting and others are not'. Consequently systematic surveys were also made of the barley and malt properties of all varieties grown in the country or in use in various local breeding programmes. The information was made available in various reports and papers culminating in a summary of the important quality properties and varietal characteristics specifically to aid plant breeders in their search for improved varieties (Anderson et al., 1943).

Over 35 years the Canadian work on malting quality has evolved a comprehensive system of variety evaluation from early generations through to pilot scale malting and brewing (see review, Bendelow et al., 1969). These investigations because of their longevity and wide ranging scope from basic to applied research are unparalleled in any other country. Many of the findings and methods are widely applicable and have influenced barley quality research everywhere.

4. Other investigations

Subsequent work on malting quality has in general confirmed and amplified the findings reviewed above. The degree of association between characters depends obviously upon the material studied. The effect of environment and variety as well as the interaction between them will influence the magnitude of the correlations. Hence, there is unlikely to be an exact agreement, of values obtained in different studies, for particular associations between agronomic and grain quality characters. But it should be possible to establish general trends to show whether, in the species as a whole, an association is large or small, positive or negative.

(a) The association of grain yield and grain protein (nitrogen) content

The negative association between grain yield and grain protein percentage referred to on page 13 has been confirmed in many other studies. Whilst, many barley breeders have, as a result of experience, tended to support the view that a negative correlation exists (Beaven, 1947; Hunter, 1952; Bell, 1957; Bell and Lupton, 1962; Raw, 1963).

Neatby and McCalla (1938) obtained a mean correlation of

r = - .72, whilst individual locations (seven in each of four years) ranged from r = - .21 to - .88. Although this indicated the differential effect of environment the authors suggest that the association was also under genetic control and would probably vary from one cross to another. Since high yield was associated with low protein it should be simple to select for improved malting barleys.

When Grant and McCalla (1949) investigated the progeny of the cross Trebi (high yield, low protein) by Peatland (low yield, high protein), they obtained a mean correlation coefficient of r = - .79** between grain yield and protein content. The authors suggest that this coefficient is higher than those usually reported because it was based on a random selection of lines rather than selected varieties. However it could also have been high because of the diversity of the parents and a range of varieties may be more representative of the variation in the crop as a whole. Grant and McCalla also suggest that, rather than specific genes for high and low protein, "physiological factors that determine yield and protein content are genetically controlled."

Barbacki (1947) also found that high protein was associated with low yield but that two row segregates tended to be higher in protein than six row segregates. This was supported by Day and Dickson (1957) who claimed that grain protein level was associated with the two row vs. six row locus, and two row segregates were on average higher in grain nitrogen. These two references are in contrast to the generally accepted view, first evidenced by LeClerc and Wahl (1909) and later supported by others, that two row barleys contain less grain nitrogen than six row.

Fischbeck (1964) found that, in a collection of varieties, low protein content of grain was associated with high grain yield, high tillering capacity and short straw. Whilst in Barbacki's material low grain protein was similarly combined with a high grain to straw ratio.

Although the evidence for a negative association between grain yield and grain protein content is strong, some authors have been unable to demonstrate any correlation. One example is Middleton et al. (1961) who surveyed the protein content of 18 six row winter barleys grown at 13 locations in North Carolina, Schmidt (1958), studying 24 varieties at several localities in Germany, found no correlation between protein content and either grain yield or thousand corn weight. He concluded that it would be feasible to breed high yielding barleys with high levels of grain protein suitable for animal feed. Whilst, Scheibe et al. (1969) reported a positive correlation between yield and grain protein in the progeny of crosses involving German winter varieties and low yielding protein rich spring barleys from the Hindu-Kush.

(b) Major studies on quality character associations

Several studies of malting quality characters have been carried out in North America in the past two decades. These have been virtually confined to six row barleys.

Den Hartog and Lambert (1953) studied the association between certain agronomic and malting quality characters in F_3 plant progenies from ten crosses involving Mars as a common parent. The characters included grain size, yield, bushel weight, grain protein content, barley extract and diastatic power. The three malting characters

were rather closely inter-related [protein content: diastatic power ($r = .64^{**}$), protein: barley extract ($r = -.52^{**}$), diastatic power: extract ($r = -.40^{**}$)]. These correlations involving diastatic power contrast with the results of the Canadian group who only found significant intra-varietal associations. Results from segregating progenies at a single site probably confound varietal and environmental effects which would explain this anomally. The authors say that "partial correlations support the belief that the correlation between diastatic power and extract is due to the association of each with protein. It thus appears that protein is an important criterion of malting quality not only because of its own particular effects but also because of its association with two other criteria of malting quality." They also found grain size and bushel weight to be associated with extract ($r = .54^{**}$ and $.47^{**}$, respectively), whilst yield was associated with all three malting characters [yield: protein ($r = -.34^{**}$), yield: diastatic power ($r = -.28^{**}$), yield: extract ($r = .54^{**}$)]. Although there was a tendency for high protein and diastatic power to be associated with low extract and yield, and vice versa, they suggested that since the relation between yield and diastatic power was not large it should be possible to obtain segregants with a high expression of both characters.

Lau (1960) who studied grain characters in a range of European malting barleys concluded that: (1) grain size was related only to percentage of plump grains, (2) short plump grains gave a higher extract than the long thin ones, (3) husk content was negatively correlated with protein content and extract, (4) protein content showed no significant relationship with extract nor any marked influence on

enzyme activities. Whilst a multiple regression of grain shape, husk content and water absorption was found to give a good prediction of malt extract.

Rutger et al. (1966) in a study of progenies from a cross between Atlas and Kindred considered the interrelationships between eight agronomic and nine malting quality characters. Although yield showed several significant correlations none were large. The largest, with extract ($r = -.35^{**}$), is in contrast to the positive association found by Den Hartog and Lambert (1953). The authors suggest that the low level of correlations with yield indicates that, provided the populations were large, "it should be possible to select for most quality traits without seriously reducing yield." In general agreement with previous studies they also found that malt extract was positively correlated with wort nitrogen to malt nitrogen ratio ($r = .57^{**}$), with percentage of plump kernels ($r = .54^{**}$), and negatively with malt nitrogen ($r = -.30^{**}$). Diastatic activity was positively correlated with malt nitrogen ($r = .44^{**}$) and with beta-amylase ($r = .97^{**}$), although in contrast to other authors it was not found to be associated with malt extract.

Streeter and Pfeifer (1966) assessed many characters in two two row and four six row varieties grown at five locations in Pennsylvania. Simple correlation coefficients were calculated for all combinations of characters for the two sets of data (two and six row). Values obtained for the two correlation matrices were in general agreement, both between themselves and with those reported earlier. No attempt was made to separate location and variety effects

which the authors suggest "confounded some of the quality interrelationships studied."

(c) Other studies on quality character associations

Several authors have drawn attention to particular quality character associations which provide additional support to the foregoing studies.

Kneen and Hads (1945) found beta-amylase of barley and malt and alpha-amylase of malt to be influenced by both variety and environment. There was a positive within variety relationship between grain nitrogen, barley beta-amylase and the malt amylases; there was also an inter-varietal relationship between barley and malt beta-amylase but not between grain nitrogen and beta-amylase activity. In contrast, Munekata et al. (1957) did find a positive correlation ($r = .73^{**}$) between these last two characters.

Day et al. (1955) studied a series of crosses involving O.A.C. 21 (high diastatic activity) which would give progenies segregating for one monofactorial gene. Analysis of the segregates in F_3 showed barley diastatic activity to be associated with the rough vs. smooth awn locus, the rough awned class having a higher mean activity than the smooth. They also found an apparent relationship between barley diastatic activity and the two row vs. six row locus, but later work showed that this was an indirect effect of the association between the two row character and barley nitrogen. See also Day and Dickson (1957).

Atkins et al. (1955) found that, over three seasons, the negative association between grain protein and malt extract, although not large, was one of the most consistent of the character associations

investigated. Schuster and Grunewald (1957) suggested that the actual slope of the relationship was a varietal characteristic. Earlier McCalla and Corns (1943) has found a highly significant negative correlation between protein and starch content, and also noted that the slopes for individual varieties were different. Whilst Lekes (1961) found grain size to have a positive association with starch content and a negative one with protein content.

More recently several authors (Rasmusson and Glas, 1965; Metcalfe et al., 1967; Foster et al., 1967; Baker, et al., 1968) have investigated malting quality in segregating populations. They all found evidence that barley protein was positively correlated with barley diastatic activity and negatively with barley extract. Partial correlations also showed that the negative association of diastatic activity and extract could be explained by the association of both characters with barley protein. The correlations involving grain size and the other three characters were not consistent between crosses although there was a tendency for grain size to be positively associated with barley protein, in contrast to the negative association reported by Anderson et al. (1941).

Attention has also been given to the relation of barley and malt properties to those of the derived beers, but this is beyond the scope of this review.

(d) Varietal differences in, and environmental effects on, malting quality characters

The above work has demonstrated that varietal differences exist for virtually every character studied. If a character showed a limited range this was probably a result of limitations in the

material investigated. Thus, the cummulated evidence might indicate that the varietal range in grain protein was not large, however, a survey of a world collection has demonstrated a considerable range and has located a variety (CI-3947, Hiproly) having 50% more protein and 30% more lysine than conventional varieties (Hagberg and Karlsson, 1969).

It is also evident that environment has an equal or greater effect than variety on malting quality characters. The confounding influences of variety and environment are of considerable importance in any study, whether chemical or genetical, of malting quality.

Meredith et al. (1962) emphasize that, as far as they are aware, "no property of barley, malt or wort that has been examined on an adequate scale has failed to exhibit varietal differences." They also point out that for each of the properties listed there were wide differences between variety means and often wider ranges for the environmental means.

McCalla and Corns (1943) found that both grain protein and starch content were under varietal and environmental control. The latter had a greater effect than variety, but both were highly significant. There was no significant variety-environment interaction. Middleton et al. (1961) obtained similar evidence whilst Schmidt (1958) found that, although the level of barley protein varied according to locality, the relative varietal values were fairly constant.

Fischbeck (1964), as a result of nine years' investigations, concluded that varietal differences in grain protein were more consistently expressed than those in yield. Whilst Lekes (1961) was

able to divide a world barley collection into six groups according to their grain nitrogen contents.

Dickson et al. (1938), summarizing a detailed study of the quality of five varieties concluded from an analysis of variance that variety, season and locality effects were significant for virtually all characters. However, variety-station interactions were only significant for grain yield, whereas variety-year interactions were significant for grain yield, husk content, barley and malt protein and diastatic power. They suggested that within any one year the quality of a variety relative to others would vary little from locality to locality. Harris and Banasik (1952) also found that all quality characters studied showed significant varietal, station and year differences with growth location in general exerting the greatest influence. Later (1957) the same authors concluded that malt and wort nitrogen were the characters most affected by locality, whilst variety exerted greatest effect on diastatic power and alpha-amylase activity.

Van Cauwenberge (1958, 1959) studied commercially available two row material from all over the world. He found, in a comprehensive survey of characters from barley through malt to beer, that varietal differences existed for every character. He made no attempt to differentiate varietal and climatic influences, since he was interested in the practical aspects of available raw material for beer production.

Varietal differences have been observed in most barley and malt enzymes including amylases, proteolytic, cytolytic and in such

enzyme dependent characters as wort attenuation limit and fermentability. (Fritz et al., 1968; Munekata and Kato, 1957b; Reiner and Fischbeck, 1966; Schuster and Dietel, 1963; Sparrow and Meredith, 1969; Van Roey and Hupe, 1955; Weinfurtner et al., 1966a). Subsequently the later authors (1966b) demonstrated rate of moisture uptake and 'swelling capacity' of the grain to be varietal characters and were supported by Hartong and Kretschmer (1958) and Chapon (1960).

Several authors have investigated the influence of variety and environment on various malt enzyme systems. Thus proteolytic, limit-dextrinase, orthophosphatase and cytolytic activities have been studied by Zoch and Olson (1949), Lowry et al. (1952), Olson et al. (1952) and Piratsky and Schrone (1962) respectively. In general these investigations have indicated that variety has a greater influence than environment.

From the above there is no doubt that variety and environment both have an important influence on malting quality. Variety-environment interactions are less well evidenced but undoubtedly occur. Varietal differences are perhaps more apparent for enzymatic activity. Environment has a dominant influence on quality in that it affects grain yield and the level of grain protein and starch (i.e., the raw material from which malt and enzymes are developed). Varietal influences also affect the constitution of this raw material. In summary it may be said that environmental influences are quantitative whereas varietal ones are qualitative.

5. Grain nitrogen content

(a) The effect of soil and climate on grain nitrogen content

The work of Bishop and his colleagues emphasised the importance of grain nitrogen as the character upon which the quality of the derived malt depended. Grain nitrogen level became, therefore, accepted as the best indicator of potential malting quality although strictly speaking this is relevant only to variation within a variety Bishop, as well as authors in the previous section, also indicated that the environment under which the crop was grown had a profound influence on the nitrogen content of the grain. Further points of this aspect will be dealt with below.

Anderson and Ayre (1938) were able to demonstrate that although variation in grain nitrogen could be attributed to both varieties and stations the latter had by far the greater influence. Since that time, the annual grain protein surveys of barley produced in the Prairie Provinces conducted by the Board of Grain Commissioners of Canada clearly indicate the extent of seasonal and locational influences on protein.

Conradie (1956), in the Netherlands, believed that malting quality was more influenced by soil nutrient level and fertilizer practice than by seasonal variation in the weather. But Postel (1957), in Germany, found that grain protein was more dependent on climatic than on soil conditions. He pointed out that although varieties differ in their protein contents these differences are more or less overshadowed by differences induced by climatic conditions whilst Plumet (1955) concluded that grain protein content

was mainly determined by environment with locality exerting a greater influence than year. Although extract (barley) was inversely related to grain protein and therefore influenced by environment it was also dependant on variety.

Djurtoft (1961) found that the level of grain protein (total and salt-soluble) was far less influenced by variety than by location. In other words climatic factors and fertilizer conditions had the dominant influence. He also found that increasing nitrogen fertilizer did not increase total grain protein until yield ceased to be improved, but the level of salt-soluble protein was entirely dependent on the level of nitrogenous fertilizer. This is not in agreement with Bishop (1928) who found salt-soluble protein to decrease with increasing grain nitrogen. However, the definition of salt-soluble protein was not the same in the two investigations.

Waldschmidt-Leitz (1959) demonstrated the existence of differences in the electrophoretic patterns of barley hordein and attributed these to environmental influences which affected grain protein level; climatic factors having a greater effect than nitrogen fertilizer. Varietal differences were, he suggested, caused by a differential response to environmental factors rather than each variety "possessing any constant ratio of the individual constituents."

In conjunction with the European Brewery Convention barley trials a "soils and climate" subcommittee, over a seven year period, examined the effect of various cultural factors on barley quality. Several reports and the publications of Aufhammer and Fischbeck (1961) and Aufhammer (1965) have presented the findings. The investigations have mainly been concerned with three varieties representing different

types available in Europe; Proctor (maritime), Haisa II (continental) and Kenia (adaptable). The general conclusions were that weather conditions influenced yield and quality to a greater extent than soil type and that the protein content of barley grain produced under maritime conditions was lower than that produced in continental areas. It was also apparent that soil type and nutritional status as well as the varietal adaptation exerted some influence on crop performance and on grain quality.

More recently Dent et al. (1968) analysing the data from British trials over the years 1962-67 found that significant variation in grain nitrogen content could be attributed to site, fertilizer and variety. Site differences were large but their ranking was not consistent and a high site-year interaction was evident. Differences due to increased fertilizer were predominantly positive but with no clear pattern of response either for site or season. Varietal differences although small were consistent and although in most years there was a significant variety-site interaction it was possible to demonstrate that some varieties consistently produced grain of a higher nitrogen content.

(b) <u>The effect of fertilizer on grain nitrogen content</u>

It is difficult to draw conclusions with confidence from studies of the effects of fertilizer application on grain nitrogen content. Rates of application have differed in each investigation; the initial soil nitrogen levels must have differed; different environment were involved.

Despite these variations it is apparent that there is a level of

nitrogen fertilization, between 20-40 kilograms/hectare, at which optimum yields can be obtained without any undue increase in grain protein content. Above that level yields may be increased slightly, or even decreased, whilst grain protein increases steadily and reaches levels which render the barley unsuitable for malting and brewing. These different patterns of response may confuse the apparent relationship between yield and grain protein if carried out under conditions of high fertility.

Studies that confirm these generalisations include (Atkins et al., 1955; Frey and Robertson, 1953; Hofmann and Niggeman, 1954; Larter and Whitehouse, 1958; Lejeune and Parker, 1954; Meredith et al., 1942; Reisenauer and Dickson, 1961).

There is evidence (Gardner 1971) that optimum yield under nitrogen fertilization is a varietal factor; grain nitrogens are likely to be influenced accordingly. Thus in a barley variety trial grown over a range of nitrogen levels two varieties had their highest yield without added fertilizer nitrogen and declined thereafter, one was had a parabolic response with a maximum at 80 kg N/ha and one increased over the whole range to peak at 275 kg N/ha.

(c) Physiological basis for varietal differences in grain nitrogen content

Little information is available on this fundamental aspect of varietal differences in grain quality, and most of the published work relates to wheat rather than barley.

Seth et al. (1960) studied two high and two low protein wheats. Although they did not find varietal differences in the nitrogen content of the vegetative parts, during grain formation the nitrogen

content of the heads increased more rapidly in the high protein varieties. They concluded that varietal differences in grain nitrogen could be associated with a differential rate of protein formation in the developing grain. On the other hand McNeal et al. (1966) found only slight differences in the proportion of nitrogen translocated from leaf and stem to grain.

Johnson et al. (1967, 1968) also studying high and low protein wheat varieties found some evidence for varietal differences in plant nitrogen content but such differences were unrelated to differences in grain protein content. They say that their "evidence strongly points to more efficient and complete translocation of nitrogen from the plant to the grain as the physiological basis of high grain protein." Whilst Kirby (1968, 1969) from data based on a small but widely representative sample of barley varieties provides evidence for variation both in nitrogen uptake and in nitrogen translocation to the grain. Thus supporting Fischbeck (1964) who concluded that varietal differences in grain protein content were a secondary effect of genetically controlled physiological processes modifying both nitrogen assimilation and protein storage in the grain.

If nitrogen translocation and, as Langer (1966) suggests, nutrient absorption are heritable characters and independent physiological systems then the way is open for considerable manipulation by the plant breeder.

6. Inheritance of malting quality characters

Dickson (1965) has said 'data obtained over the years on varietal differences for malting quality characters are adequate evidence that most factors are under genetic control'. However, information on the

inheritance of these characters is limited because of the time and equipment necessary to process sufficient samples for genetic analysis.

(a) Linkage studies

The malting quality of lines from populations segregating for certain marker genes has been measured in order to examine the association between quality and morphological characters. Day et al. (1955) found the rough vs. smooth awn locus (chromosome 7) to be associated with barley diastatic activity, with the rough awn class higher in activity than the smooth. They also found an apparent relationship between the two row vs. six row locus (chromosome 2) and the same activity. But, using isogenic lines, this was later shown to be the indirect effect of the association between this locus and barley nitrogen content, the two row segregates having higher grain nitrogen than the six row (Day and Dickson, 1957). More recently Hagberg (1963) has confirmed this association, using the same material, and shown that the two row character is associated with an increase in grain protein (20%), salt-soluble protein and enzymatic activity. Studies of isogenic lines have also demonstrated the association of the orange lemma character (chromosome 6) with high malt alpha-amylase activity (Dickson, 1965).

An association between the two row character and increased grain protein is in agreement with Barbacki's (1947) results but is contrary to the general experience that six row varieties are higher in protein and enzyme activity than two row. This points to the dangers of generalising about quantitative characters in results obtained from isogenic lines which by their nature are genetically limited.

Among the varieties they studied Sallans and Anderson (1938) found two distinct levels of 'free' beta-amylase. Bendelow (1964) investigating a wider range of varieties was also able to show that 16 varieties, all six row, with a low level of 'free' enzyme (about 50%) had, with only one exception, very slow endosperm modification during malting and were thus of unacceptable quality. Varieties with a high level of 'free' enzyme (about 70%), although not all classified as malting barleys, had a more rapid modification. Progeny of crosses between varieties with high and low levels showed the character to be dependent upon the action of a single gene pair with incomplete dominance and independent of total beta-amylase activity. More recently, Baker et al. (1968) have evidence that the controlling gene pair is inherited independently of aleurone colour.

(b) Genetic studies

Several studies of the malting quality of hybrid bulks have been reported. This approach avoids the labour of handling large numbers of segregants whilst still providing an estimate of dominance or epistatic effects and the possibility of calculating the 'combining ability' of the parent varieties. However, genetic analysis of malt characters that depend for their expression on enzyme-substrate interactions could be liable to misinterpretation. In a heterogeneous mixture of malt, such as an early generation hybrid bulk, enzymes from one genotype could attack the substrate from any other producing a result which deviates from the average of all genotypes. In other words, apparent genetic effects could be confounded by the interaction of genotypes (Sparrow, 1969). This criticism applies only to those measurements made after malt has been ground and mashed e.g. malt

extract, attenuation and the fractions of wort nitrogen.

Lofgren and Peterson (1962) crossed ten six row varieties and studied the grain quality characters of bulk F_1, F_2 and BC_1 generations. Dominance was found to be incomplete or non existent for grain size and barley extract but present for grain nitrogen and diastatic power. In a similar study Glas et al. (1963) investigated the quality of malts produced from F_2, F_3, F_4 and F_5 bulk hybrids involving eight European two row varieties. In the F_2 generation all the characters (malt nitrogen, malt extract, Kolback index and final attenuation) showed significant and positive deviations from the mid-parent value indicating the influence of dominant factors. In both studies there was evidence, in all characters, for in-breeding depression. Johnson and Aksel (1964) also made a study of F_1, F_2 and F_3 hybrid bulks from a 12 variety (six row) diallel set. The results were subjected to a comprehensive genetical analysis, based on Hayman's (1954) procedure, which demonstrated the presence of dominance influencing all five characters (grain size and nitrogen content, malt extract, wort nitrogen and diastatic power). Low levels of grain nitrogen and high levels of malt extract were associated with dominant genes whilst high levels of the other characters were related to either recessive or dominant genes.

The potential of hybrid barley and the extent of heterosis in the quality characters of eight parent varieties and their F_1 hybrids was investigated by Rasmusson et al. (1966). On average the hybrids were significantly higher than the midparents in malt extract and significantly lower in malt nitrogen content. In the other characters

(wort nitrogen, diastatic power, beta-amylase activity) heterosis was not significant. The authors suggest that 'malting quality of F_1 hybrids depends largely on the frequency of favourable genes with additive effects'. Although for malt extract and malt nitrogen content 'genes with favourable dominance and/or epistatic effects may be of importance'.

The results above are in contrast to the case in wheat where several studies of flour and grain protein content have not provided evidence of dominant genes controlling either high or low protein levels. (Davis et al., 1961; Stuber et al., 1962; Haunold et al., 1962; Kaul and Sosulski, 1965). However, in the case of the high protein wheat Atlas 66 there is evidence that relatively few genes are involved in the expression of this character. Whilst the genetic control of the high protein and high lysine content of the barley variety Hiproly, is still under investigation. Although a preliminary report (Munck et al., 1970) gives no information on the inheritance of protein content it does indicate that the altered amino-acid composition is controlled by a single recessive gene that segregates independently of protein content.

Extensive studies of segregating material have been limited for reasons mentioned but some examples have been reported. The inheritance of grain protein content was investigated by Barbacki (1947) in crosses between high protein six row and low protein two row varieties. F_1's were intermediate in protein content whilst F_2 selections showed evidence of transgressive segregation. It was suggested that six genetic factors were operative all having an additive effect. Lejeune

(1946) also found evidence, from the progeny of the cross O.A.C. 21 x Chevron, that the inheritance of grain protein content was governed by multiple factors.

Whitehouse (1963) assessed the malting quality of random selections from three crosses. Close agreement was found between the mean of the selections (cross mean) and the midparent indicating that the quality characters were inherited additively without large epistatic effects. Although in almost every case the cross mean was lower than the midparent value, the difference was not large enough to suggest dominance.

Rutger et al. (1966) made an extensive analysis of random F_2 progenies from the cross Atlas x Kindred. For each of 13 malting quality characters the distribution of the progenies was skewed and their mean deviated from the midparent value in the direction of Atlas, the parent with the poorer quality. The approximate range in performance of the progenies extended between that of the two parents although there was transgressive segregation for barley nitrogen, grain size and malt extract.

Metcalfe et al. (1967) investigated the quality of random F_2 progenies from three crosses involving two good quality and two poor quality varieties. In the cross between the two good quality varieties the progeny mean and the midparent value showed good agreement for all characters whilst the distribution of the progenies was narrow. The authors suggested that although this points to the additivity of the controlling genes it is more likely that the two varieties had a number of genes in common. On the other hand, in the crosses between

good and poor quality parents there was poor agreement between progeny means and midparent values, whilst the distributions were narrower than expected and skewed towards the better parent. This was taken as indicative of the dominance effects of desirable quality characters.

In the literature there are therefore examples of both additive and dominance effects controlling malting quality characters, whilst the latter have been found to favour either good or poor quality. An additional complicating factor is reported in a paper by Necas (1960) who found significant reciprocal differences in beta-amylase activity in several crosses studied in F_1 (F_2 grain, effectively first segregating generation). Although dominance for good quality has the most published support, Rutger et al. (1966) provide an example of dominance for low quality that is paralleled by my own experience that progeny from crosses involving the poor quality Egyptian variety CI-3576 are strongly inclined to the same type. Thus, the apparent genetic control of malting quality characters depends on the material studied. However, the validity of genetic analysis of some malting quality characters can be questioned in view of the empirical nature of their measurement. Although genetic analysis and heritability estimates are an aid to the plant breeder's manipulation of these characters there are obvious dangers in making sweeping conclusions until the basic germinative processes are investigated.

(c) Heritability

In dealing with quantitative characters, under the control of many genes, plant and animal breeders have sought to determine the

relative importance of environmental and genetic effects in the expression of the characters. The ratio of genotypic to total variance was termed 'heritability' by Lush (1949). The concept of heritability has been found useful in determining the degree to which differences among phenotypes result from genotypic causes, which alone are capable of manipulation in a breeding programme. Thus the estimation of heritability has been used, for various characters in many crop plants, as a guide to the potential for selection and improvement. A value for heritability near 100% indicates that the phenotype is a good index of genotypic merit and that genetic gains will result from selection, whilst a value near zero indicates that genetic gains will be difficult if not impossible to obtain (Frey and Horner, 1955; Johnson and Frey, 1967). In which case, only by changing the environment could an improvement be made in the character.

In plants two methods have commonly been used for the calculation of heritabilities. The first of these, parent-progeny regression, involves the calculation of the regression of values from a set of lines on values obtained from the material from which they were derived; for example F_3 rows on F_2 plants. The two generations are either grown together or in successive years. In regard to the latter, Frey and Horner (1955) point out that it is the more realistic in that it approximates the procedure used in selecting within segregating populations, and incorporates genotype-year interactions that are inherent in the procedure.

The second method, the variance components procedure, is in its simplest form the ratio of the total genotypic variance ($\sigma^2 g$) to the

total phenotypic variance (σ^2ph). The latter is usually partitioned into genotypic (σ^2g), genotype-environment interaction (σ^2ge) and residual error (σ^2res) components which can be obtained from the appropriate mean squares in an analysis of variance.

Thus Heritability = $\sigma^2g/(\sigma^2g+\sigma^2ge+\sigma^2res)$

However the genotypic or heritable variance here includes the dominance, epistatic and additive genetic variances and heritability is referred to in the 'broad sense'. Whereas 'narrow sense' heritability is the ratio of only additive genetic variance to total variance. If dominance and epistasis are operating the two estimates of heritability, narrow and broad, should approach each other with successive generations of selfing' Frey et al. (1954). Whilst Lush (1949) suggested that heritability in the narrow sense came close to that calculated by the parent-progeny regression method.

When working with plants, measurements are normally made on replicated trials grown in several environments. It is necessary then to calculate heritabilities in terms of the mean of r replicates and e environments.

Thus Heritability = $\sigma^2g/(\sigma^2g+\sigma^2ge/e+\sigma^2res/er)$

Hanson (1963) has pointed out that by increasing the number of replicates or the number of tests over locations and seasons, it is possible to increase the calculated heritability to almost any desired level even for yield. As a result he suggests that the only heritability of meaningful concern to the breeder is that calculated for the number of tests on which selection is customarily based.

The heritability of malting quality characters has been the

subject of several investigations. These, mainly confined to six row varieties grown in North America, have been applied to segregating populations as a guide to the potential for selection in the characters under consideration.

Day et al. (1955) calculated the broad sense heritability of barley diastatic power in the F_3 progeny of three crosses; heritabilities ranged from .31 to .34. In contrast Dickson (1965) briefly reported that in an extensive study of the heritability of barley and malt quality characters values greater than .75 were obtained for grain size, grain nitrogen, malt extract, wort nitrogen, diastatic power and malt alpha-amylase. Whilst Hsi and Lambert (1954) studied 50 F_5 and corresponding F_6 lines from 10 crosses. Inter-generation correlation coefficients, rather than parent-progeny regressions, were calculated for several agronomic and grain characters. The coefficient for barley diastatic power ($r = .84^{**}$) showed that character to be highly heritable, with lower values for grain protein content ($r = .47^{**}$) and barley extract ($r = .16$); yield showed a relatively high value ($r = .56^{**}$).

To obtain information on the effectiveness of early generation selection for malting quality Rasmusson and Glass (1965) calculated, in three crosses, heritabilities from the regression of F_4 family means on the parent F_3 lines. Mean heritabilities (Table 7) were highest for barley diastatic power (.56) and low for protein content (.08) although values for the latter varied widely between crosses. The authors concluded that, in F_3, selection would be effective for diastatic activity, but less so for grain plumpness and extract, and

ineffective for protein content. They also point out that increased genetic variation between the test parents would tend to increase heritability and hence the effectiveness of selection. Later the same authors (1967) calculated heritabilities by the variance component method on results obtained, in the F_5, F_6 and F_7 generations, from two populations of F_3 derived lines. Heritability estimates (Table 7) were highest for heading date (.86) and lowest for grain nitrogen (.54) although for the latter the results obtained for the two populations were widely different. This was attributed to 'large differences in the estimation of genotypic variance rather than differences in the interaction or error components of variance'.

Rutger et al. (1966) calculated the heritability of 13 malting quality traits as well as certain agronomic ones using the variance components obtained from the analysis of trials of progenies from the cross Atlas x Kindred. The heritabilities obtained ranged from malt diastatic power (.86) to grain nitrogen (.38), (Table 7). The value for yield was (.48) but in general the agronomic characters showed a lower heritability than the malting quality traits. A similar tendency was noted in wheat by Baker et al. (1968b).

Foster et al. (1967) compared the parent-progeny regression and variance component methods amongst the progeny of ten crosses comprising a diallel of five varieties. Estimates obtained by the regression of F_3 rows on F_2 plant values were generally low for all characters and all crosses indicating that there would be little relationship between prediction tests made on F_2 plants and subsequent performance in F_3. Barley diastatic power averaged a somewhat higher heritability (.23) than barley extract or nitrogen. Estimates obtained

using the variance component method of F_3 data were relatively high (Table 7) and it was suggested that effective selection could be made on the basis of prediction tests in the F_3 generation although attention was also drawn to the complicating influence of genotype-environment interactions.

Baker et al. (1968a) also compared the two methods but calculated parent-progeny regressions from mean F_4 values on F_3 values. They found high heritabilities for grain nitrogen and total beta-amylase (Table 7) by both methods and suggested that selection for these characters would be effective in F_3. However, since the two generations were grown together the environmental effect was reduced, which may have made the prospects for selection appear more favourable than would occur in practice. Further the authors point out that estimates of heritability are biased by genotype-environment interaction and that quantitative genetic theory indicates that such a bias would usually make the estimates too high.

The published results of heritability estimates are summarized in table 7. It is apparent that the values for the various estimates differ quite widely. This can be attributed to (1) the method of estimation; parent-progeny regression or variance components, (2) the generation of the material studied; involving the possible influence of dominance and epistatic effects, (3) the diversity of the material; the magnitude of the genotypic variance, (4) the effect of the environment; the magnitude of the environment variance and of genotype-environment interaction. However, despite all these limitations there is some agreement in the relative ranking of the results. Hence diastatic activity is more highly heritable than the other

TABLE 7

Summary of published data on heritabilities of agronomic and quality characters in barley

Parent-progeny regressions	Diastatic activity	Barley extract %	Barley nitrogen %	Grain plumpness %	Grain Yield	Plant Height	Heading Date
Hsi & Lambert, (1954) Correlations F6:F5	.84	.16	.43	-	.56	-	-
Rasmusson & Glass, (1965) Regression F4 on F3	.56	.16	.08	.24	-	-	-
Foster et al., (1967) Regression F3 on F2	.23	.08	.12	-	-	-	-
Baker et al., (1968a) Regression F4 on F3	.94	-	.76	-	-	-	-
Variance Components							
Day et al., (1965) F_3 progenies	.32	-	-	-	-	-	-
Rutger et al.+, (1966) F_4 progenies	.86	.69	.38	.90	.48	.69	.61
Rasmusson & Glass, (1967) F_5, F_6, F_7 progenies	.84	.64	.54	.64	.61	.73	.86
Foster et al., (1967) F_3 progenies	.79	.71	.81	-	-	-	-
Metcalf et al., (1967) F_3 progenies*	.55	.43	.38	-	-	-	-
Baker et al., (1968a) F_3 progenies	.94	-	.84	-	-	-	-

+Rutger et al. examined malt diastatic activity and malt extract; other authors studied only grain quality characters.

*Calculated by authors from their data but not published.

grain characters, with extract and grain plumpness intermediate and grain nitrogen content the least heritable. For plant characters maturity and height are highly heritable and yield less so. This general ranking agrees with what is known about the genetic background and effect of environment on these characters. Thus those that are highly heritable are relatively simply inherited and only slightly affected by environment, whilst those that have low heritability are complexly inherited and influenced to a considerable extent by environmental changes. Such information can have an important bearing on the way in which these characters are handled and selected in a breeding programme.

7. The measurement of genotype-environment interaction

The significance to plant breeding of genotype-environment interactions is readily apparent from the foregoing discussion on heritability. Two related approaches to the statistical measurement of these interactions have been developed.

(a) By analysis of variance

In an analysis of variance, applied to a single field experiment, the components of variation can be attributed to differences between varieties (genotypes) between replicates, and an error. If two or more agronomic treatments have been applied a treatments component can also be calculated. It then becomes possible to separate interaction components, such as genotype-treatment, to determine whether varieties have shown a differential response to treatments. The interactions involving replicates are normally pooled with error, which is used to determine the significance of the other components

in a variance ratio test.

Immer et al. (1934) described an extension of this form of analysis to cover a series of experiments involving varieties grown at different stations over several years. Variation was partitioned into that due to Varieties, Stations, Years and the appropriate interactions. With regard to the latter it was pointed out that the following questions could be answered; (a) did varieties respond differentially to stations (genotype-station interaction), (b) did varieties respond differentially to years (genotype-year interaction), (c) was the relative performance of varieties the same at all stations for both years (second order interaction).

Yates and Cochran (1938) discussed the principles involved in combining separate analyses into one including all sites. They make the point that the pooling of error components, provided individual estimates are substantially similar, 'gives a more accurate estimate than those derived for each separate experiment, since a larger number of degrees of freedom is available'.

The mathematical model underlying the analysis became:

$$Y_{ijk} = \mu + G_i + E_j + (GE)_{ij} + R_{jk} + e_{ijk}$$

where Y_{ijk} = yield of genotype (i) at environment (j) and replicate (k).

μ = mean of all genotypes over all environments and replicates.

G_i = mean effect of genotype (i).

E_j = mean effect in environment (j).

$(GE)_{ij}$ = effect of genotype (i) at environment (j).

R_{jk} = effect of replicate (k) within environment (j).

e_{ijk} = error of genotype (i) at environment (j) and replicate (k).

The environmental effect can be further divided into location, year and location-year effects, with the concurrent division of genotype-environment interaction into genotype-location, genotype-year and genotype-location-year components. Comstock and Moll (1963) present this expanded model and discuss genotype-environment interactions at length. They emphasis that what is measured as the genotypic effect (G_i) is an average phenotypic expression over the range of environments under test and not an 'inherent absolute quality of the genotype'.

Examples of the application of this type of analysis are available for a range of crop plants (Sprague and Federer, 1951; Salmon, 1951; Horner and Frey, 1957; Sandison, 1959; Miller et al., 1959; Rasmusson and Lambert, 1961; Schutz and Bernard, 1967; Baker, 1968). Whilst Matzinger (1963) in considering the analysis has reviewed other reports. In general the aim of these combined analyses has been to determine the optimum number of replicates, locations and years to be used for efficient variety testing and recommendation. The basis for this information being the magnitude of the genotype-location and genotype-year components relative to that for genotype. However Rasmusson and Lambert (1961), Liang et al. (1966) and Rasmusson and Glass (1967) all found the second order interaction (genotype-location-year) to be greater than those of the first order. This demonstrated 'there was a rather important differential response to environment that was not accounted for by either year or location groupings'. The interplay of inconsistent patterns, over locations and years, of rainfall, temperature and disease incidence, with

variations in planting date and maturity combine to create 'specific environments to which varieties respond differentially'. This, perhaps, points to the inadvisability of considering more than genotype-environment interaction in testing and Hanson (1963) on theoretical grounds backed up by a consideration of published results suggested that the location and year groupings can be taken as a random sample of environments.

Few authors have reported the evaluation of genotype-environment variance components for barley quality characters. Torrie and Dickson (1943) obtained results for several characters in a trial of five varieties carried out at six stations over four years. Since the malting tests were made on composite samples replicated results were not available and the second order interaction had to be used as an estimate of experimental error. Significant genotype-year interactions were obtained for grain yield, steep time and malt diastatic power but not for other characters including barley protein content and malt extract. The only significant genotype-location interaction obtained was for grain yields. The authors suggest that because of the small interaction components varieties tended to maintain the same relative rankings, with regard to quality characters, over locations and years. That being so 'most of the important quality factors can be determined reliably at a few representative stations'.

A major disadvantage to the determination of genotype-environment interaction by the analysis of variance approach is that it only considers the average performance of all genotypes over environments. Although a significant interaction may be indicated there is no

measure of the response of individual genotypes to the range of environments. Immer et al. (1934), Salmon (1951) and Plaisted (1960) have described procedures whereby a value can be calculated to indicate the relative contribution of individual varieties to the genotype-environment interaction component. Allard (1961) obtained individual variance components for each of 10 lima bean varieties grown over 16 environments by means of a separate analysis for each variety. Whilst Wricke (1962), and Rasmusson (1968) in barley, applied a somewhat similar approach. The individual genotype-environment variances were considered as providing a measure of the consistency or stability of performance over a range of environments. Baker (1969) has suggested a further step in which the individual genotype-environment variances can be divided into components due to regression and deviations. This approach overlaps that in the next section.

(b) By regression analysis

In discussing the combined analysis of variance Yates and Cochran (1938) suggested that the genotype-environment interaction could be partitioned into components for linear regression and deviations from the regression. The regressions were those of the yields of the separate varieties on the mean yield of all varieties at each environment. The latter, commonly referred to as site mean yield, provided a grading of environments in terms of their productivity. Whilst the varietal regression coefficients permitted a graphical representation of the differences in varietal performance over the range of environments.

Walton (1957) suggested the use of the yield of a standard

variety, or the mean of all entries in a trial, as a 'measure of general productivity'. He also advocated the calculation of variety on trial mean regressions to measure varietal performance over a range of conditions. He pointed out the importance of both overall performance and genotype-location-year interaction in the evaluation of lines that were to be grown commercially under varying environmental conditions.

The basic regression method of analysis, or as it is more often termed adaptation analysis, of variety trials was developed further by Finlay and Wilkinson (1963) who expanded the biological interpretation of the results. They analysed yield data obtained from trials of a collection of 277 barley varieties grown over three years at three locations in South Australia. The mean yield of the set of varieties in each trial, 'site mean yield', provided 'a numerical grading of sites and seasons' and a simple measure of the environment 'without the complexities of defining or analysing the interacting edaphic and seasonal factors'. Varietal means and regressions on site mean yield were calculated from logarithmically transformed data' since it was found by this means a high degree of linearity was induced in the regressions'. An analysis of variance similar to that described by Yates and Cochran (1938) was also performed and indicated that '79% of the genotype-environment interaction could be attributed to linear regressions'; while the variance for deviations from regressions was 'little more than 50% higher than the error variance'.

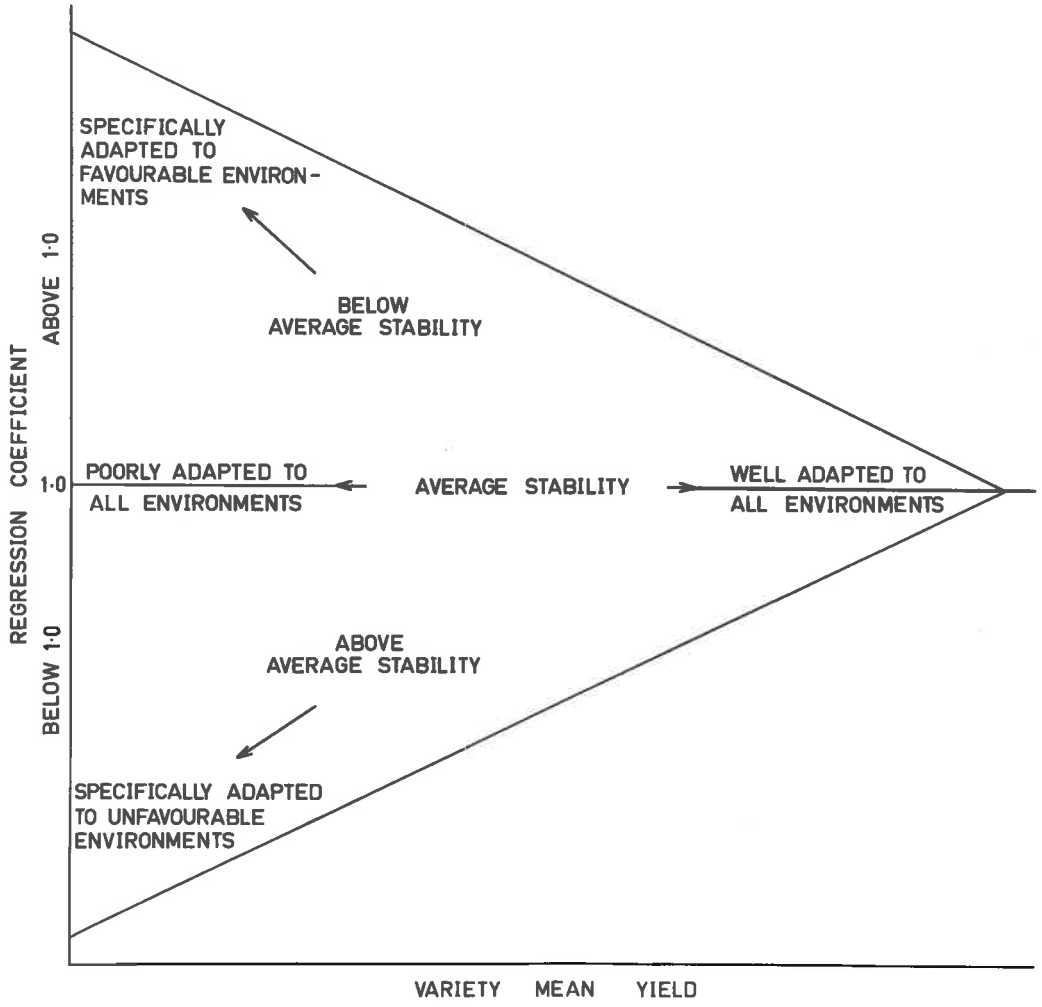
The two indices derived, for each variety, from the adaptation analysis are the variety mean yield over all environments and the

regression coefficient. The mean 'provides a comparative measure of performance of individual varieties', whilst the regression, also termed 'stability index', represents their relative response to changing environmental conditions and is a measure of phenotypic stability. It should be noted that 'because the individual variety yields are plotted against the mean of all variety yields the population mean has a regression coefficient of 1.0'. Thus coefficients near to 1.0 indicate average stability; those above 1.0 describe varieties sensitive to environmental change and adapted to high yielding environments (below average stability) those below 1.0 show varieties resistant to change and adapted to low yielding environments (above average stability). The two components of varietal performance can be plotted as coordinates in a scatter diagram. Figure 1, taken from Finlay and Wilkinson's (1963) paper, provides a generalised version of the interpretation that can be applied to the position of individual points.

In this and subsequent papers (Finlay, 1963; 1968) the implications of the adaptation components are discussed in relation to various aspects of varietal performance and selection in breeding programmes. With regard to yield, Finlay suggests that the ideal variety would have maximum potential in the most favourable environment allied with maximum phenotypic stability (b = 0.0). But, in practice the best commercial variety would have a high overall mean and average stability (b = 1.0); it would be relatively high yielding in all environments likely to be encountered in the region where it is cultivated. Finlay (1968) found that the two components of adaptation

FIGURE 1

A generalised interpretation of the variety population pattern obtained when variety regression coefficients are plotted against variety mean yields (Finlay and Wilkinson, 1963).


SPECIFICALLY ADAPTED TO FAVOURABLE ENVIRON-MENTS
BELOW AVERAGE STABILITY
ABOVE 1·0
REGRESSION COEFFICIENT
1·0
BELOW 1·0
POORLY ADAPTED TO ALL ENVIRONMENTS
AVERAGE STABILITY
WELL ADAPTED TO ALL ENVIRONMENTS
ABOVE AVERAGE STABILITY
SPECIFICALLY ADAPTED TO UNFAVOURABLE ENVIRONMENTS
VARIETY MEAN YIELD

were largely independent of one another, inferring that at least some progress can be made towards selecting the combination of high mean yield and above average stability. Perkins and Jinks (1968a) believe that 'separate genetic systems are involved in the control of the two aspects of the phenotype'. Scott (1967) provides evidence for the effectiveness of selection for stability of yield in maize and suggests that this character is under genetic control. Sparrow (1966b) has found that crosses between a barley parent with average stability (b = 1.0) and one with below average stability (b > 1.0) (i.e. high yields in favourable environments) has been particularly productive of progenies with increased yield and adaptation.

Eberhart and Russell (1966) extended the analysis by drawing attention to a third index, that of the deviations from the regression (S^2d). This component not only provides a means of comparing the significance of differences between two varietal regressions coefficients but also tests the probability of obtaining the response to environmental change predicted by a regression. They suggest that the ideal stable variety, in addition to b = 0.0, ought also to have $S^2d = 0.0$. Breese (1969) goes further and states 'the term stability should now rather be reserved to describe measurements of unpredictable irregularities in the response to environment as provided by the deviations from regression'. A divergence of opinion with regard to the use of the term 'stability' exists; Sparrow (1969) in an attempt to clarify the situation has used 'stability' to describe the type of response to the environment (i.e. the slope of the regression) and suggests that S^2d is the 'reliability' of the response (i.e. the standard error of the regression coefficient).

Several authors have used an adaptation analysis to examine genotypic response to environmental change in various crop plants. These include; Rasmusson (1968), Clay and Allard (1969) with barley; Johnson et al. (1968), Walton (1968), Qualset (1968) with wheat; Smith et al. (1967) with soybeans; Athwal and Singh (1966) with millet. In all of these papers, which deal exclusively with crop yield, calculations have been made on the natural data instead of with the logarithmically transformed data used by Finlay. Walton (1968) expressed the opinion that 'data need not be transformed provided the varieties are compared in small, related groups'.

Certain aspects of the adaptation analysis are still undergoing investigation and development. A genetical approach has been developed by workers at the Birmingham University Department of Genetics, including Bucio-Alanis (1966), Perkins and Jinks (1968a; b), Hill and Perkins (1969), but will not be reviewed here. More recently Knight (1970) has drawn attention to certain dangers in the use of site mean yield as an environmental index. If environmental variation in a single factor ranges both above and below the optimum, then super- and sub-optimal mean yields of equal value will be juxtaposed as environmental indices, although it is unlikely that varietal rankings will be similar at super- and sub-optimal conditions. When more than one environmental factor is operating, as in field situations, the position becomes even more complex. However, since it is impossible to measure every environmental factor and individual varietal responses to each factor it is admitted that, providing the limitations are realised, the adaptation analysis 'will continue to

aid the plant breeder in his task of selecting genotypes with various responses to the environment'.

Both Knight and Lawrence (1970) point out that logarithmic transformation of the data, as carried out by Finlay and Wilkinson, changes the underlying mathematical model relating yield of a genotype to the environment from an arithmetic to a geometric relationship, with the result that the biological interpretation altered. The effect of the logarithmic transformation is to maximise varietal differences at the low values and minimise them at high values. Exceptionally high yields have a greater influence on the mean yield and regression coefficient when calculated from natural data than on a logarithmic scale. Knight pointed out that the two indices for a variety are often positively correlated when obtained from natural data although there is no correlation (as found by Finlay and Wilkinson, 1963) when the data is logarithmically transformed. This effect of scale is particularly apparent where the range of environments and varietal types is wide but is less obvious where the variation is reduced. 'The choice of scale will depend upon the degree of variation but the parameters of the arithmetic model are more easily understood in biological terms than the parameters of the geometric model' (Lawrence 1970).

Few authors have reported on the evaluation of barley quality characters by means of an adaptation (regression) analysis. Torrie and Dickson (1943) applied Yates and Cochran's (1938) method to results from five varieties grown in 24 environments. Varietal regression coefficients for barley protein content were not signifi-

cantly different, but for grain yield and malt diastatic activity significant differences were obtained. Thus, Trebi (b = 1.19) was found to increase in yield, more than the other varieties, in the high yielding environments. Whilst Wisconsin Barbless (b = 0.50) had a more consistent, although lower, diastatic activity than other varieties; for this character there was a tendency for the regression coefficient and the overall mean to be correlated. Regression coefficients for other characters were not calculated since in an analysis of variance the interaction components were not significant.

Plumet (1955) provides graphical representation of varietal-environmental response regressions for grain protein, husk percentage and barley extract. Differences between the coefficients were too small to be significant and are not discussed. Reiner (1964) presented a scatter diagram of the varietal regressions by varietal means for the malt extracts of eight varieties grown in 14 European Brewery Convention trials in 1965. The range of coefficients (0.78-1.25) is quite wide and shows a tendency to a negative correlation with mean level of extract.

8. Multivariate analysis

Although methods for the reduction of multivariate data have been available for a considerable period it is only in the last decade, with the widespread introduction of electronic computers, that it has become feasible to apply these methods to biological problems.

Two basic types of multivariate analysis can be distinguished:

1. Component analysis, a 'technique for summarizing a set of related measurements as a set of derived variates, frequently fewer in number, which are definable as

independent linear functions of the original measurements'. (Holland, 1969).

2. Canonical or discriminant analysis, 'a procedure for discriminating as clearly as possible between two or more multivariate normal universes with the same variance - covariance (or correlation) matrix'. (Seal, 1964).

Component analysis can be divided into principal component analysis and factor analysis. In the former, in the correlation form, unities are placed on the diagonal of the original p x p correlation matrix, on the grounds that a variable will correlate perfectly with itself; whereas in the latter, the values on the diagonal, termed communalities, are generally less than one. These taken together represent the proportion of the variance of the variables accounted for by the common factors, leaving a residual to be accounted for elsewhere, by other, unspecified factors. Although Cattel (1965) argues that the latter model seems preferable for biological interpretation, since it is unlikely that any sample of variables will cover all the real influences in the total universe of variation, there is some controversy with regard to its mathematical validity.

Factor analysis can be criticised on two grounds. First, that the communalities are only estimates; the commonly used square of the multiple correlation with the other variables only constitutes a lower limit. Inherent in the use of a value less than one is the generation of negative latent roots for some of the resultant factors, which are excluded from further computation. Additional insignificant

factors may also be excluded at this point so that the number of factors eventually interpreted is the result of subjective choice. Hence the total variation in the original variables is not reproduced in the derived variables. Second, because of the residual variation excluded from the analysis, the resultant matrix of factor loadings is not situated in the original multi-dimensional space, is not unique and can be rotated to other solutions. Since the rotation to 'simple structure' is also relatively subjective, interpretation of the factors can present difficulties.

On the other hand principal component analysis is preferred mathematically. It can be described as the orthogonal transformation of a set of variables into a derived set of variables which will be uncorrelated with each other. Because the total variation in the derived variables will be equal to the total variation in the original variables no information is lost by the transformation which is situated in the original space. The first derived variable will account for the largest proportion of the total variation and subsequent variables will be extracted in descending order of importance; the latent root of each variable being an estimate of its variance. The derived variables will be linear functions of the original variables.

The number of components (or factors) to be interpreted and/or rotated is determined from a consideration of the magnitude of their latent roots; usually those accounting for about 90% of the total variance. Alternatively a statistical test can be applied to determine which latent roots are indistinguishable and, if small, excluded as

due to random error. Subsequently the components (or rotated factors) are interpreted by a consideration of the magnitude and sign of the variables on which they are loaded. In addition, values for the derived components can be assigned to the original entries; since these values are uncorrelated they are more amenable to the simpler forms of statistical analysis. These can be used to aid the interpretation of the derived components which will provide an insight into the underlying processes governing the phenomena under study. However, the subjective nature of the interpretation imposes certain limitations. Or, as Pearce (1965) has suggested 'the hypotheses evolved by multivariate methods.....should be accepted only if they can be co-ordinated with other knowledge and can be confirmed by experimental evidence'.

Although the two forms of component analysis have been applied to a number of biological problems only one is pertinent to the present study. Jardine et al. (1963) carried out a factor analysis of two sets of data comprising the grain and flour qualities of samples from a series of wheat variety trials. Both sets gave reasonably comparable results where, after oblique rotation, it was possible to distinguish four basic quality factors which were designated 'strength', 'hardness', 'stability' and 'stiffness'. The 17 quality test measurements were all shown to depend on one or more of these four relatively independent, common factors. Thus despite the inherent complexity of the wheat grain these four properties gave an adequate description of its quality. In a more recent paper Wrigley and Moss (1968) have discussed these properties further. Thus 'strength' is

largely associated with protein content and is more under environmental than genetic control. 'Hardness' appears to be inherited and can be measured by several tests not correlated with other factors. Whilst 'stability' and 'stiffness' are aspects of protein quality and to some extent inter-related.

The potential use of component analysis to elucidate the complexities of grain quality will be readily apparent. If underlying components (or factors) can be detected then the use of tests strongly correlated to these components would simplify selection for improved quality. There is also the possibility that the components, as fundamental properties, would be under simpler genetic control than quality as a whole.

The other form of multivariate analysis, discriminant or canonical analysis, has certain practical applications in the study of variability that could be useful in plant improvement programmes. As already mentioned this type of analysis can assist in the grouping of material into mutually similar or dissimilar populations. The presence of significant differences between populations and the level of significance required to distinguish between individual populations can be derived by statistical tests akin to those employed in analysis of variance.

Several variables are used to delineate the multi-dimensional space occupied by the material under study. As in principal component analysis this space is described in terms of a series of uncorrelated derived variables or components. These components minimize the within population variances and maximize the between population

variances. The data are converted so that each entry, and thus each population mean can be described by a series of coordinates on the components. The linear distance between pairs of populations can be calculated, whilst least significant distances can also be calculated and used to discriminate between populations. Where the first two components account for a high proportion of the total variance an approximation to the distribution of population means can be studied graphically by plotting the coordinates of these components on two dimensional graph paper. It is also possible to determine the relative importance of the original variables in the discrimination between populations.

Canonical analysis has been used, in a number of instances, in the measurement of genetic divergence in crop plants; the details are not pertinent to this review. In several of these studies (Murty and Arunachalam, 1966; Bhatt, 1970) it was found that there was no direct relationship between genetic divergence and geographic distribution. Singh and Gupta (1968) came to a similar conclusion with regard to the yield components of cotton. But they suggested that since yield is a complex character with polygenic inheritance similar phenotypes could be produced by many different combinations of genes and phenotypic similarity was unlikely to be indicative of a common geographic origin.

Whitehouse (1968) has suggested an extension of canonical analysis as an end towards the choice of parents in a crossing programme. The most likely position in multi-dimensional space for a hybrid population will be midway between its parents, although dominance and epistasis will shift the position of the hybrid. When the

breeder's 'ideal' variety is described in terms of the original variables a target can be plotted in canonical space. It is then a simple matter to determine which combination of parent varieties will most likely produce a hybrid population close to the target variety.

Whitehouse (1969) has also applied canonical analysis to malting quality data obtained from 14 varieties grown in European Brewery Convention Barley Trials from 1960 to 1966. Although the varieties represent only a small restricted group, two row malting types, significant distances were apparent between varieties and certain groupings could be distinguished. One group contained varieties acceptable for malting in the British Isles whilst another comprised three varieties from southern Germany.

Canonical analysis, therefore, provides a useful method for the study of genotypic differences. It's extension into the area of parent choice is relatively new and untried but may have considerable potential.

9. Gibberellins in germination and malting

Kurosawa (1926) in Japan, showed that an extract from the fungus Gibberella fujikuroi, the causal agent of 'Bakanae' disease, caused abnormal growth in rice and other plants. The active component was purified and named 'gibberellin' (Yabuta et al., 1939; 1941). Subsequently 12 distinct but related compounds have been classified as gibberellins; these occur widely in the plant kingdom and function as hormones in controlling various physiological processes. (Brian, 1959; Paleg, 1965). One of these compounds, gibberellin A_3 (GA_3) or gibberellic acid is available commercially (Curtis and Cross, 1954;

Borrow et al., 1955).

Hayashi (1940) found that treatment with gibberellins stimulated the germination of barley and rice and increased the production of amylase in the germinating grain. Japanese workers also were the first to test the use of gibberellins in malting (Hayashi, 1940; Munekata and Kato, 1957).

In Europe, Sandegren and Beling (1958; 1959) reported the industrial application of gibberellic acid in malting and recommended 2-3 mg of GA_3 per kg. of dry barley. They found that this application reduced germination time and increased malt extract, alpha-amylase activity and wort nitrogen of the resultant malt.

Since then a general reduction, to as low as .1 mg/kg, has occurred in application rates. Whilst potassium bromate, at about 100 p.p.m., has been recommended to control excessive proteolysis and reduce malting loss (Macey and Stowell, 1961a; b).

Fundamental investigations directed towards the mode of action of the applied GA_3 within the germinating barley grain have been carried on parallel with the practical developments. These investigations have led, in turn, to a better understanding of the role of the gibberellins in germination, of the development of enzymatic activity in the germinating grain and of the whole process of malt modification.

Several studies have shown that GA_3 stimulates the aleurone layer to release hydrolytic enzymes (Paleg, 1960a; b; 1961; 1964; MacLeod and Millar, 1962; Briggs, 1964; Paleg and Hyde, 1964; Varner, 1964). Yomo (1960) suggested an amylase-inducing substance secreted by detached embryos was a gibberellin; Radley (1959) observed gibberellin-like materials in malt, and Cohen and Paleg (1967) have

demonstrated that barley embryos release a gibberellin during germination.

The observation by Stadler et al. (1960) that damaged grains modified satisfactorily when treated with GA_3 suggested that grains from which the embryo had been removed or rendered inactive could be malted if treated with GA_3. This effect was demonstrated by Paleg and Sparrow (1962) and Paleg et al. (1962) who found that grain, from which the embryo had been removed, treated with GA_3 showed a sugar and nitrogen release pattern similar to untreated grain with intact embryo, although the degradation occurred more rapidly. Sparrow (1964) using micro-malting techniques was able to malt embryo-less barley after treatment with GA_3 and to produce kilned malts with analyses approaching commercial requirements.

Paleg et al. (1962) found that the response curve for sugar release from endosperm halves treated with GA_3 has a sigmoid form. Concentrations as low as 0.00001 p.p.m. produce a measurable sugar release (Nicholls and Paleg, 1963) and provide the basis for a sensitive bioassay technique for the hormone (Coombe et al., 1967a; b). In the presence of an embryo a concentration of GA_3 in excess of 0.01 p.p.m. was found necessary before an appreciable sugar release occurred (Paleg et al., 1962). With crushed grain a concentration of 0.001 p.p.m. produced a slight increase in malt extract and wort nitrogen, and at higher concentrations the response pattern was similar to that for sugar release (Sparrow 1965). Briggs (1963) in a review of published results points out that many responses to GA_3 within the range 0.1-3.0 p.p.m. are proportional to the logarithm of

the concentration applied. A sigmoid response curve is probably a general phenomenon for GA_3 stimulus in grain with the slope and position of the curve depending on the method and duration of treatment.

Varietal differences in response to applied GA_3 occur although the reasons are not yet clear. In a report from the Secobrah Laboratories (1961) the results are given for the varieties Aurora, Beka and Carlsberg malted with GA_3 applied at rates from 0.1 to 3.0 p.p.m. There is some evidence that the slope of the response curve differed for the three varieties but the main finding was that the level of GA_3 above which no appreciable improvement occurred was a varietal character.

Ruppert (1960) micro-malted, with and without GA_3 (0.15 p.p.m.) samples of several barley varieties with similar grain nitrogen contents. He found in the presence of GA_3 the enzymatically weak varieties gave a much improved modification, whereas the varieties which normally modified well showed no real improvement.

Atanda and Miflin (1970) found that varietal differences in alpha-amylase production were greater for germinated intact grains than for embryo-less grains treated with GA_3 (1.0 p.p.m.). Unfortunately they did not test the relative response of intact grain to GA_3, although suggested that varietal differences were most likely due to the rate of transport of the gibberellin to its site of action.

Varietal responses in micro-malting, to a range of GA_3 concentrations have been investigated by Sparrow (1966; 1969) and form part of this thesis.

10. Conclusions and Objectives

The work of Bishop and his colleagues and then of the Canadian group have provided a basis for all subsequent studies on malting quality. These established: (1) the importance of grain nitrogen content, its dependence on environmental factors and its subsequent influence on malt characters, (2) the important relationships between barley and malt characters and helped in an understanding of the complicated physiological processes taking place during malting; (3) differentiated barley varieties according to these characteristics and distinguished between hereditary and environmental influences; (4) these in turn led to the formulation of selection criteria for malting quality in barley improvement programmes.

The literature reviewed has provided evidence for an inverse correlation between grain yield and grain nitrogen content. This facilitates the task of the barley breeder selecting for improvements in both yield and malting quality. However, there are reports of exceptions to this rule which are of interest in the production of feed grain varieties.

It is well established that grain nitrogen and thus malting quality are influenced by climate, soil and fertilizer. But it is also evident that varietal differences have been found for all quality characters that have been studied. The environment has a quantitative influence on quality through grain yield, grain nitrogen, starch and lesser components, whereas varietal influences are qualitative and affect the constitution of raw materials within the grain.

The inheritance of malting quality characters have been

investigated, but, the complexity of the characters and the influence of the environment on their expression have limited such analyses. The imprecise empirical definition of many quality characters precludes an exact analysis of their genetic control. On the other hand the assessment of heritability and the magnitude of the environmental influences has been useful in the more pragmatic approach of the plant breeder.

Most of the studies on the heritabilities of agronomic and malting quality characters have been carried out in environments experienced in North America and on six row varieties. Less work has been reported with two row barleys and this has been restricted to the types of variety grown in N.W. Europe with a considerable history of selection for malting. This thesis, therefore, fills an interesting gap in that a study is made of a far wider range of two row varieties, some of which have never been under selection for quality. In addition these were studied in an environment, the Mediterranean climate of southern Australia, in which little if any work on malting quality has been reported. The background to this work and its context in a local barley improvement programme has already been outlined in the Introduction.

Although the importance of environmental influences on malting quality has been widely acknowledged little has been done to investigate the differential response of varieties to such influences and to genotype-environment interactions. Methods for analysing these interactions have been developed recently by the extension of the analysis of variance to include genotype-location, genotype-year and

genotype-location-year interactions for all varieties in a set of trials as well as for each variety individually. A further development has been the use of a regression analysis enabling varietal response to a set of environments to be described by a regression coefficient and the deviations from that coefficient. With regard to barley quality characters there remains considerable scope for the investigation and elucidation of patterns of varietal response to environmental change and this has been another objective in the present study.

Other developments, in multivariate analysis, have only come into prominence with the development of electronic computers; there has been little time for such methods to have an impact on the biological sciences. However since multivariate analysis provides methods of reducing data which are more or less interrelated it offers considerable scope in the study of malting quality. In this thesis principal component analysis has been used to extend the interpretation of the correlations between the grain and malt characters and to determine whether it would be possible to elucidate any basic factors underlying these empirical characters. A discriminant analysis was also used to aid the study of varietal differences, and to determine the main quality characters responsible for the differentiation in the hope that they would eventually be of use in selection for malting quality in segregating populations.

The past decade has seen an advance in the understanding the basic metabolism of the germination and malting processes. The elucidation of the role of the gibberellins in controlling these

processes has been a major contribution to knowledge. At the same time the malting industry has made considerable use of the commercially available gibberellic acid as an aid to more efficient conversion of barley to malt. As already mentioned in the Introduction this has proved of considerable importance to the Australian industry. Therefore, because of its local importance and also because of the lack of information elsewhere a study of varietal response to gibberellic acid was undertaken.

MATERIALS AND METHODS

1. Experimental material

A set of 40 two row varieties, was chosen for study, comprising material from Western Europe and the Mediterranean basin, together with five Australian varieties, and several North American selections. Details of the varieties, their country of origin and parentage are given in Table 8.

The European varieties are considerably interrelated but within that area represent a wide range in latitudinal adaptation and date of release. All of this group, except Portugal 2-row, have at some time been grown commercially in their country of origin. Goldthorpe-Spratt represents the first wave of British varieties produced by hybridisation between 1900-1920, the only one that was currently available in the Waite Institute collection. In Irish trials it had a yield and quality comparable to Plumage Archer and Spratt Archer which were, however, preferred commercially (Hunter, 1952). The majority of the European varieties derive germ plasm from the Binder x Gull combination that has had so wide an impact on two row improvement. Of the exceptions Boa Fe, Haisa II, Piroline, Union, Juliane and Beka trace back, like Binder, to the original Moravian Hanna. Portugal two-row, Goldthorpe Spratt and Morgenrot are not related to this main stream of improvement.

Some doubt exists as to the actual origin of the particular Hanna included in the set of varieties. Although morphologically similar to the general Hanna type it is earlier maturing than other lines of the same name. The Hanna type was originally obtained from

TABLE 8

Geographic and genetic origins of the 40 varieties studied.

	VARIETY	CEREAL INDEX	COUNTRY OF ORIGIN	YEAR OF RELEASE	PARENTAGE
1	Domen		Norway	1952	Opal B x Maskin
2	Freja		Sweden	1942	Seger x Opal
3	Rika		"	1950	Kenia x Isaria
4	Bonus		"	1952	Maja x (Seger x Opal)
5	Rigel		Denmark	1945	Kenia x Maja
6	Delta		Netherlands	1959	Kenia x (H. laevigatum X Gull)
7	Cambrinus		"	1962	Balder x Franken III
8	Emir		"	1962	Delta x ((Agio x (Kenia)2) x Arabic)
9	Impala		"	1963	Wisa x (Balder x Nordstamm)
10	Goldthorpe Spratt		Ireland	1920	Goldthorpe x Spratt
11	Proctor		England	1952	Kenia x Plumage Archer
12	Maythorpe		"	1954	Maja x Goldthorpe
13	Baldric		"	1962	Freja x Spratt Archer
14	Beka		France	1954	Bethge XIII x Kneifel
15	Ceres		"	1962	Piroline x (Bordia x Kenia)
16	Portugal 2-row		Portugal	-	
17	Boa Fe		"	1953	Selection from Hanna
18	Morgenrot		Germany	1943	Franken x Australian Early
19	Haisa II		"	1950	Haisa x W.M.R
20	Piroline		"	1953	W.M.R. x Morgenrot
21	Union		"	1956	(W.M.R. x Donaria)x Firlbeck III
22	Juliane		"	1961	(Monachia x Haisa) x W190/1330
23	Kankyo	CI5869	U.S.S.R.	-	From N.I. Vavilov's collection
24	Hanna	CI906	U.S.A. (Minn)	-	Selection from an Austrian Hanna
25	Goldfoil	CI928	" (Minn)	-	Selection from a Bohemian barley
26	Compana	CI5438	" (Idaho)	1941	Selection from Composite Cross I
27	Long Outer Glume	CI6168	"	-	" "
28	Prior's Chevalier		Australia	1904	Selection from Chevalier
29	Prior A		"	1951	Backcross derivative from Prior
30	Noyep		"	1961	Selection from Prior
31	Research M.R.		"	1948	Backcross derivative from Research
32	Resibee		"	1962	Selection from Research
33	CPI. 18197		Algeria	-	
34	CPI. 18198		"	-	
35	Waite 775		Egypt	-	
36		CI3576	"	-	
37	Retu	CI3726	"	-	
38	Glaucous Head Sina	CI3955	"	-	
39	Turk	CI5611	Turkey	-	
40	White Smyrna	CI910	"	-	

W.M.R. - Weihenstephaner Mehltauresistente I

the Moravian land race; it was reselected in many parts of Central Europe through to Southern Russia so that several variants exist (Broekhuizen, 1963). The line used in this investigation was a selection made in Minnesota, about 1909, of material obtained from Austria. At about the same period Goldfoil was selected from Bohemian barley.

The group of Mediterranean varieties are far more diverse than the European and includes material from Egypt, Algeria and Turkey. The North American selections, Goldfoil, Compana, Hanna, Long Outer Glume, and Kankyo although also of diverse origin have some similarities of field performance which indicate an adaptation to spring sowing in a dry short season continental climate.

The Australian varieties are also interrelated and stem from Prior's Chevalier, an early maturing Chevalier type selected by a South Australian farmer and first grown commercially about 1904 (Sparrow and Doolette, 1971). The varieties Prior A and Research M.R. are similar in type to their parents and were produced, by repeated backcrossing, at the Waite Institute in the 1940's. Both contain the Mlk gene for resistance to Erysiphe graminis derived from the Manchurian variety Kwan (Pugsley, 1950-51).

The complete set of 40 varieties was used for the first part of the investigation and in a final assessment of their general malting response to gibberellic acid. A subset of eight varieties (Domen, Proctor, Long Outer Glume, CI. 3576, CPI. 18197, Prior, Resibee, Beka) was used for the preliminary work on gibberellic acid and only four varieties (Long Outer Glume, CI. 3576, Prior, Resibee) for a more

detailed study of varietal response to gibberellic acid.

2. Experimental methods

(a) Field trials 1963-66

The 40 varieties were grown in trials at four sites for four years. Each trial comprised four replicates of a randomised complete block.

Seeding was carried out with the small plot drill described by Finlay (1963b). The plots were sown at a rate equivalent to 2 bushels/acre (110 kg/ha) which, although higher than used for local farm crops, experience has shown to be necessary for even seed distribution with this drill. The initial plot length of 13 feet (3.96 metres) was cut back to 10 ft. (3.05 m) within a month of germination. The plots consisted of three rows 7 inches (17.78 cm) apart and 10 ft. long. A space 14 in. (35.56 cm) wide was left between plots which were arranged in blocks separated by a 3 ft. (.91 m) path. Each block was bordered by two buffer plots and the complete trial was arranged with a buffer block at each end. This is a standard form of layout that has been used in Waite Institute cereal breeding trials over a number of years. In the present experiment each block was one replicate of the trial.

Before harvest a further 1 ft. (.3 m) was removed from each end of the plot to eliminate edge effects and uneven ripening. Single plots 8 ft. (2.44 m) long were harvested by means of a Waite plot harvester. The harvested grain samples were recleaned in a vertical peg-drum de-awner and winnowed before weighing to obtain grain yield. In the trials of the first three years (1963-65) the number of grains in 15 gram subsamples were counted with an electronic seed counter

and the thousand grain weight calculated. The same subsample was finely ground (Christie and Norris mill, 1.00 mm sieve) and the grist used for grain nitrogen and, in selected trials, insoluble carbohydrate determinations. In the 1966 trials data for grain yield only was recorded since it was not originally intended to include the results in this thesis.

The trials were grown on farm properties in the South Australian cereal belt (Latitude 34°S). The properties were situated near the towns of Monarto South (referred to herein as Bundaleer, the name of the farm), Clinton and Minlaton; and at the Waite Institute, Adelaide. These locations represent the range of soil types and rainfall patterns under which the South Australian barley crop is grown (Finlay and Wilkinson, 1963). The edaphic and climatic features of the trial sites for the four years are listed in Table 9.

No data is available from the trial grown at Minlaton in 1964. Immediately after harvest and before plot yields had been recorded all grain samples from the site were lost in a fire.

As well as this series of trials, larger plots of a subset of varieties were grown in 1966, at Aldinga, South Australia. Grain from these plots together with bulked material from Bundaleer 1963, Waite 1964, Bundaleer and Waite 1966 were used to test varietal reaction, in malting, to the addition of gibberellic acid.

Of the 11 trials grown in the first three years (1963-65) only eight produced sufficient seed for micro-malting. Six of these were chosen for malting on the basis of grain nitrogen content to give a range of means from 1.4 to 2.4% nitrogen (Table 10).

TABLE 9

Environmental data for the experimental sites

	Field trial sites			
	Bundaleer (B)	Clinton (C)	Minlaton (M)	Waite Inst. (W)
Soil type	Sandy mallee	Loamy mallee	Shallow sand overlying limestone	Red-brown earth
Normal sowing time	Mid May	Early June	Early June	Late June
Normal harvest time	Late November	Early December	Mid December	Mid December
Rainfall (inches)				
1963 Annual Total	17.83	16.93	19.11	28.69
April-Nov.	15.13	16.66	17.46	24.98
Sept.-Nov.	4.62	2.46	2.56	3.69
1964 Annual Total	14.59	16.64	19.96	29.11
April.-Nov.	13.29	15.14	18.23	27.09
Sept.-Nov.	6.54	7.31	7.91	11.02
1965 Annual Total	9.05	10.15	12.67	17.62
April-Nov.	8.29	9.60	11.81	15.59
Sept.-Nov.	3.03	2.30	1.89	3.38
1966 Annual Total	12.98	12.77	18.56	25.33
April-Nov.	8.46	10.33	14.11	19.27
Sept.-Nov.	2.71	3.46	4.69	5.21

It is only the April-November inclusive rainfall that is considered effective for plant growth.

The September-November rainfall is that having most influence on grain formation.

TABLE 10

Site mean grain nitrogen % of trials malted

(LSD 1% = .04)

	Grain nitrogen % (site mean)
Clinton 1964	1.42
Bundaleer 1964	1.54
Waite 1964	1.76
Bundaleer 1963	1.81
Minlaton 1963	2.06
Waite 1965	2.43

(b) Malting procedures

For each trial chosen for malting the grain of two replicates was further cleaned to remove half grains and those less than 2.0 mm in width. The amount of material removed at this stage was never more than 5% of the sample. Two samples of grain were prepared; one of 25 grams dry weight for pilot steeping to determine water uptake rate and steep time, the other of 100 grams dry weight for micro-malting.

Micro-malting was carried out in equipment similar to that described by Anderson (1937); details of the malting schedule are given in Table 11. Samples were set to commence steeping at a time, calculated from pilot steeping, that allowed all samples in a batch to reach 44% moisture at the same time. At steep-out the samples were drained and weighed; minor adjustments in removal or addition of water were made to provide the correct moisture content before

TABLE 11

Details of malting schedules

	Variety experiment	GA_3 response experiment	
		First experiment (8 vars.)	Subsequent experiments (4 vars. or 40 vars.)
Steeping 10°C (50°F)	(11 hours water, 1 hour air rest) for period determined by pilot steep test. (Adjusted to 44% moisture at steep-out).	48 hours water or GA_3, with a change after 24 hours.	(6 hours water, 6 hours air rest) for 48 hours. GA_3 added and adjusted to 44% moisture at steep-out.
Germination	6 days at 13.5°C (56°F)	4 days at 13.5°C (56°F)	
Kilning	48 hours on following schedule. 0-6 hours rising to 50°C 6-24 hours 50°C 24-30 hours 50°C-65°C 30-40 hours 65°C 40-44 hours 65°C-80°C 44-48 hours 80°C	24 hours on following schedule. 0-9 hours 50°C 9-12 hours 50°C-65°C 12-18 hours 65°C 18-21 hours 65°C-80°C 21-24 hours 80°C	

the start of germination. After kilning the samples were cleaned and polished by hand, and stored in air-tight jars until analysed.

The samples were malted in batches of 20 (half a replicate) together with a batch control (a commercial barley sample which was used in all experiments in any one year). If the malt analyses of any batch control differed significantly from the mean of a series of controls the batch was re-malted. This only occurred twice in these experiments and was caused by malfunction of the kiln.

The experiments with gibberellic acid, other than the first, were carried out at a later date than the variety trials. Samples of 25 grams dry weight were subjected to a modified malting schedule (Table 11) and were not pilot steeped. The longer air rest periods were found to reduce steep time and varietal differences in this character, but also to give a more rapid and even germination. For this reason, together with the effect of gibberellic acid, germination time was reduced to four days. Gibberellic acid was applied, on a weight for weight basis, as a solution at steep-out when the normal weight adjustment was made. One millilitre of solution was applied from a capillary pipette and mixed into the sample. The smaller malt samples were also found to dry out more rapidly on the kiln and the schedule was therefore compressed into twenty four hours.

In the first experiment with gibberellic acid the samples were steeped in water or a gibberellic acid solution for 48 hours with a change of steep after 24 hours. The malting and kilning schedules thereafter were the same as outlined above.

In this first experiment, with eight varieties, five concentrations

of gibberellic acid were used (0, .001, .01, .1, 1.0 ppm). In the second experiment, with four varieties, gibberellic acid was applied at rates from .01 to 2 ppm which the earlier work had shown to be the range over which response, when plotted against log concentration, was virtually linear. Fifteen concentrations (0, .01, .02, .03, .04, .05, .07, .1, .2, .3, .4, .5, .7, 1.0, 2.0 ppm) were applied. In the final experiment duplicate samples of all 40 varieties were treated with either water or one concentration (1 ppm) to obtain a measure of their general response to gibberellic acid.

3. Data recorded for various characters

All characters except yield and thousand grain weight are expressed on a dry weight basis. Moisture contents were determined; for grain with a Marconi moisture meter; for malt by the method of the American Society of Brewing Chemists. (3 g of ground malt, 3 hours at 104°C, loss in weight used to calculate original moisture content).

(a) Grain characters

Grain yield was measured for each plot in all 15 trials. It was recorded and analysed in terms of grams/plot without adjustment for moisture content, which varies little under Australian harvest conditions. For the size of plot employed an approximation to bushels/acre can be obtained by dividing grams/plot by 10 (1 bushel of barley = 50 lb).

Thousand grain weight was calculated by determining the number of grains in a 15 gram sample. This character was recorded for the 11 trials grown from 1963-65.

Grain nitrogen content was determined by the biuret method (Jennings, 1961). Throughout this thesis the results are expressed as percentage nitrogen and have not been converted to an estimate of protein content. This character was recorded for the 11 trials grown from 1963-65.

Insoluble carbohydrate content was determined by the method of Bishop and Marx (1934). This is a modified crude fibre assay involving a digestion of ground grain successively in dilute acid and dilute alkali. The original authors suggest that it was an estimate of the spent grains i.e. the material not solubilized by malting and mashing. This character was only determined for the samples which were malted.

(b) Malt characters

Steep time was estimated by means of a pilot steep. Samples of 25 grams dry weight were steeped using the same schedule as that for micro-malting (Table 11). After 24, 48 and 72 hours, the weight of the steeped samples was measured after drainage and removal of excess water by suction on a buchner funnel. The results were used to calculate the number of hours required to bring the grain to 44% moisture content (Appendix 1).

Malting loss, the percentage dry matter lost during malting, was calculated as the difference between the dry weight of the kilned, polished malt and the original dry weight of the sample, as a percentage of the latter.

Malt extract (hot water extract), for samples from the variety trials, was determined by the Institute of Brewing Method (1961). A coarse grist was extracted with distilled water for one hour at 65.5°C with constant stirring. Specific gravity of the filtered

extract was measured by means of a Reischauer pycnometer attempered in a water bath held at 20°C. The results were first used to calculate extract as brewer's pounds per quarter (336 lb) but then transformed (x .737) to a percentage figure to providing a value that is more widely understood. It should be made clear that this transformation estimates the true percentage extract and not one that would be obtained if a fine grist had been extracted by a concoction mash. The value is not, therefore, strictly comparable with that obtained by the methods of the American Society of Brewing Chemists and the European Brewery Convention. For this reason and also because a coarse rather than a fine grist was used the values are lower than usually obtained by those methods. Nonetheless the results are relative and the use of a coarse grist has been found to facilitate varietal discrimination.

For the 25 gram samples a small-scale determination of extract was employed (Kirsop and Pollock, 1958). This method has the advantage of requiring only 10 grams of malt. The exact weight of the grist and the weight of the mash (volume 100 ml) are included in the calculation of extract. Specific gravity was measured as above and the calculated extract transformed to a percentage figure.

Cold water extract was also determined by the Institute of Brewing Method. 10 grams of a coarse grist were extracted in 200 ml of distilled water containing 12 ml of 0.1N ammonia for three hours at 21°C. The specific gravity of the filtered extract was determined and the percentage extract calculated.

Wort nitrogen content was determined by semi-micro kjeldhal method. The results are expressed as a percentage of the dry weight

of the malt sample extracted.

Diastatic activity was determined by the method proposed by Bendelow (1963). Five grams of ground malt were extracted for 2.5 hours with a 0.5% aqueous solution of sodium chloride at 20°C. After filtration an aliquot of the diluted filtrate was assessed for total diastatic activity. Following starch hydrolysis the amount of reducing sugar released was measured by means of the colour change of the reagent dinitrosalicylic acid (DNS). The results obtained were expressed in terms of milligrams of maltose produced per one milligram of malt.

(c) Derived characters

Predicted extract was calculated from Bishop's (1934, 1948) equation, involving the nitrogen content (N) and the insoluble carbohydrate content (I) of the grain as follows

$$E = 138.2 - 9.5N - 3.0\ I$$

E is the predicted extract in brewers' pounds per quarter, which, as with malt extract, was converted to a percentage figure. The constant 138.2 is a general value taken to represent the extract if the whole grain were composed of digestible material. This equation has particular use with material of unknown performance since unlike other prediction equations, a constant for each variety is not required.

Relative extract is the difference between the extract predicted and that obtained from the malt. Whitehouse (1963) has suggested that the ability of a variety to produce the extract predicted is an important character to be considered when selecting for malting quality. The inclusion of insoluble carbohydrate in the prediction

equation is on the assumption that the polysaccharides which are not solubilized during malting vary in amount from variety to variety in proportion to the variation in the insoluble carbohydrate, the so-called carbohydrate regularity principle (Bishop and Marx, 1934). That this ignores the complexity of this polysaccharide material and its susceptibility to enzymatic degradation during malting will be obvious. Relative extract, therefore, provides an indirect measurement of the degree of this dissolution. It should also be noted that Meredith (1949) found the difference between barley extract and malt extract to be closely related to wort viscosity (page 24).

4. Statistical analysis of data

The majority of the statistical analyses were carried out at the University of Adelaide's Computing Centre using the programmes indicated below.

The most detailed analyses were carried out on the data from the six trials that were micro-malted. Consideration is also given to grain yield obtained from the total set of 15 trials and to thousand grain weight and grain nitrogen content obtained from the 11 trials grown 1963-65. All analyses have been carried out on natural scale data.

(a) Analysis of Variance

Using the GENSTAT programme (Baxter and Wilkinson, 1970), each character was subjected separately to an analysis of variance combining data from all sites. The partitioning of the total sums of squares included the subdivision of the genotype-environment interaction into components due to linear regression and to deviations from

linearity. These are appropriate to the adaptation analysis (qv).

(b) Heritability estimates

For each character the variance components obtained from the analysis of variance were used to calculate a heritability estimate. For this investigation the most appropriate model, in the analysis of variance, for the average values of the mean squares is model II (random) (Eisenhart, 1947). The derivation of the variance components and the method for calculating the heritability estimates are given in Table 12.

(c) Adaptation analysis (see Literature Review, page 57)

For each character three parameters were estimated from the following regression model: (See also model for combined analysis of variance (page 54).

$$Y_{ijk} = \mu + G_i + b_i (E_j - \bar{E}) + \delta_{ij} + R_{jk} + e_{ijk}$$

Where Y_{ijk} = value of genotype (i) at environment (j) and replicate (k).

μ = mean of all genotypes over all environments and replicates.

R_{jk} = effect of replicate (k) within environment (j).

e_{ijk} = error of genotype (i) at environment (j) and replicate (k),

and the three parameters were:

1. (G_i) the mean of genotype (i) over all environments.
2. The linear regression (b_i) for genotype (i) on the site means ($E_j - \bar{E}$).

   These first two parameters are those suggested by Finlay and Wilkinson (1963).
3. The deviation from regression (δ_{ij}) for genotype (i) was suggested by Eberhart and Russell (1966).

TABLE 12

Derivation of variance components and calculation of heritability estimates
(Eisenhart, 1947 ; Hanson, 1963)

Source	d.f.	Average value of mean square
Environments	e-1	$\sigma^2 + r\sigma^2GE + rg\sigma^2E$
Genotypes	g-1	$\sigma^2 + r\sigma^2GE + re\sigma^2G$
Genotype x environment	(g-1)(e-1)	$\sigma^2 + r\sigma^2GE$
Residual (error)	(r-1)(g e-1)	σ^2

where: e = number of environments

g = number of genotypes

r = number of replicates

and $\sigma^2G = \sigma^2$ genotypes

$\sigma^2GE = \sigma^2$ genotype x environment

$\sigma^2 = \sigma^2$ residual

thus $\sigma^2PH = \sigma^2$ phenotypes $= \sigma^2G + \sigma^2GE/e + \sigma^2/er$

Heritability is either $h^2 = \sigma^2G/\sigma^2PH$

or $h^2 = \Delta G/S\sigma PH$

where the genetic gain for a standardised selection differential of S is

$$\Delta G = S(\sigma^2G/\sigma^2PH)\sigma PH$$

The estimates of these three parameters can be tested for significance by an F-test using the appropriate mean squares in the analysis of variance (for 1 and 3 the residual mean square, for 2 the deviation mean square).

In Eberhart and Russell's (1966) modification of the analysis, the deviation mean square (S^2d) is derived from the third parameter as follows:

$$(S^2d)_i = \sum_{j=1}^{S} (\delta^2_{ij})/d.f.$$

whilst the standard error of the regression coefficient, quoted in the appendices of this thesis is obtained from

$$s.e.(b) = \sqrt{\frac{S^2d}{\Sigma (E_i - \bar{E})^2}}$$

The linear regression for each genotype can be tested for difference from unity by a t-test. The homogeneity of individual deviation variances can be measured by Bartletts test and their significance (greater than zero) by an F-test as follows:

$$F = (S^2d)_i / \sigma^2 \text{ res}$$

where σ^2 res = residual mean square.

In the Finlay and Wilkinson (1963) form of adaptation analysis, the genotype yields are plotted against site mean yields and therefore the population mean has a regression coefficient of unity ($\bar{b} = 1.0$) and individual regressions may vary around b = 1.0. However, Perkins and Jinks (1968a) by analysing genotype and environmental effects as deviations from the grand mean, derive a mean regression coefficient $\beta_i = 0$ and distinguish this from the $(1 + \beta_i) = 1.0$ of other authors.

Similarly, the ADAP programme (Lawrence 1970) used in this study, calculated the regression coefficients as deviations from the population mean regression (i.e. $b - \bar{b}$ and therefore $\Sigma b = 0$). Thus, throughout this thesis, adaptation coefficients near zero indicate average response to environmental change; positive coefficients describe genotypes relatively sensitive to change and negative coefficients those relatively resistant to change.

(d) Simple correlations

The STATSCRIPT programme (Lamacraft, 1969) was used to calculate the various correlation coefficients.

(e) Multivariate Analysis

For all these analyses use was made of the BMD Biomedical Computer Programs (Dixon 1968).

Stepwise Regression (BMD 02R) was used to obtain the best fit to a series of multiple regression equations of the form

$$y = b_o + b_1x_1 + b_2x_2 + \ldots\ldots\ldots\ldots\ldots\ldots + b_nx_n$$

The dependent variable (y) was varied to include, in turn, each malting quality variable, excluding derived characters; the remaining 9 variables were designated as independent variables. The observations for each variable were entered as two subseries, site means and variety means.

In the stepwise procedure the multiple regression equations are obtained by adding one variable at a time to provide a series of intermediate equations. The variable added is the one which makes the greatest improvement in 'goodness of fit'; equivalent to the variable with the highest partial correlation with the dependent

variable excluding the variables already added to the equation. Variables are added only if their F level is above a critical value. If as a result of the addition of further variables any variable's contribution falls below a critical F level it is removed from the equation. The final equation, therefore, includes only significant variables. The programme allows the critical F value to be set as desired. This is normally the value where the numerator has one degree of freedom and the denominator, approximately, the residual degrees of freedom when the equation is complete.

In the present study the multiple regressions derived from the programme have been used to determine what proportion of the variance of each dependent variable could be accounted for by the independent variables.

Principle Component Analysis (BMD01M) was used to compute the principal components of the standardized data (deviations from mean in standard deviation units) of the 10 non-derived variables and relative extract. The new variables, which are not correlated, are linear weighted sums of the original variables. The programme orders the principal components in terms of their size and also calculates, for each component, a score for each original case.

Stepwise Discriminant Analysis (BMD07M) performs a multiple discriminant analysis in a stepwise manner. At each step one variable is entered into the set of discriminating variables. The variable entered is selected as that with the largest F value; equivalent to that which gives the greatest decrease in the ratio of within to total generalized variances. As with the stepwise regression the critical F level can be set as desired and a variable will be excluded if its F

values becomes too low. A summary of the final discrimination shows the order in which the variables entered and their F value at entry. This provides information on the variables which contributed to the between population discrimination. At each step in the discrimination a set of partial F statistics is available to test the discrimination between genotypes. The final between population matrix is rotated to derive the canonical axes and the canonical coefficients of each genotype are calculated. These have been used to plot the dispersion of the genotypes on the first two or three axes. In addition a further programme was written to derive the Mahalanobis distances (D^2) between pairs of genotypes.

Other details of both principal component analysis and discriminant analysis have been discussed in the literature review.

RESULTS

1. Environmental variation

Although the four sites at which the field trials were grown do show differences in soil type (Table 9) it is apparent from earlier work (Cornish, 1950) that seasonal variability in rainfall is probably the most important factor influencing the performance of cereal crops in southern Australia.

The extreme variability in rainfall both between sites and between seasons is evident from the figures presented in Table 9 (page 80). Since, in general, precipitation during the summer months is subject to rapid evaporative loss only that recorded from April to November is considered effective for crop growth. In addition, for cereal crops, with anthesis towards the end of September the rainfall in the three spring months (September-November) has a considerable influence on grain formation and thus on grain quality.

The 1963 and 1964 seasons had above average rainfall but this was distributed differently in the two years so that the spring of 1963 was considerably drier than that of 1964. In 1965 rainfall was below average throughout the season and at all four sites. Whilst 1966 was drier at Bundaleer and Clinton than at Minlaton and the Waite Institute. In general the sites show an ascending order of average rainfall from Bundaleer to the Waite Institute. This is reflected in the normal sowing and harvest times; in the drier sites early sowing is employed to escape the tendency to spring drought, and in the wetter sites later sowing is practised to avoid excessive vegetative growth and thus increased transpiration and depletion of soil moisture during grain formation. These four years and four

sites provided a contrast in environments that would be typical of the range of conditions encountered in the South Australian cereal belt.

In Table 13 the site mean yields (mean of 4 replicates of 40 varieties) for each of 15 trials, and the site mean grain weight and grain nitrogen content for 11 trials have been set out alongside the rainfall at each trial site during the growing season and the spring months. Some of the correlations between these five characters are included in the table. The sowing date of each trial is also given. The values of grain size and grain nitrogen for Waite 1966 were obtained from only one replicate and have not been included in the calculations.

For all 15 sites the correlation between seasonal rainfall and yield is negligible ($r = .12$), but if the data are plotted it is apparent that two sites have given an anomalous result (Fig. 2). If these two results are omitted the correlation becomes significant ($r = .75^*$).

Inspection of the graph indicates that at Bundaleer grain production per unit rainfall is more efficient than at the other sites. It would require longer term experiments than this series to determine whether there was a characteristic site response to seasonal rainfall and the underlying reasons. There is no correlation ($r = .24$) between spring rainfall and yield; although Waite 1964 is again somewhat anomalous, its removal does not improve the correlation.

The two anomalous results can be considered in more detail. During the winter of 1963 rainfall at the Waite Institute was excessive with more than five in. in each of the three months May to July.

TABLE 13

Sowing date, rainfall, mean yield, grain size and nitrogen content at 15 trial sites (means of 4 replicates)

Trial Site	Sowing Date	Rainfall (in.) Apr-Nov	Rainfall (in.) Sept-Nov	Yield (g/plot)	1,000 gr. wt. (g)	Grain nitrogen %
Bundaleer 1963	24/5	15.13	4.62	397.3	36.35	1.82
Clinton 1963	13/6	16.66	2.46	319.6	36.68	2.10
Minlaton 1963	25/7	17.46	2.56	419.1	40.80	2.37
Waite 1963	12/8	24.98	3.69	64.3	35.17	2.38
Bundaleer 1964	3/6	13.29	6.54	397.3	41.10	1.51
Clinton 1964	11/6	15.14	7.31	243.2	39.57	1.42
Waite 1964	8/6	27.09	11.02	269.9	38.28	1.83
Bundaleer 1965	26/6	8.29	3.03	203.8	33.60	2.43
Clinton 1965	1/7	9.60	2.30	103.2	30.58	2.31
Minlaton 1965	7/7	11.81	1.89	180.2	36.39	2.41
Waite 1965	21/7	15.59	3.38	264.1	36.39	2.63
Bundaleer 1966	7/6	8.46	2.71	238.3	-	-
Clinton 1966	9/6	10.33	3.46	232.3	-	-
Minlaton 1966	26/7	14.11	4.69	244.0	-	-
Waite 1966	30/6	19.27	5.21	450.6	43.08+	2.22+
LSD 1%				17.5	0.71	0.05

Correlation Coefficients

Apr-Nov Rainfall	.115	.336	-.131
Sept-Nov Rainfall	.235	.459	-.706*
Apr-Nov Rainfall (omitting W63 and W64)	.751*	.688*	-.215
Sept-Nov Rainfall (omitting W64)		.546	-.867**
Yield (11 sites)		.718*	-.411
1,000 grain weight			-.539

+ results from one replicate only, not included in the calculation of correlations.

FIGURE 2

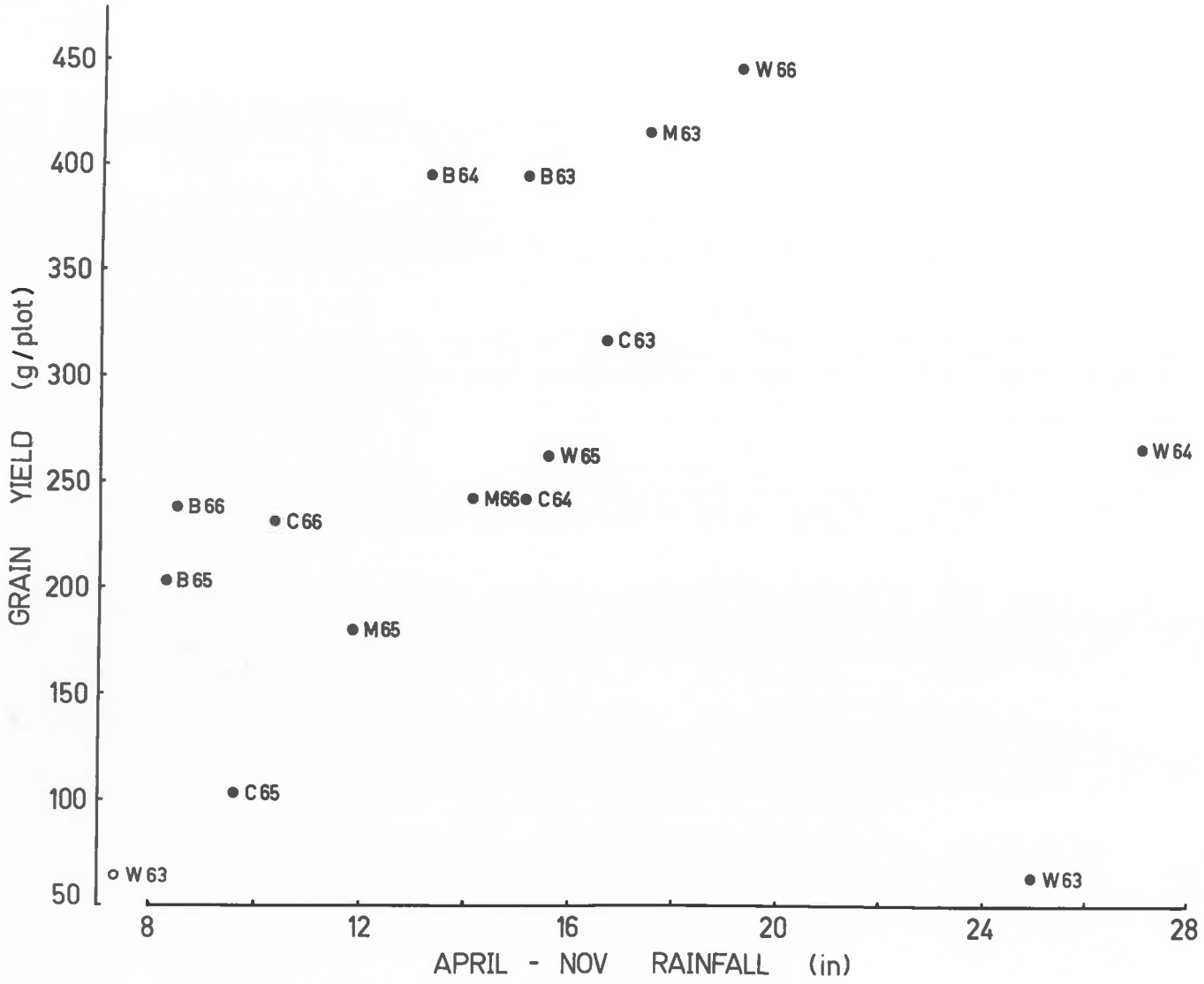
The relation between grain yield and seasonal rainfall at 15 sites over 4 years

B = Bundaleer

C = Clinton

M = Minlaton

W = Waite Institute

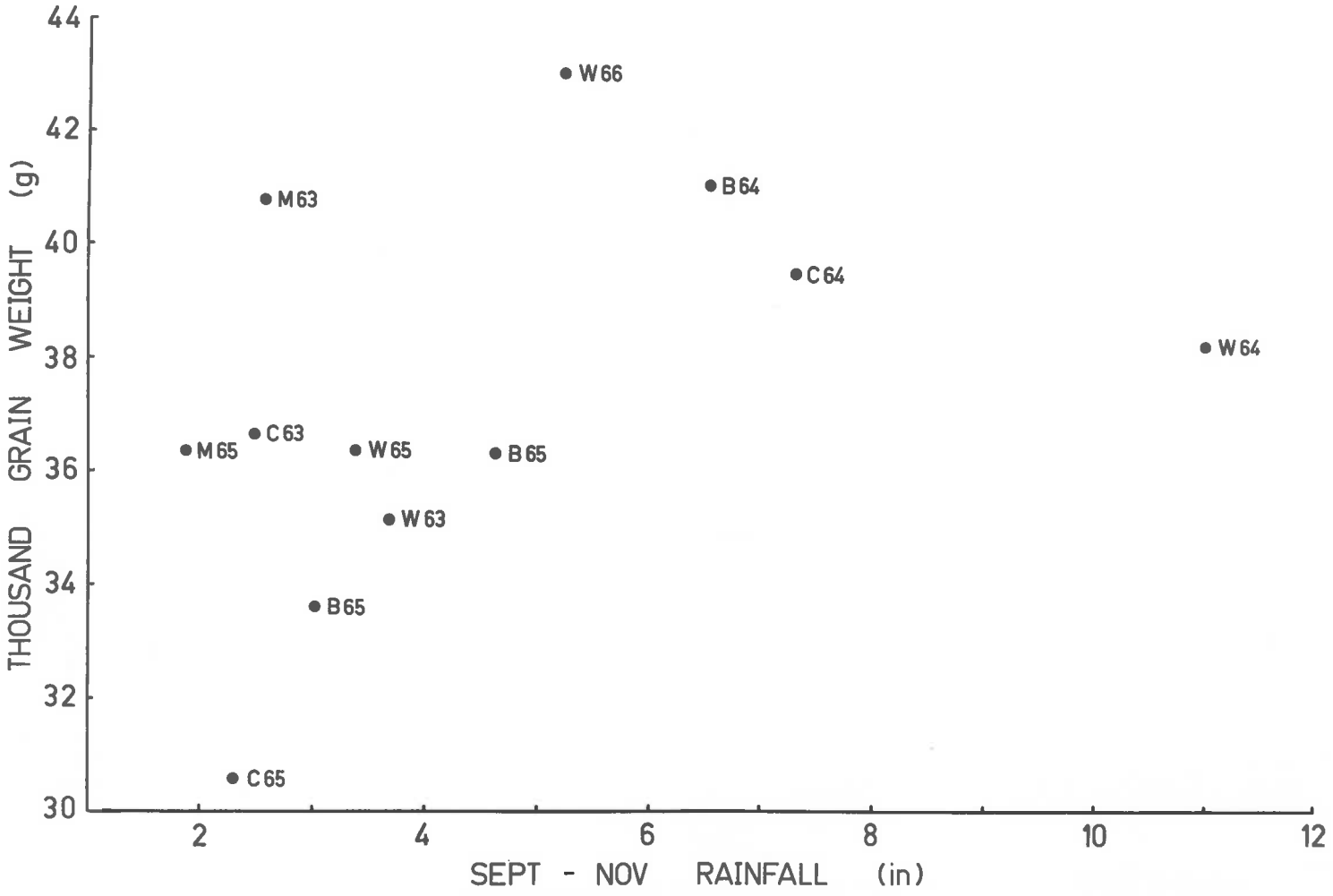

GRAIN YIELD (g/plot)
450
400
350
300
250
200
150
100
50
W66
M63
B64
B63
C63
W65
W64
B66
M66
C64
C66
B65
M65
C65
W63
W63
8
12
16
20
24
28
APRIL - NOV RAINFALL (in)

Consequently land preparation was delayed and the trial could not be sown until early August. Subsequently a dry, early finishing spring restricted crop growth and yield. An arbitary estimate of the moisture available to the crop could be taken as the rainfall in the four months August to November plus one in. (i.e. 7.45 in). Even if soil water storage was as high as three in. it would not greatly alter the correlation. If the yield of the trial is plotted against this figure it falls into line with the other 13 trials (Fig. 2). On the other hand, in 1964, the trial at the Waite Institute was sown earlier than normal and experienced above average rainfall for the remainder of the season. This resulted in heavy growth which eventually became badly lodged. In consequence the yield potential was not achieved and grain filling was restricted; the conditions were in fact above the optimum for barley production in South Australia.

Over 11 trial sites thousand grain weight showed a correlation with yield ($r = .71^*$); as a component of yield this is not unexpected. The only other significant correlation was with the April-November rainfall when the two anomalous sites are omitted ($r = .69^*$). The correlation with spring rainfall just fails to reach significance even if Waite 1964 is omitted ($r = .55$), but from a graph of the data (Fig. 3) it can be seen that, without this site, a slightly curvilinear relationship may exist. This would be reasonable if grain filling, to an asymptotic value for grain size, were dependent on spring rainfall. However, the well filled grains at Minlaton 1963 may indicate that soil water from earlier rainfall could have mitigated the stresses of a dry spring; at that trial site there is a clay subsoil with good water-retention. On the other hand the association between grain size,

FIGURE 3

The relation between grain size and spring rainfall at 12 sites over 4 years.


44
42
40
38
36
34
32
30
THOUSAND GRAIN WEIGHT (g)
W66
B64
M63
C64
W64
M65
C63
W65
B65
W63
B65
C65
2
4
6
8
10
12
SEPT - NOV RAINFALL (in)

seasonal rainfall and yield indicates that size is also dependent on factors that earlier determine yield potential.

Grain nitrogen content shows a negative, but non-significant, correlation with yield, thousand grain weight and April-November rainfall, and a significant negative correlation with spring rainfall ($r = -.71^{**}$). This correlation becomes ($r = -.87^{**}$) if Waite 1964 is omitted from the calculation. A graph of the data (Fig. 4) shows that the latter may not be anomalous if Waite 1966 is included and that the Waite Institute, with its heavier soil type is prone to producing a higher grain nitrogen than the other three sites. Although decreases in grain nitrogen may be due, in part, to increases in grain size the correlation ($r = -.54$) is not sufficient to account for all the variation. As has already been discussed spring rainfall does not account for all the variation in grain size, but precipitation during the September to November period obviously does have an important influence in the grain nitrogen content.

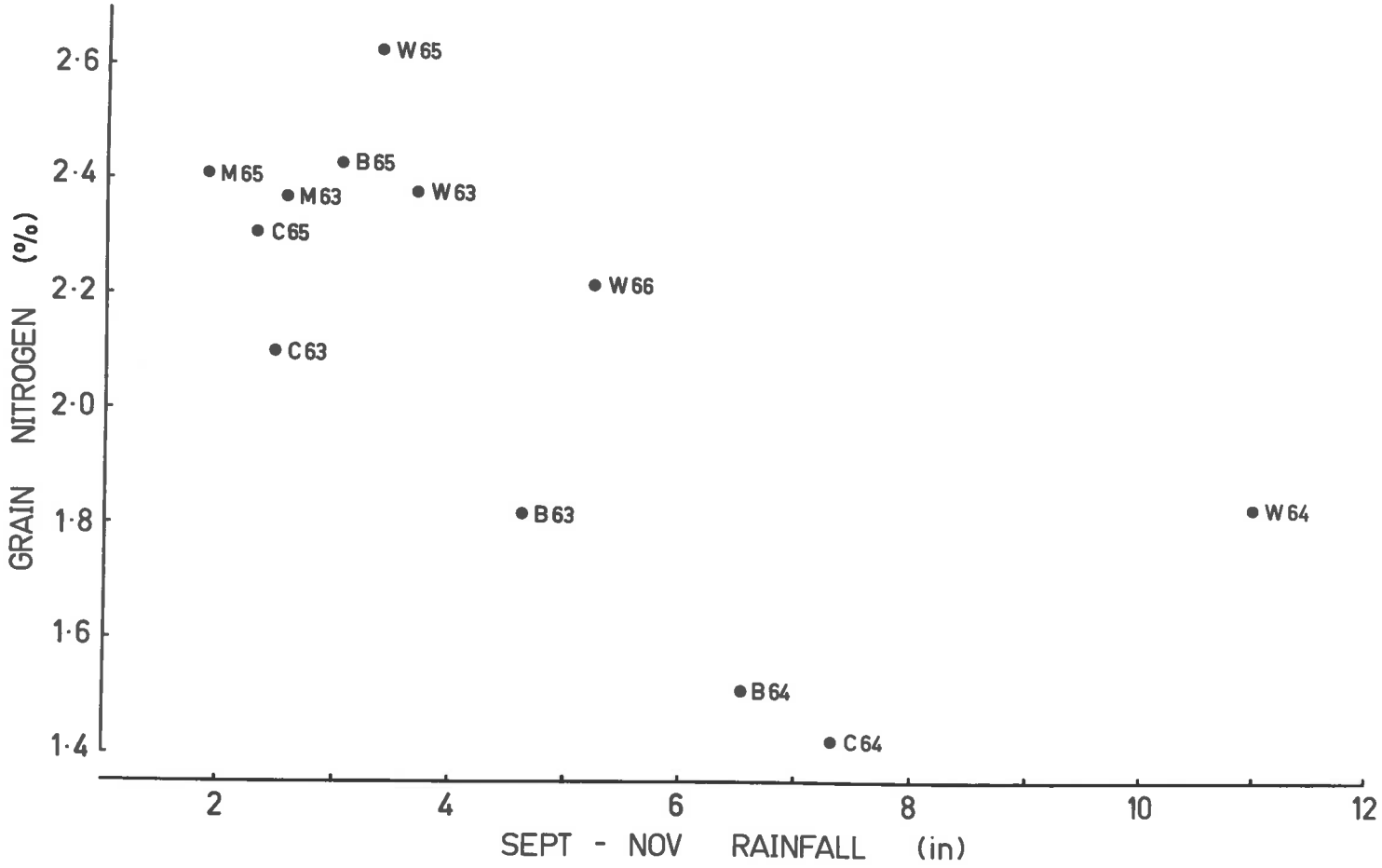
A considerably more detailed investigation would be required to confirm these seasonal influences on grain quality in barley. The result presented herein providesan introduction to the types of environment under which the present study of genotypic differences in malting quality was conducted.

2. Genotypic variation

Average differences in maturity, yield, grain size and grain nitrogen content of the 40 varieties will be presented in order to illustrate the range of genotypic material used in this study. This will be followed by a detailed consideration of the environmental and genotypic variation encounted in all the grain and malt characters

FIGURE 4

The relation between grain nitrogen content and spring rainfall at 12 sites over 4 years.


GRAIN NITROGEN (%)
2·6
2·4
2·2
2·0
1·8
1·6
1·4
W65
B65
M65
M63
W63
C65
W66
C63
B63
W64
B64
C64
2
4
6
8
10
12
SEPT - NOV RAINFALL (in)

investigated. [Note: Genotype and variety are treated as synonymous terms and used according to custom. Thus in the partitioning of variances genotype is preferred to variety which is generally used elsewhere.]

The geographic origins and parental details of the varieties have already been presented in the section on experimental material (Table 8, page 77). Table 14 contains further details of their comparative performance under South Australian conditions.

The maturity of each variety is given as the number of days after September 1 on which earing occurred. Earing was taken as the date on which at least one in. of awn had emerged on 75% of plants in a plot. The value for the data of earing, is the mean of results from three trials (Clinton 1963, Waite 1964 and Bundaleer 1965) all of which were sown in June. Date of earing is dependent on sowing date and winter temperature, two factors which would vary from site to site, and photoperiod, which although interacting with the former variables, follows a similar pattern over all sites in the area under consideration.

The earliest varieties, those earing less than 35 days after September 1, are in general adapted to a Mediterranean type of climate where decreasing rainfall and increasing temperature in the spring cause, through extreme moisture stress, the rapid senescence of annual crops. Thus the very early variety Noyep (19 days) is adapted to the driest (< 15 in annual rainfall) parts of the South Australian cereal belt where there is little effective rainfall after September. At the other extreme the varieties Beka and Research M.R. (36 days) are adapted to the milder and longer rainfall season areas of central

TABLE 14

AVERAGE PERFORMANCES OF 40 VARIETIES

	VARIETY	EARING DAYS * FROM SEPT 1	YIELD (G/PLOT) N=15	1000 GRAIN WEIGHT N=11	GRAIN NITROGEN CONTENT N=11
1	DOMEN	40	231	36.3	2.17
2	FREJA	42	298	33.8	2.10
3	RIKA	44	263	32.5	2.11
4	BONUS	44	281	33.4	2.14
5	RIGEL	44	285	34.1	2.08
6	DELTA	40	308	34.7	2.12
7	CAMBRINUS	40	296	34.9	2.08
8	EMIR	42	311	31.6	2.11
9	IMPALA	40	312	31.4	2.10
10	G/SPRATT	48	199	32.8	2.19
11	PROCTOR	46	245	30.9	2.01
12	MAYTHORPE	44	275	34.1	2.10
13	BALDRIC	42	307	34.4	2.15
14	BEKA	36	295	33.0	1.97
15	CERES	42	294	35.2	2.12
16	PORT 2 ROW	34	230	36.7	2.08
17	BOA FE	46	231	32.0	2.30
18	MORGENROT	44	253	33.8	2.10
19	HAISA II	42	236	33.6	2.16
20	PIROLINE	40	262	32.9	2.11
21	UNION	40	271	34.9	2.04
22	JULIANE	44	255	34.1	2.07
23	KANKYO	28	248	39.8	2.03
24	HANNA	28	264	37.9	2.05
25	GOLDFOIL	46	211	32.0	2.21
26	COMPANA	32	253	39.0	2.13
27	L O GLUME	32	242	40.3	2.15
28	PRIORS	32	265	38.1	2.05
29	PRIOR A	32	262	38.1	2.11
30	NOYEP	19	240	39.9	2.18
31	RESEARCH M R	36	262	36.1	1.94
32	RESIBEE	34	261	38.7	1.99
33	CPI 18197	28	298	43.0	2.21
34	CPI 18198	32	279	50.8	2.12
35	WAITE 775	26	328	44.9	2.00
36	CI 3576	26	341	43.6	2.07
37	RETU	26	317	43.9	2.00
38	G H SINAI	32	291	44.2	2.18
39	CI 5611	50	245	42.1	2.22
40	WHITE SMYRNA	40	192	39.0	2.18
	LSD 1 %		29	1.4	.09

*AVERAGE DATE FROM 3 TRIALS, CLINTON 63, WAITE 64, BUNDALEER 65

Portugal and southern Victoria respectively. The three early non-Mediterranean varieties Kankyo (28 days) Compana (32 days) and Long Outer Glume (32 days) are probably derived from a dry Continental climate where although spring sowing is the rule rapid development to escape summer drought is essential in grain crops. Hanna (28 days) also appears to fit into this category.

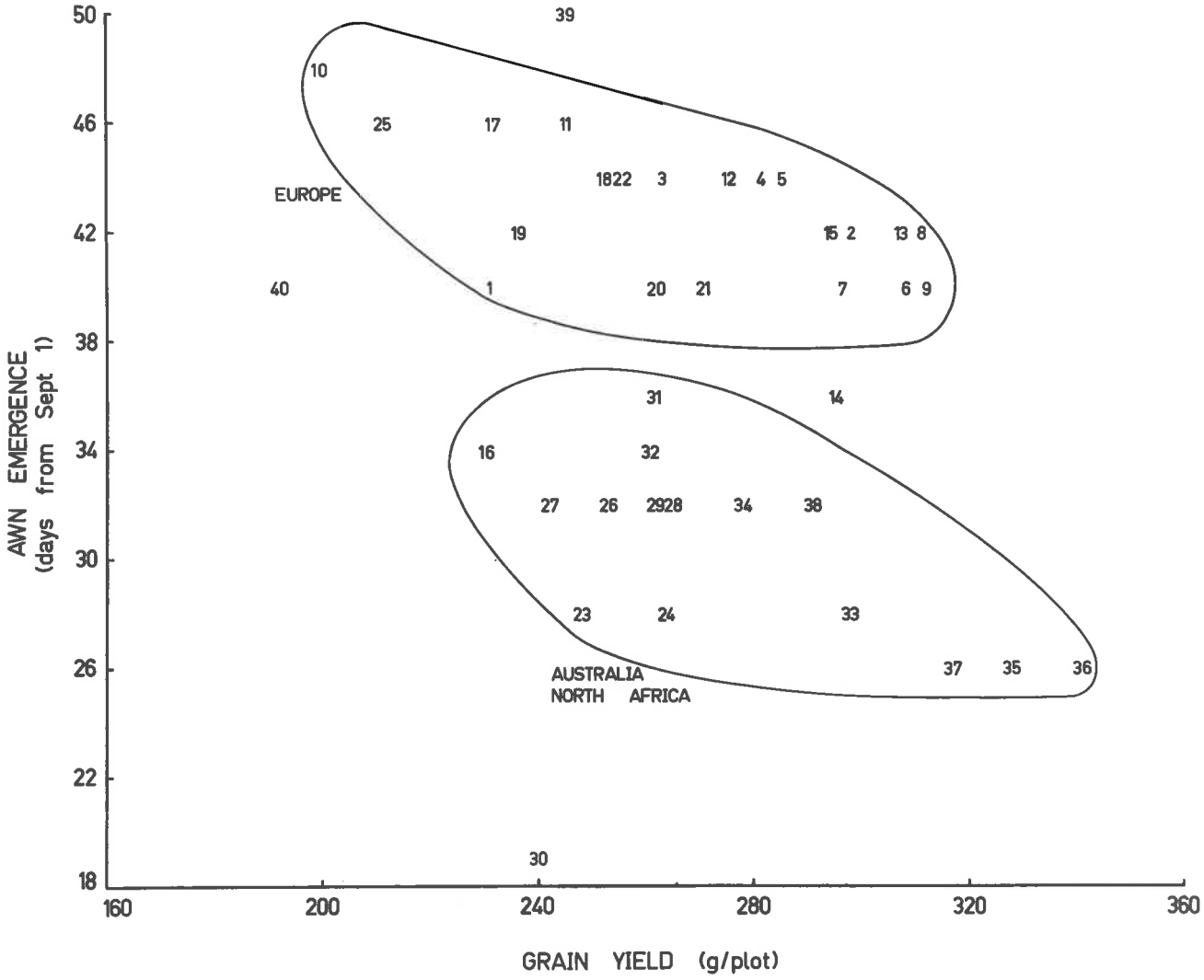
The European varieties are all relatively late maturing; more than 40 days after September 1. In consequence, under South Australian conditions, their grain formation is liable to be restricted by moisture shortage at sites or in years in which spring rainfall is low and their performance is likely to be more erratic than that of earlier maturing varieties. The two Turkish varieties, White Smyrna (40 days) and Turk (50 days) although from the Mediterranean area are late maturing. The latter variety overcomes this disadvantage to some extent by very rapid grain formation, but both varieties are probably adapted to a rather specific environment and do not perform well elsewhere. The Portuguese variety Boa Fe (46 days) is also late maturing but originates from mid-European stock.

From Figure 5 it is apparent that average yield performance is to some extent dependent on maturity. The correlation ($r = -.30$) is not significant because there are considerable differences in the inherent yield potential of the material under study. Nevertheless the earlier varieties are in general at an advantage under the climatic conditions of southern Australia for reasons mentioned above. The association between yield and maturity is clearer if the varieties are divided into two sub-groups, 1. Europe and 2. Mediterranean (including Australia and Continental). The anomalies to this grouping

FIGURE 5

The relation between grain yield and maturity for 40 varieties.

(For key to varietal numbering see Table 8, page 77a)


AWN EMERGENCE
(days from Sept 1)
50
46
42
38
34
30
26
22
18
160
200
240
280
320
360
GRAIN YIELD (g/plot)
EUROPE
AUSTRALIA
NORTH AFRICA
39
10
25
17
11
1822
3
12
4
5
19
15
2
13
8
40
1
20
21
7
6
9
31
14
16
32
27
26
2928
34
38
23
24
33
37
35
36
30

are the two Turkish varieties, already discussed, and Noyep (30) which is the earliest variety. Noyep is liable to lose grain by shedding and probably has a higher yield potential than that obtained but its earliness also restricts its potential for tillering and hence its inherent yielding ability. Beka (14) falls between the two groups reflecting its French origin and Portuguese adaptation. [For Figure 5 and subsequent figures each variety is indicated by the number originally assigned to it in Table 8.]

On the other hand there is a good correlation ($r = -.69^{***}$) between maturity and an average thousand corn weight (Fig. 6). This may reflect the tendency for the later varieties to be restricted, by moisture stress, in the grain filling. However the average size of Proctor (11) (30.9 g) and Union (21) (34.9 g) are smaller than those obtained, 33.6 and 37.8 respectively, by Kirsop and Pollock (1961) under British conditions and this may indicate that long term selection for malting types in Europe has favoured the smaller grain varieties; the non-European varieties have larger grains and also a greater diversity in grain size. They range from CPI. 18198 (34) (50.8 g) to Research M.R. (31) (36.2 g) which is just overlapped by the largest European variety Domen (1) (36.3 g).

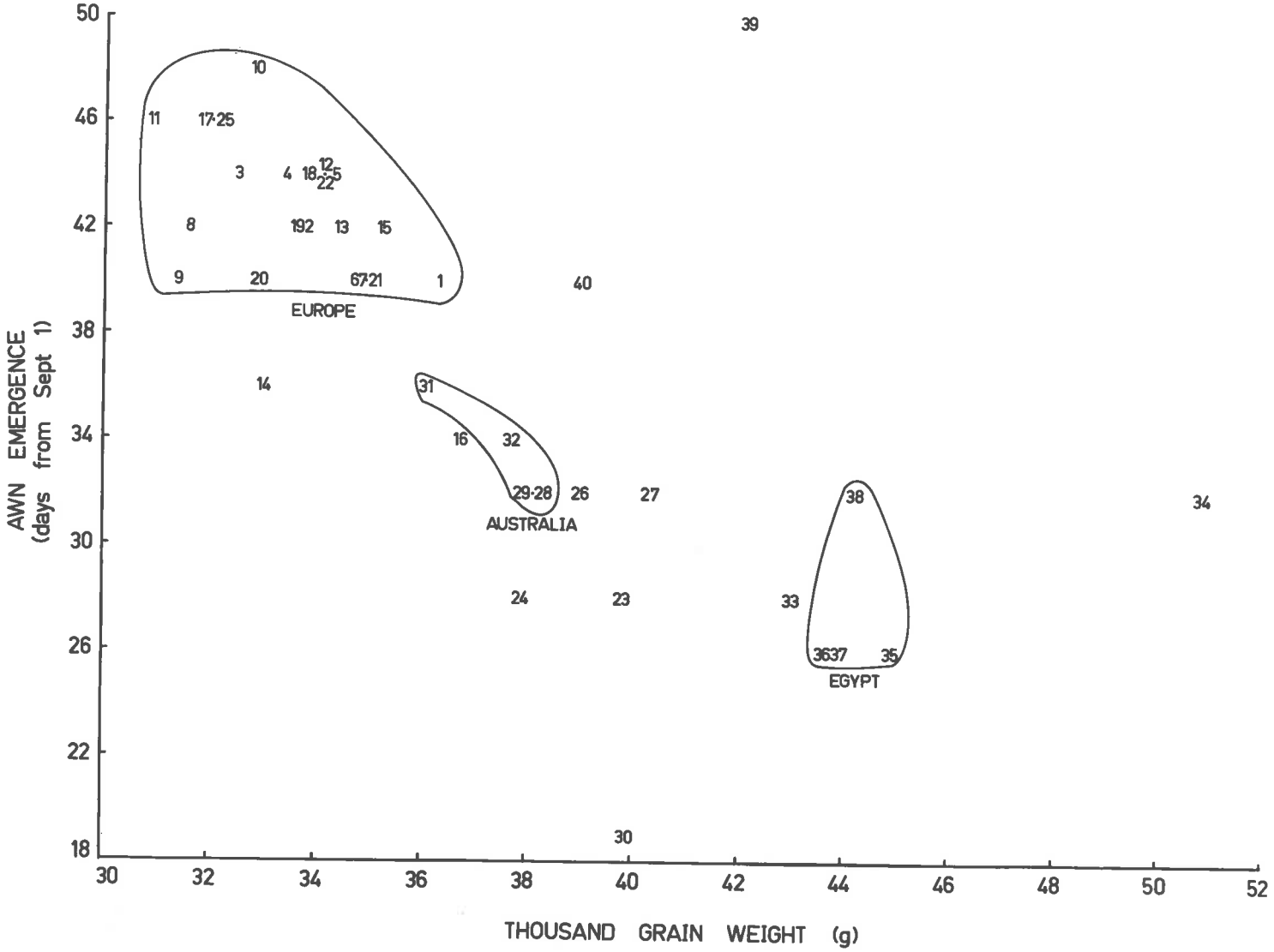
In contrast to the above there is no apparent relationship between maturity and average grain nitrogen content ($r = .28$). Neither is there any grouping of varieties in the latter; the range of the European and non-European varieties is similar.

3. Genotype-environment interaction

In the following sections details are given of the effect of genotype-environment interaction for each character studied. For

FIGURE 6

The relation between grain size and maturity for 40 varieties.


AWN EMERGENCE
(days from Sept 1)
50
46
42
38
34
30
26
22
18
30
32
34
36
38
40
42
44
46
48
50
52
THOUSAND GRAIN WEIGHT (g)
EUROPE
AUSTRALIA
EGYPT
10
11
17·25
3
4
18
12
25
22
8
192
13
15
9
20
67·21
1
40
39
14
31
16
32
29·28
26
27
34
38
24
23
33
3637
35
30

insoluble carbohydrate, steep time and the five malt characters the analyses of variance and adaptation analyses have been obtained from the combined data of the six trials listed in Table 10 (page 81). For yield, thousand grain weight and grain nitrogen content, since data were available from a larger number of trials and replicates, these characters are, for the sake of greater accuracy, considered over the full range of sites; 15 for yield and 11 for thousand grain weight and grain nitrogen content.

(a) Grain yield

The relevant portion of the combined analysis of variance is given in Table 15. The environmental mean square was very highly significant, far above the .1% level, and environment accounted for 58.6% of the total variation. This is a reflection of the wide range of environments covered by the 15 trials and further emphasises the extreme variability of the environment of the South Australian cereal belt. Site mean yields (Table 13) showed a seven-fold range from 64.3 g/plot at Waite 1963 to 450.6 g/plot at Waite 1966.

The replicate mean square was also very highly significant; inspection of the original data indicates that replicate effects were fairly variable in most of the trials. This was most probably due to inherent soil differences and was encountered in all characters.

The mean square attributable to genotypes although considerably smaller than those for environment was still significant at the .1% level. This is to be expected in view of the diversity of genotypes and their two-fold range in yield (Table 14).

The interaction between genotypes and environments was also significant at the .1% level. Partition of the interaction mean square

TABLE 15

Mean squares from Analysis of Variance of three grain characters for 40 varieties grown in fifteen or eleven trials

	YIELD		THOUSAND GRAIN WEIGHT		GRAIN NITROGEN CONTENT	
	D.F.	Mean Squares	D.F.	Mean Squares	D.F.	Mean Squares
Environments	14	2014120 ***	10	1542.400 ***	10	26.2600 ***
Replicates within environments	45	40748 ***	33	46.190 ***	33	.4374 ***
Genotypes	39	70625 ***	39	914.100 ***	39	.2504 ***
Genotype: environment interaction	546	16452 ***	390	21.634 ***	390	.0743 ***
Linear regressions	39	35571 ***	39	41.418 ***	39	.1879 ***
Deviations from regressions	507	14981 ***	351	19.435 ***	351	.0616 ***
Residual	1755	3594	1287	5.839	1287	.0273

For linear regressions variance ratios were calculated against the deviations mean squares.
For all other components of variation the residual mean squares were used.

showed the component for linear regression to be very highly significant indicating that the genotypic response to environment could be accounted for by the regression of individual yields on site mean yields. However the deviation from regressions was also very highly significant so that the response of at least some varieties could not be accurately accounted for by a linear relationship. This deviation mean square was examined for each genotype (S^2d) and tested for significance against the residual mean square. Only four varieties had significant deviations CI. 3576, CI. 3726, and Waite 775 from Egypt, and Turk from Turkey. Inspection of the original plot yields suggested that this was due to the relatively poor performance of these varieties at Minlaton in 1963, probably caused by lodging, and for the Egyptian varieties relatively good performance under the dry conditions in 1965 at Clinton and Waite.

Details of the yield performance and response to environment for each genotype are given in Appendix 2; similar details for all other characters are listed in subsequent appendices. The three indices of performance were; mean yield over all sites ($\bar{x}$), regression coefficient of individual yield against site mean yield (b) and the standard error of the regression coefficient which was derived from S^2d. (See also section on Adaptation Analysis in Materials and Methods, page 88). These data are also presented graphically in Figure 7 where the mean yield and regression coefficient of each genotype has been plotted on a two dimensional scatter diagram whilst those varieties with a significant S^2d have been indicated on the graphs.

In order to clarify the interpretation of these data the individual performance of four contrasting varieties is presented in Figure 8,

FIGURE 7

The relation between mean yield over 15 sites and the stability of yield (regression coefficient) for 40 varieties.

(Circled varieties had a significant deviation mean square).

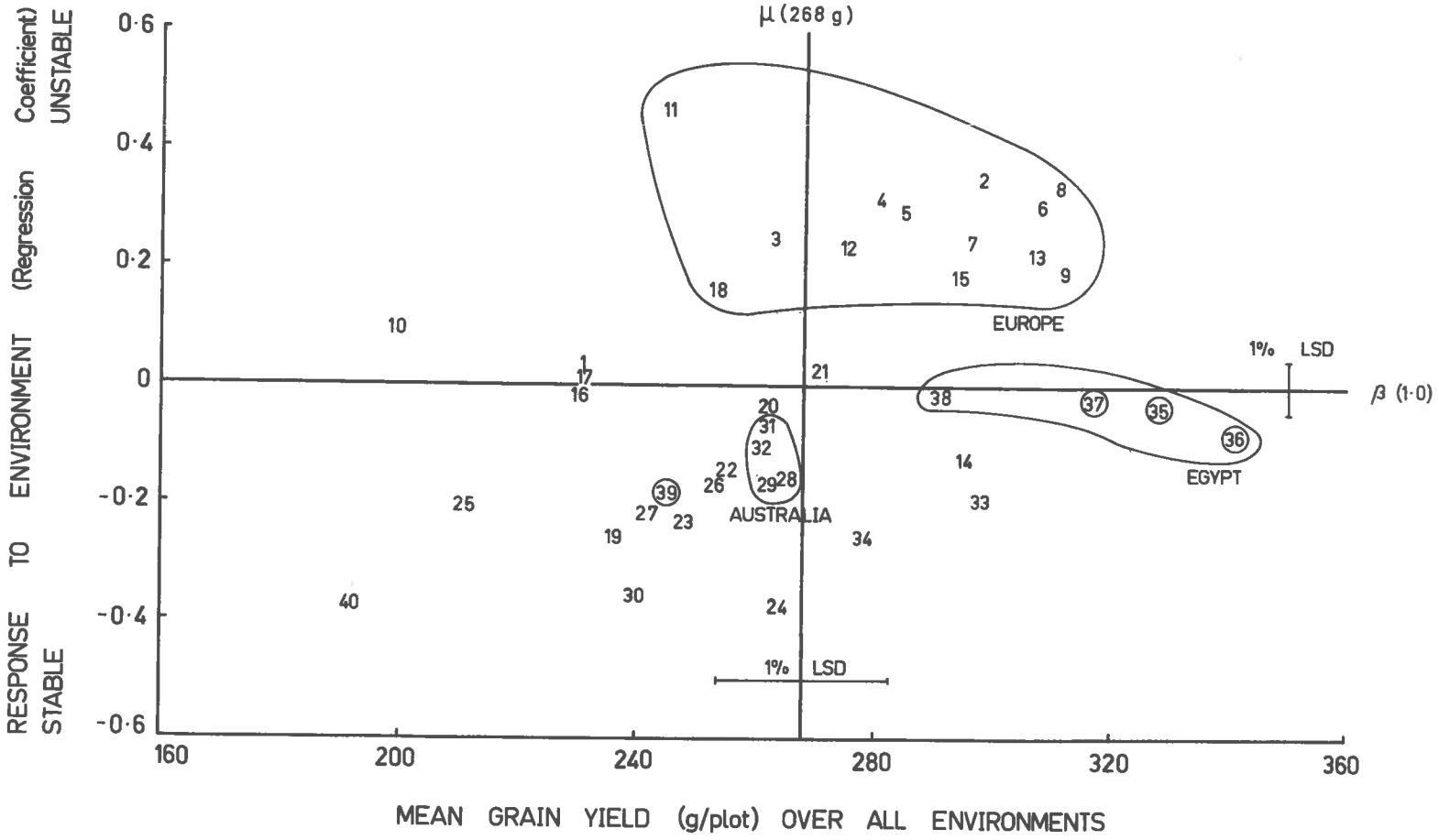
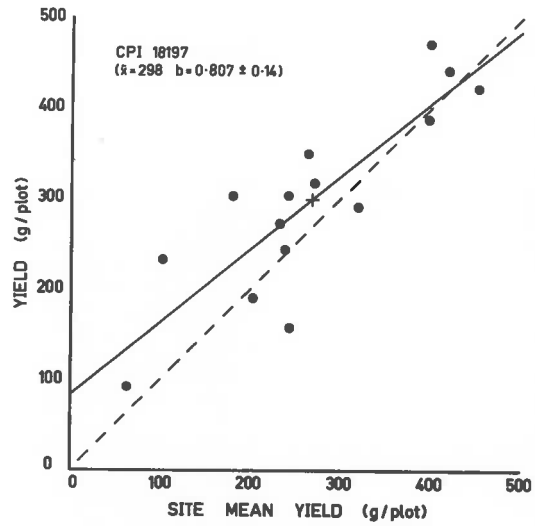
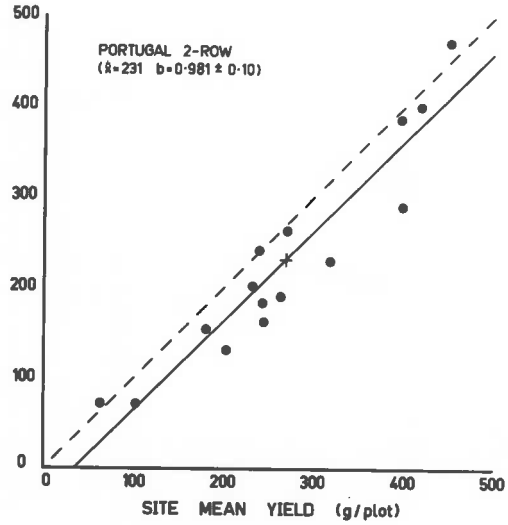
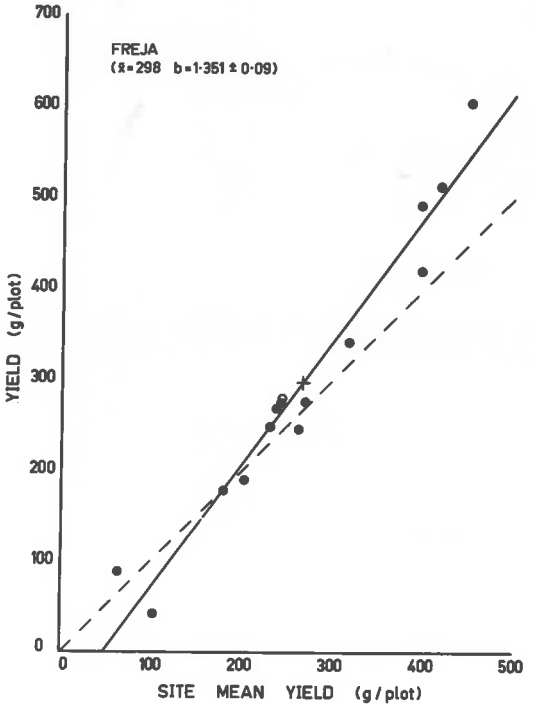

RESPONSE TO ENVIRONMENT (Regression Coefficient)
UNSTABLE
STABLE
0·6
0·4
0·2
0
-0·2
-0·4
-0·6
μ (268 g)
β (1·0)
1% LSD
1% LSD
EUROPE
EGYPT
AUSTRALIA
160
200
240
280
320
360
MEAN GRAIN YIELD (g/plot) OVER ALL ENVIRONMENTS

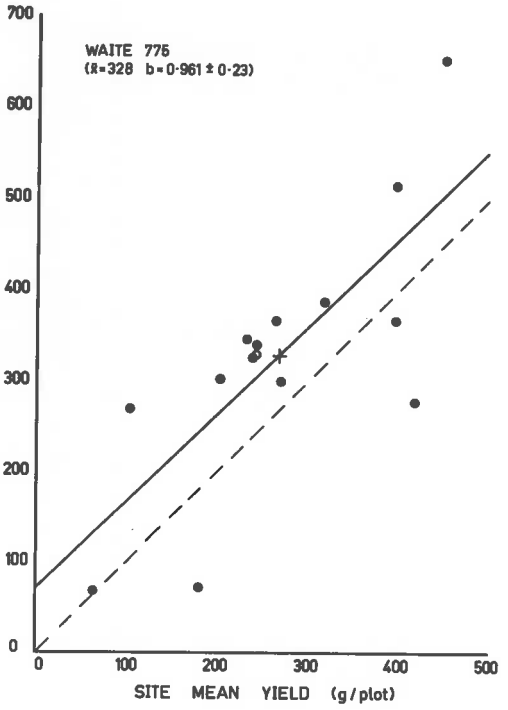
FIGURE 8

The relation between site mean yield and the individual yields of 4 varieties over 15 sites.


CPI 18197
(R=298 b=0·807 ± 0·14)
YIELD (g/plot)
SITE MEAN YIELD (g/plot)
0
100
200
300
400
500


PORTUGAL 2-ROW
(R=231 b=0·981 ± 0·10)
SITE MEAN YIELD (g/plot)
0
100
200
300
400
500


FREJA
(R=298 b=1·351 ± 0·09)
YIELD (g/plot)
SITE MEAN YIELD (g/plot)
0
100
200
300
400
500
600
700


WAITE 775
(R=328 b=0·961 ± 0·23)
SITE MEAN YIELD (g/plot)
0
100
200
300
400
500
600
700

which will be considered first. Thus Portugal 2-row (16) and Waite 775 (35) were markedly different in mean yield although they had a similar, near average, response to environmental change. However in the former variety the yields at each site showed only a slight scatter about the regression line (low S^2d) whilst those in the latter variety were markedly scattered. The performance of Portugal 2-row could be reliably predicted from the regression coefficient whereas that of Waite 775 could not. In this context Eberhart and Russell (1966) would have termed the two varieties stable and unstable respectively.

The other two varieties in Figure 8, CPI. 18197 (33), Freja (2) have yielded similarly when averaged over all sites but showed different reactions to environmental change. Freja gave high yields at the best sites but was adversely affected at the drier, low yielding sites; it was thus very sensitive to environmental change. In absolute terms and as originally applied by Finlay and Wilkinson (1963) Freja (2) had a regression coefficient well above 1.0; in relative terms as a deviation from the average population coefficient it had a large positive coefficient as depicted in Figure 7. In contrast, CPI. 18197 (33) was relatively insensitive to environmental change and only showed a slight increase in yield over the range of sites. In absolute terms it had a coefficient less than 1.0 which in relative terms became a negative coefficient.

Returning to Figure 7 which summarises, for the 40 varieties, their comparative yield performance over the range of environmental conditions. The correlation between mean yield over all sites and regression coefficient although just significant ($r = .38^*$) was not

large enough to indicate a strong association between the two indices. The data of other authors (Finlay and Wilkinson, 1963; Eberhart and Russell, 1966; Perkins and Jinks, 1968a) when analysed on a natural scale show that there is a tendency for these two aspects of performance to be correlated. The present result suggests that an association between the two indices need not necessarily occur.

On the graph the varieties showed certain groupings which have been indicated. Thus the majority of European varieties had average to above average yields and were relatively sensitive to environmental change; as depicted for Freja (2) in Figure 8. This is as would be expected of varietal material developed in the comparatively moist conditions of Europe growing under the harsher and potentially drier conditions of southern Australia. The highest yielding varieties in this group, all recent releases, approached the yield performance of the highest yielding of the 40 varieties. They therefore provide an important source of parental material for local breeding programmes. There are, however, several European varieties which fell outside the group. The apparently greater stability of Goldthorpe Spratt (10), Domen (1), Union (21), Juliane (22), and Haisa II (19) is not easy to explain, but Finlay and Wilkinson (1963) did find that varieties from Central Europe, amongst which the last three are included, were more stable than those from the maritime countries of Western Europe. Piroline (20) may also qualify under that heading but its comparative earliness and rapid ripening are contributory factors to its stability. The extreme stability of Hanna (24) is consistent with its geographic origin discussed earlier. The other three European varieties Boa Fe (17) Portugal 2-row (16) and Beka (14) showed a stability consistent with

their adaptation to the cereal growing areas of Portugal.

The Australian varieties were of average yield and were fairly insensitive to environmental change. Noyep (30) was even less sensitive than this group due no doubt to its extreme earliness.

The potential of the Egyptian varieties is readily evident; a high average yield allied to a stability akin to the Australian material. The remaining varieties, of Mediterranean or Continental origin showed average stability but at a lower level of yield.

(b) Thousand grain weight

The analysis of variance for this character (Table 15) showed that all components of variation were very highly significant. However, in contrast to grain yield and also grain nitrogen content the mean square attributable to genotypes was large and approached the same order of magnitude as the environmental mean square. In other words varieties and trial sites had nearly comparable effects on the variation in this character. In a subsequent section the relative influence of these two factors, for all the characters investigated, will be assessed in terms of variance components and heritability estimates (i.e. the ratio of genotypic to total variance). The closeness of these two mean squares is, in part, a reflection of the varietal and environmental range in grain size. Thus the latter varied from 30.6 grams at Clinton 1965 to 41.1 grams at Bundaleer 1964 (Table 13) whilst the former was spread from Proctor averaging 30.9 grams to CPI. 18198 with 50.8 grams (Table 14).

The genotype-environment interaction and its components; interaction due to linear regressions and deviations from those regressions, were all very highly significant. Three varieties had significant

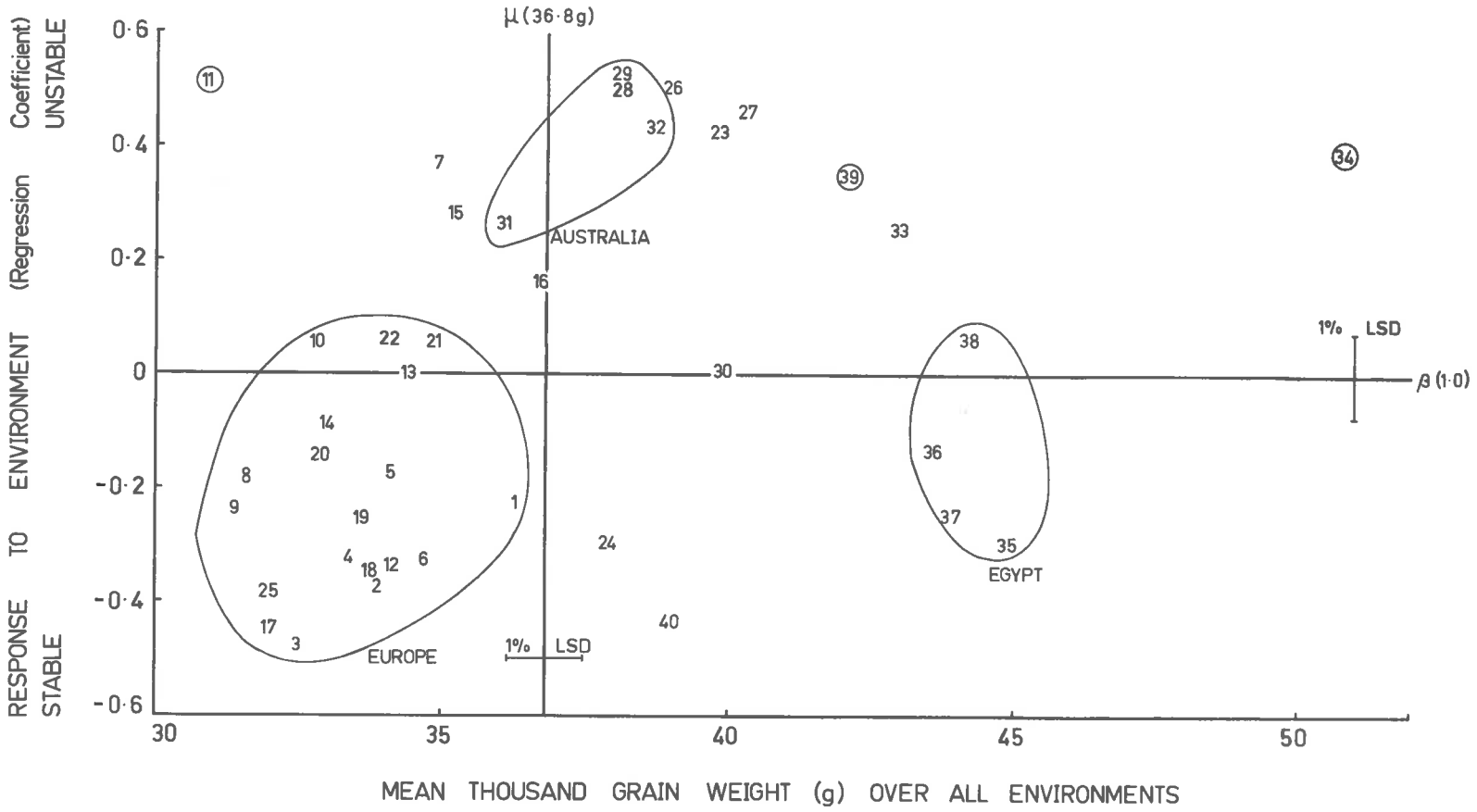
individual deviation means squares; Proctor (11) and CPI. 18198 (34) the varieties at the two extremes of grain size, and the Turkish variety CI. 5611 (39). This variety was also erratic in its yielding ability and as noted early is probably adapted to a specific environment. Proctor is late maturing and is considerably affected by dry seasons but apparently this influence was not consistent with regard to grain size. The inconsistent grain filling of CPI. 18198 may be a property of its inherently large grain which could, because of the large amount of photosynthate required, be most sensitive to day to day stresses during the ripening period.

The scatter diagram (Figure 9) of individual means and regression coefficients for thousand grain weight shows only a weak association between the two indices ($r = .34^*$). The majority of European varieties are small grained and relatively insensitive to environmental change. The lack of correlation between size and sensitivity seems to argue against the possibility that small grained varieties are easier to fill and thus are less influenced by environmental change. Further, although the European varieties are late maturing they cannot be at a consistent disadvantage because there is no correlation between maturity and sensitivity. In contrast, the Egyptian varieties have a larger grain, are early maturing, but are also relatively insensitive to environmental change. The Australian varieties, other than Noyep, with an average grain size, were relatively sensitive, as were the remainder of the Mediterranean and Continental types.

Lack of readily explicable relationship between grain size and response to environmental change probably indicates that several

FIGURE 9

The relation between mean grain size over 11 sites and the stability of grain size for 40 varieties.


RESPONSE TO ENVIRONMENT (Regression Coefficient)
UNSTABLE
STABLE
0·6
0·4
0·2
0
-0·2
-0·4
-0·6
μ(36·8g)
β(1·0)
1% LSD
1% LSD
AUSTRALIA
EUROPE
EGYPT
11
34
39
30
35
40
45
50
MEAN THOUSAND GRAIN WEIGHT (g) OVER ALL ENVIRONMENTS

complex influences are involved. The wide range of types present also shows that selection for specified size and sensitivity would be feasible throughout this range.

(c) Grain nitrogen content

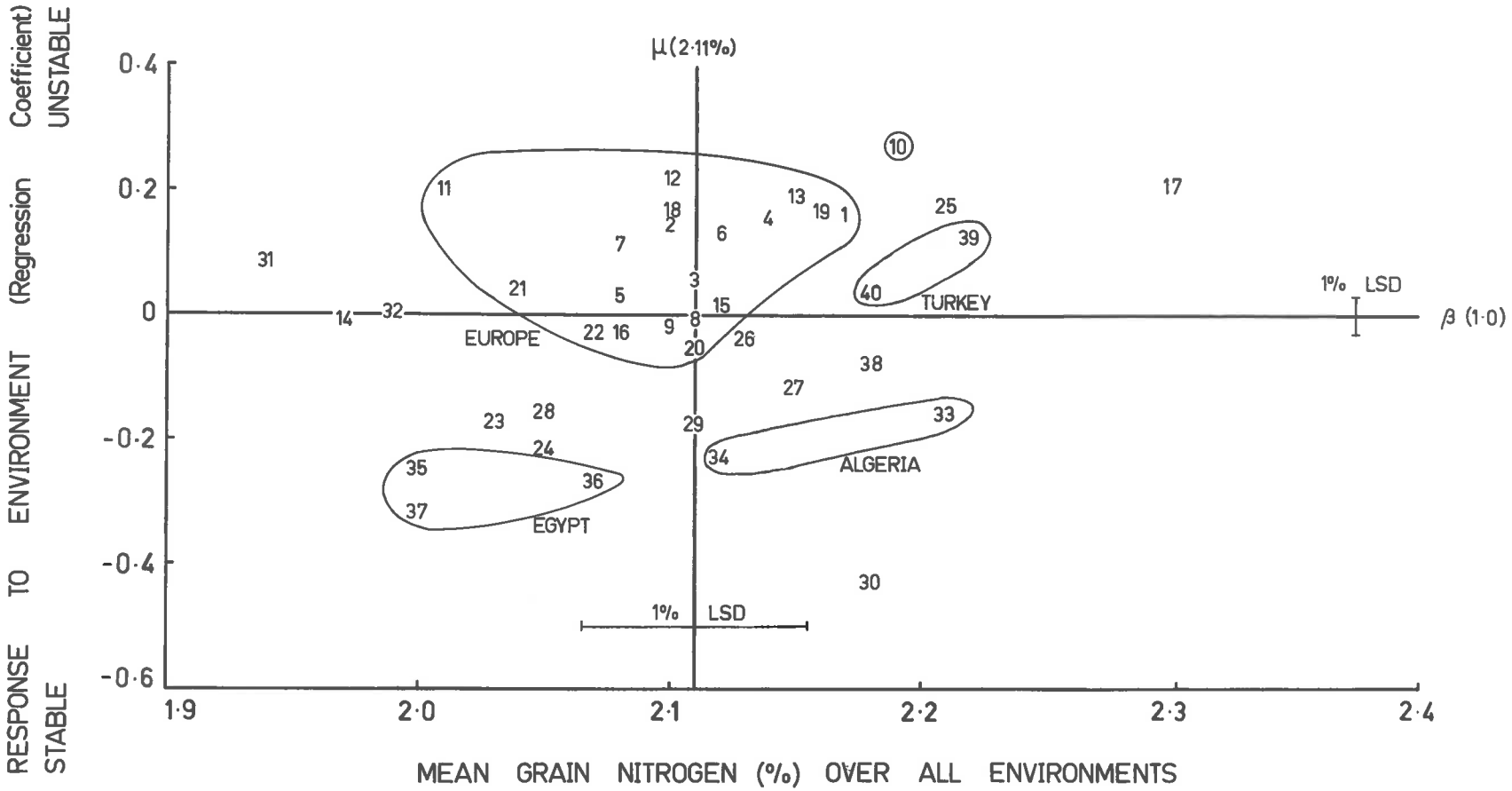
As with the previous two characters all components of variation were very highly significant (Table 15). The environmental variance is by far the largest, which agrees with the conclusion of earlier workers that this factor has the greatest influence on grain nitrogen content. However, varietal differences do exist and although the range in percentages was small, from Research M.R. at 1.94% to Boa Fe at 2.30%, the 1% level L.S.D. of .09 implies that there were a considerable number of significant differences. [Note: For grain nitrogen and several other characters the results are given as percentages; since these cover only a small range angular transformation before analysis was not considered appropriate.]

The components of genotype-environment interaction were both significant at the .1% level. In contrast to grain yield and grain size the variance ratio for interaction due to linear regressions was larger than that for deviations from the regressions. This high proportion of linearity in response to environmental change was reflected in the low standard errors of the individual regressions (see Appendix 3) whilst only one variety, Goldthorpe Spratt (10), had a significant deviation mean square. The L.S.D. between regressions was only .06 at the 1% level so that quite small differences in varietal response to environmental change were statistically significant.

In the graph (Figure 10) of the two indices of performance some

FIGURE 10

The relation between mean grain nitrogen content over 11 sites and the stability of grain nitrogen for 40 varieties.

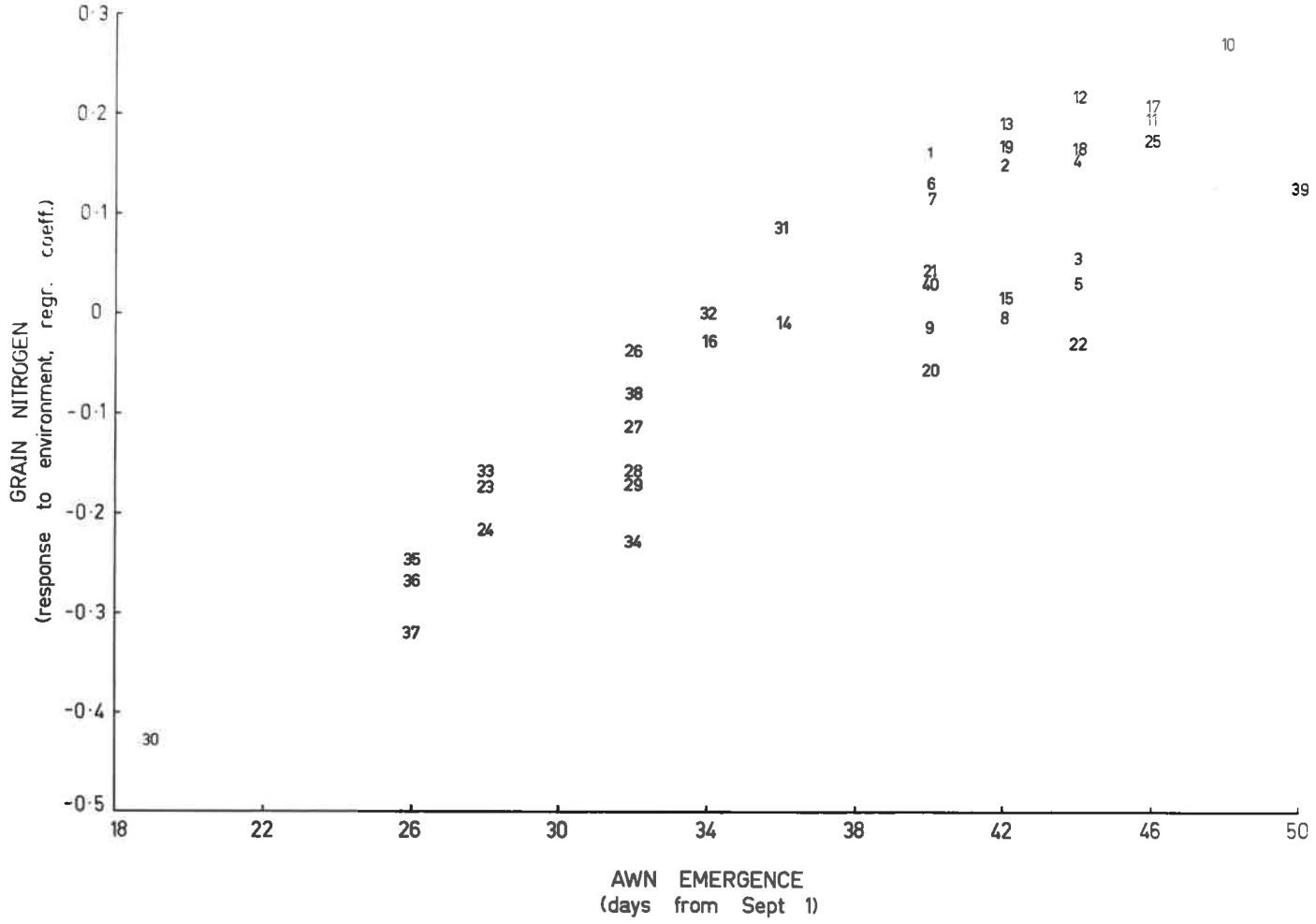

RESPONSE TO ENVIRONMENT (Regression Coefficient)
STABLE
UNSTABLE
μ(2·11%)
0·4
0·2
0
-0·2
-0·4
-0·6
1·9
2·0
2·1
2·2
2·3
2·4
β (1·0)
1% LSD
1% LSD
EUROPE
TURKEY
ALGERIA
EGYPT
MEAN GRAIN NITROGEN (%) OVER ALL ENVIRONMENTS

groupings are apparent. The European varieties tended to have an average grain nitrogen content and an average to fairly sensitive response to environmental change. The two Turkish varieties showed a similar response at a higher level of nitrogen content whereas the other Mediterranean varieties as well as the Australian and Continental varieties, were less sensitive. The Egyptian varieties, other than Glaucous Head Sinai (38) had a below average nitrogen content and the two Algerian varieties were above average. The three varieties with the lowest grain nitrogen contents, Beka (14), Resibee (32) and Research M.R. (31) include two that were derived from Research a variety that was specifically selected for ≡ low nitrogen as a means of selecting for improved malting quality (Raw personal communication). The variety with the lowest percentage among these three was not, however, significantly different from the lowest European variety Proctor (11), nor from Kankyo (23), Waite 775 (35) and Retu (37). Although the former has excellent malting quality the last three are very poor in this respect. Selection for grain nitrogen content would therefore, provide no guide to potential malting quality within this set of varieties.

The lack of an association between varietal mean and regression coefficient (r = .26) suggests that independent selection of either index should be possible. However, there was a strong association between maturity and regression coefficient (r = .90***). As can be seen from Figure 11, the later maturing varieties were more sensitive to environmental change with regard to grain nitrogen content. In other words, varieties, which under South Australian conditions, are more likely to be subjected to a restriction in grain filling,

FIGURE 11

The relation between maturity and grain nitrogen stability for 40 varieties.


GRAIN NITROGEN
(response to environment, regr. coeff.)
0·3
0·2
0·1
0
-0·1
-0·2
-0·3
-0·4
-0·5
18
22
26
30
34
38
42
46
50
AWN EMERGENCE
(days from Sept 1)
10
12
17
11
13
25
19
18
1
2
4
6
39
7
31
3
21
5
40
15
32
8
14
9
22
16
26
20
38
27
33
28
23
29
24
34
35
36
37
30

generally the European varieties, showed a greater variation in grain nitrogen content.

(d) Insoluble Carbohydrate Content

For this character, and all subsequent ones, the analysis of variance (Table 16) was calculated from the results obtained from six trials (see Table 10, page 81). The major components of variation were again very highly significant but unlike the previous characters the largest proportion of the total variation was attributable to genotypes, whilst that due to environments was considerably smaller. Varietal differences were, therefore, larger than those induced by environmental change; the former ranged from Juliane with a mean of 6.5% to CPI. 18198 at 10.3%, the latter from Minlaton 1963 at 7.8% to Waite 1965 at 8.3%. Even at the .1% level the L.S.D. for varietal means was only .5% so that quite fine distinctions could be drawn between varieties.

Inspection of the varietal means (Appendix 4) shows that the European varieties are all relatively low in insoluble carbohydrate with none exceeding 8.0%. As mentioned in the literature review this character is a guide to potential extractability, an important aspect of malting quality (Bishop and Marx, 1934; Sallans and Anderson, 1940). In the present study a strong varietal correlation between insoluble carbohydrate and malt extract ($r = .89^{***}$) confirms this; inter-character correlations are detailed in a subsequent section. The European varieties have a history of selection for malting quality which has, presumably, lead to a low level of insoluble carbohydrate. Of the Australian varieties Prior's Chevalier, Prior A and Noyep fall within the European range but Research M.R. and Resibee at 8.5%

TABLE 16

Mean squares from Analysis of Variance of two grain characters for 40 varieties grown in six trials

	D.F.	INSOLUBLE CARBOHYDRATE Mean Squares	STEEP TIME Mean Squares
Environments	5	2.0350 ***	1956.800 ***
Replicates within environments	6	.5708 ***	410.383 ***
Genotypes	39	11.4884 ***	505.272 ***
Genotype: environment interaction	195	.3500 ***	64.617 ***
Linear regressions	39	.4145 N/S	74.695 N/S
Deviations from regressions	156	.3339 ***	62.098 ***
Residual	234	.1374	27.136

For linear regressions variance ratios were calculated against the deviations mean squares. For all other components of variation the residual mean squares were used.

and 8.1% respectively are a little higher although neither are of poorer quality. With values of around 6.6% available in other varieties there is obvious scope for a reduction in insoluble carbohydrate level in material adapted to Australian conditions. On the other hand, the very high levels of this character in some of the other varieties, especially the Egyptian, suggests that it may be more difficult to select malting quality lines from their crosses.

Although the genotype-environment interaction was significant the interaction due to linear regressions was not. Thus there was no regular pattern of varietal response to environmental change; probably because of the small environmental component. It is, therefore, inappropriate to plot a scatter of varietal means and regression coefficients for this character.

(e) Steep time

The major components of variation for this character were all very highly significant (Table 16). The varietal range was 26 hours and the L.S.D. at the 1% level 5.6 hours. The majority of the European varieties had an intermediate steep time of 45-50 hours. At the two extremes the Australian varieties required steeping for up to 60 hours whilst the North African varieties needed only 35-40 hours (Appendix 4). Deviations from regressions was the only significant component of genotype-environment interaction and again one is not justified in plotting the linear response to environmental change against the varietal means.

(f) Malting loss

The analysis of variance here (Table 17) followed a similar

TABLE 17

Mean squares from Analysis of Variance of three malt characters for 40 varieties grown in six trials

	D.F.	MALTING LOSS Mean Squares	MALT EXTRACT Mean Squares	COLD WATER EXTRACT Mean Squares
Environments	5	50.256 ***	993.716 ***	76.924 ***
Replicates within environments	6	3.057 ***	22.388 ***	7.492 ***
Genotypes	39	11.998 ***	228.729 ***	37.820 ***
Genotype: environment interaction	195	.768 *	5.477 ***	1.030 ***
Linear regressions	39	.857 N/S	9.697 ***	1.254 N/S
Deviations from regressions	156	.745 N/S	4.423 ***	.975 ***
Residual	234	.601	1.857	.507

For linear regressions variance ratios were calculated against the deviations mean squares. For all other components of variation the residual mean squares were used.

pattern to that for steep time except that genotype-environment interaction was only just significant at the 5% level and neither interaction component was significant. Varietal means ranged from the high values of Beka (10.5%) and Juliane (10.1%) through the European varieties, all at or above 8%, to the low values, mostly less than 7% for the Egyptian and Turkish varieties. The Australian and Algerian varieties were comparable with the European varieties (Appendix 4).

(g) Malt extract

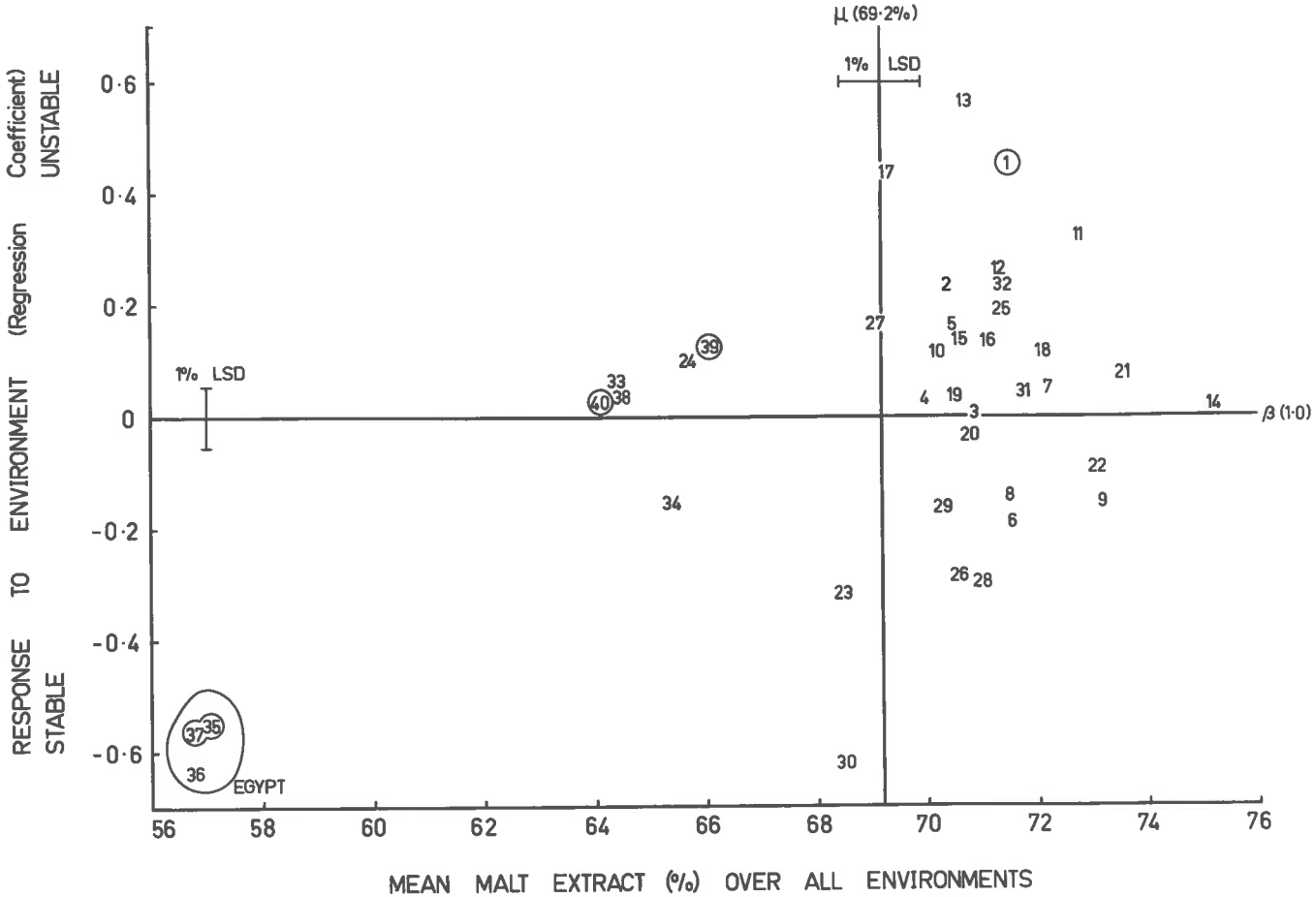
The analysis of variance, for this character, set out in Table 17, follows the general pattern of previous characters. Variation ranged, for environments, from a mean of 63.1% at Waite 1965 to 73.4% at Bundaleer 1964 (Appendix 8) and, for genotypes, from CI. 3576 with a mean of 56.8% to Beka with 75.2% (Appendix 5). Interestingly, the 5% level LSD for varietal means of 1.1% is only slightly higher than that found in the Canadian studies (Meredith and Anderson, 1938) and comparable to that of other unpublished investigations. There are, therefore, major differences in extractability between these varieties.

Genotype-environment interaction and both of its components were significant. Four varieties had significant deviation mean squares; CI. 5611 (39) had the largest deviation, and as noted for other characters was relatively inconsistent in its behaviour. The other varieties were White Smyrna (40), the Egyptian variety, Waite 775 (35), and Domen (1) which just reached significance at the 5% level.

The wide range of extractability is evident in the graph of variety means and regression coefficients (Figure 12). The Egyptian varieties, excluding Glaucous Head Sinai (38) were characterised by an extremely low level of extract which was relatively insensitive to environmental change. In other words, the extract and malting quality of these three varieties was poor throughout the range of conditions under which the trials were conducted. CI. 3576 (36) which averaged 56.8% extract had a range over the six trials from 53.4% at Waite 1965 to 59.9% at Waite 1964. It might have been expected that the Egyptian varieties would be lower in extract than the European group since they come from areas where barley is used for stock feed rather than malting. The only other variety of comparable insensitivity was Noyep (30) although at a considerably higher level of extract. At the other end of the scale Beka (14) had an average extract of 75.2%, significantly above that of all other varieties; it also showed average stability and, therefore, a greater range of extracts, from 67.5% at Waite 1965 to 78.3% at Bundaleer 1964. The European and Australian varieties averaged from 70 to 73% extract but with a range of environmental sensitivities from Baldric (13) at + 0.57 to Prior's Chevalier (38) at - 0.30. The remaining varieties, with two exceptions, were lower in extract than the European and tended to average stability. The exceptions were Goldfoil (25) which was selected from a European stock and Compana (26) selected for malting in North America; it is interesting that in many characters this last variety has shown a closely similar performance to the Prior types (28, 29). It has already been pointed out that Hanna (24)

FIGURE 12

The relation between mean malt extract over 6 sites and the stability of malt extract for 40 varieties.


μ (69·2%)
1% LSD
1% LSD
β (1·0)
RESPONSE TO ENVIRONMENT (Regression Coefficient)
UNSTABLE
STABLE
0·6
0·4
0·2
0
-0·2
-0·4
-0·6
56
58
60
62
64
66
68
70
72
74
76
MEAN MALT EXTRACT (%) OVER ALL ENVIRONMENTS
EGYPT
13
17
1
11
12
2
32
25
27
5
15
16
10
18
21
24
39
33
40
38
4
19
31
7
14
3
20
22
34
29
8
9
6
26
28
23
30
37
35
36

although derived from Europe is rather different to the original Hanna type which may explain its low extract in these investigations.

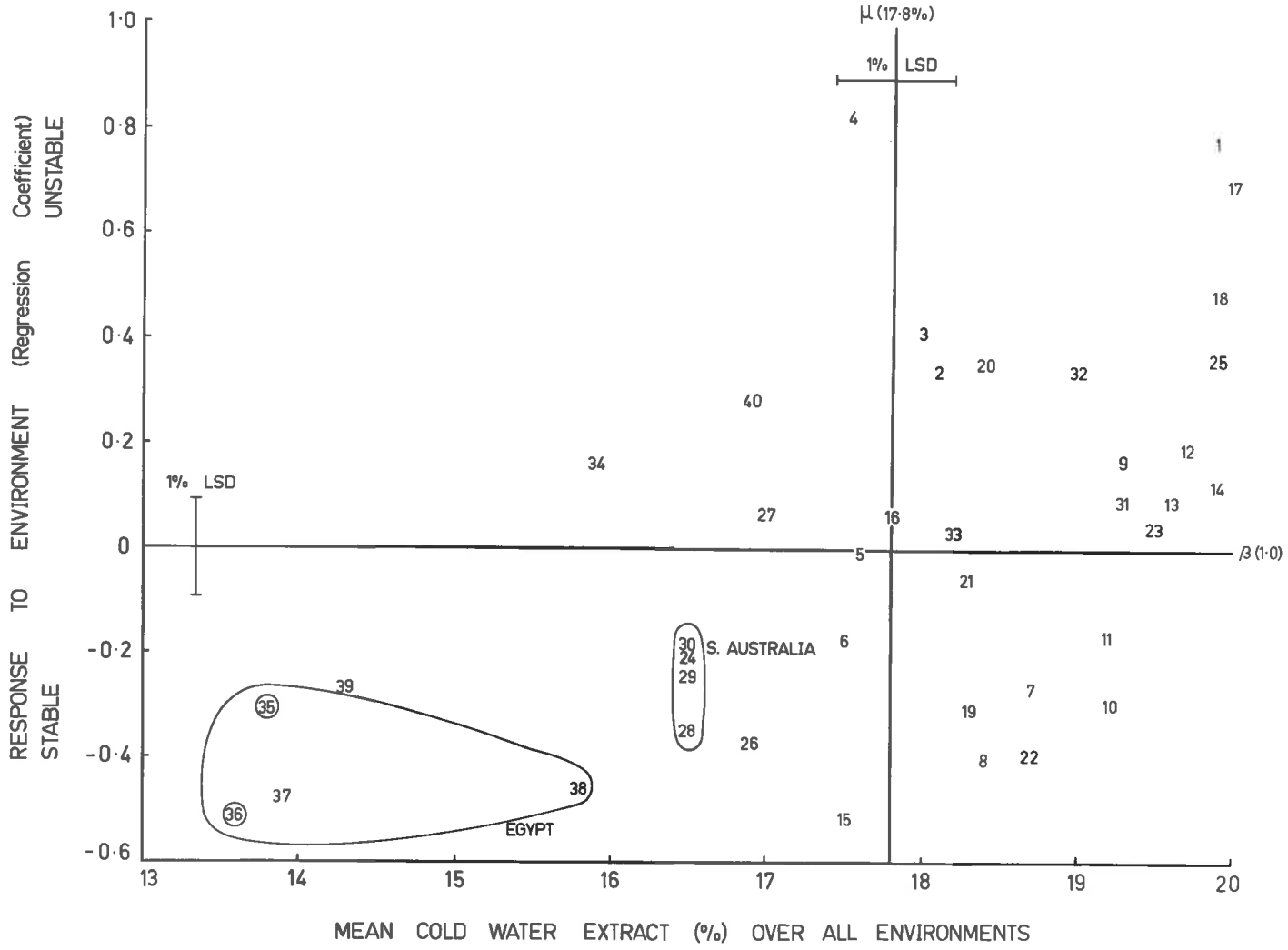
Although the association between varietal means and regression coefficients was significant (r = .53***) it was greatly influenced by the position of the three Egyptian varieties. The diversity of regression coefficients for the better quality varieties indicates that it should be possible to combine high extract with nearly every type of response to environmental change.

(h) Cold water extract

Here the analysis of variance (Table 17) was to an extent similar in pattern to that for malt extract except that the proportion of variation due to genotypes was larger and that due to genotype-environment interaction smaller. The genotype-environment interaction attributable to linear regressions just failed to reach significance at the 5% level. However, a scatter diagram of varietal means and regression coefficients is plotted (Fig. 13) to show the similarity to that for malt extract Fig. 12, page 111). This is not surprising as the means of these two characters were strongly correlated (r = .80***) (Table 23, page 125a). Thus Beka (14) at 19.9% and CI. 3576 (36) at 13.6% characterized the extremes of the varietal range as they did for malt extract (Appendix 5). As a group the European varieties were above average for both extracts although there were some changes in relative position of individual varieties. For example Domen (1), Maythorpe (12), Boa Fe (17) and Morgenrot (18) all had comparable extracts to Beka, as also did Goldfoil (25). Of the non-European varieties Kankyo (23) and CPI. 18197 (33) had relatively higher values for cold water extract than malt extract,

FIGURE 13

The relation between mean cold water extract over 6 sites and the stability of cold water extract for 40 varieties.


μ (17·8%)
1% LSD
1% LSD
β (1·0)
RESPONSE TO ENVIRONMENT (Regression Coefficient)
UNSTABLE
STABLE
1·0
0·8
0·6
0·4
0·2
0
-0·2
-0·4
-0·6
13
14
15
16
17
18
19
20
MEAN COLD WATER EXTRACT (%) OVER ALL ENVIRONMENTS
S. AUSTRALIA
EGYPT
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40

whilst for the South Australian varieties (28, 29, 30) and Compana (26) the reverse was the case.

(i) Wort nitrogen content

A large proportion of the variation in this character was due to environment (Table 18). This is somewhat similar to the result obtained for grain nitrogen content as might be expected since wort nitrogen is derived from the grain nitrogen and is indirectly subject to the same influences. Genotype-environment interaction and its components were highly significant.

The graph (Fig. 14) of variety means and regression coefficients also has some similarities to that for malt extract (Fig. 12). The Egyptian varieties, excluding Glaucous Head Sinai (38), again only developed a low level of wort nitrogen, about .35%, which was relatively insensitive to environmental change although not so extreme as with malt extract. On the other hand, the Algerian varieties (33, 34) and Noyep (30) were more insensitive to change but had a higher mean level of the character. The majority of varieties fell between .55% and .60% with generally, a little above average sensitivity (Appendix 6). The relationship between mean and regression coefficient ($r = .47^{**}$) was not strong and may well be due, at least partially, to the effect of maturity on the varietal grain nitrogen response to environment (Fig. 11, page 107). Thus the later varieties are more sensitive to environmental change, but are of better quality with a tendency to higher levels of wort nitrogen. The four Scandinavian varieties, Freja (2), Rika (3), Bonus (4) and Rigel (5) were rather lower in wort nitrogen than the other European varieties; they have closely similar genetic origins which could

TABLE 18

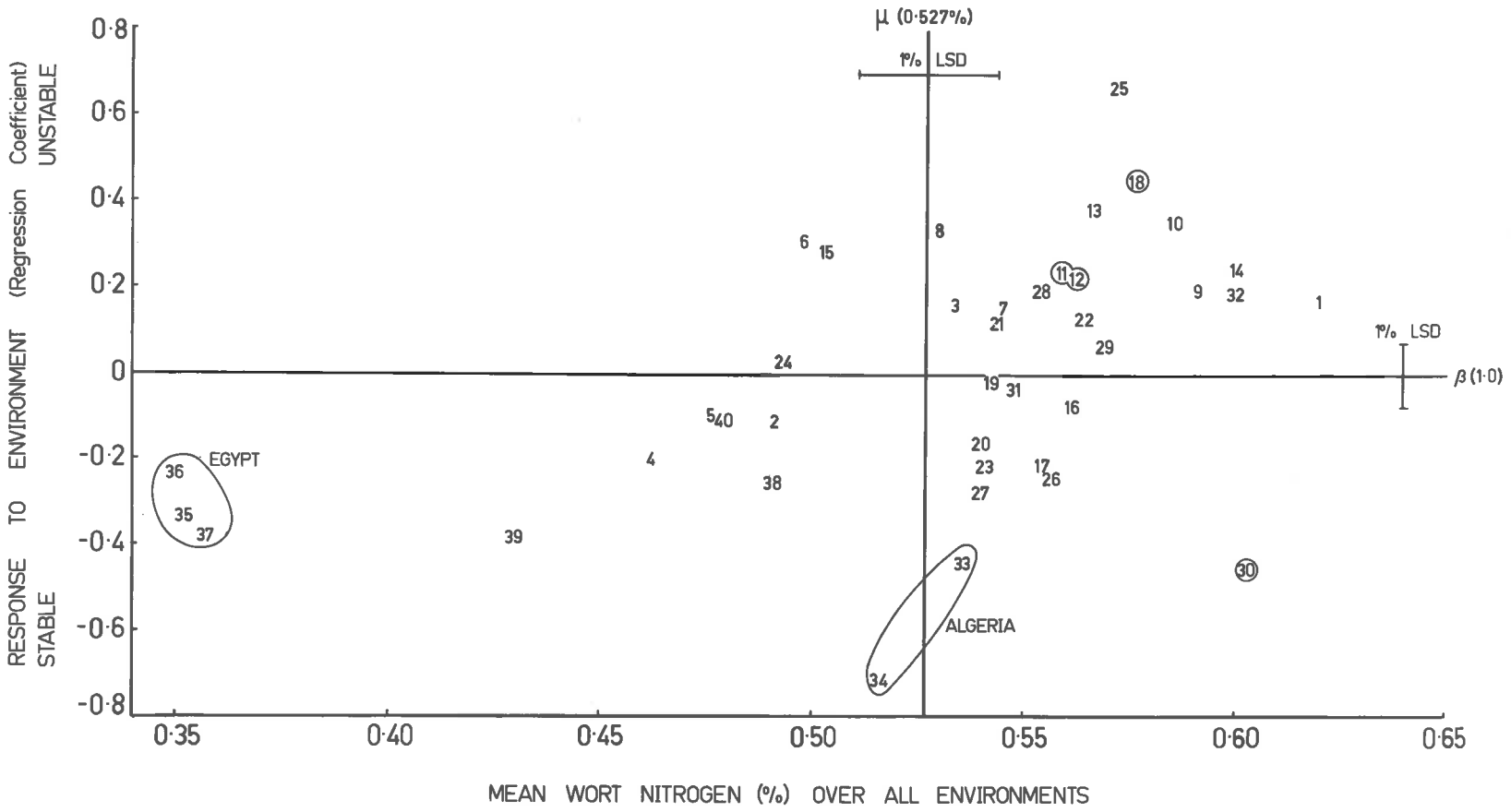
Mean squares from Analysis of Variance of two malt characters for 40 varieties grown in six trials

	D.F.	WORT NITROGEN Mean Squares	DIASTATIC ACTIVITY Mean Squares
Environments	5	.29999 ***	1.4497 ***
Replicates within environments	6	.00460 ***	.0299 ***
Genotypes	39	.05041 ***	.2836 ***
Genotype: environment interaction	195	.00243 ***	.0140 ***
Linear regressions	39	.00324 **	.0279 ***
Deviations from regressions	156	.00222 ***	.0106 ***
Residual	234	.00097	.0047

For linear regressions variance ratios were calculated against the deviations mean squares. For all other components of variation the residual mean squares were used.

FIGURE 14

The relation between mean wort nitrogen over 6 sites and the stability of wort nitrogen for 40 varieties.


μ (0·527%)
1% LSD
1% LSD
β (1·0)
RESPONSE TO ENVIRONMENT (Regression Coefficient)
UNSTABLE
STABLE
0·8
0·6
0·4
0·2
0
-0·2
-0·4
-0·6
-0·8
0·35
0·40
0·45
0·50
0·55
0·60
0·65
MEAN WORT NITROGEN (%) OVER ALL ENVIRONMENTS
EGYPT
ALGERIA
25
18
13
10
8
6
15
14
11
12
28
9
32
3
7
1
21
22
29
24
19
31
16
5
40
2
20
4
23
17
26
38
27
36
35
37
39
33
30
34

indicate a particular varietal type with lower proteolysis. Varieties with a somewhat similar origin, through the variety Kenia, include Delta (6), Emir (8) and Ceres (15) which were also lower in wort nitrogen and the English varieties Proctor (11), Maythorpe (12) and Baldric (13) which were not.

(j) Diastatic activity

Here again (Table 18) a large proportion of the variation was due to environment; the mean square for that component was five times larger than that for genotypes. The close parallel between the analysis of variance for diastatic activity and wort nitrogen content reflects the interdependence of the two characters (Table 23, page 125a). Genotype-environment interaction and its components were all very highly significant. Four varieties had significant deviation mean squares. Goldthorpe Spratt (10) and Proctor (11) had the largest deviations as a result of higher than expected values at Waite 1965; Kankyo (23) and Baldric (13) had smaller deviations due to a general inconsistency of results.

The relationship between varietal means and regression coefficients (Fig. 15) is stronger for diastatic activity than any of the other characters studied ($r = .66^{***}$). The response of diastatic activity to changes in environment was largely dependent upon the mean diastatic activity of each variety and the greater the mean activity the greater the response to change in the environment. This effect is illustrated in Figure 16 where, for six varieties the calculated regression slopes of varietal activity against site mean activity are plotted. Although the individual varieties were differentially influenced by the environment, at any point, within the range

FIGURE 15

The relation between mean diastatic activity over 6 sites and the stability of diastatic activity for 40 varieties.

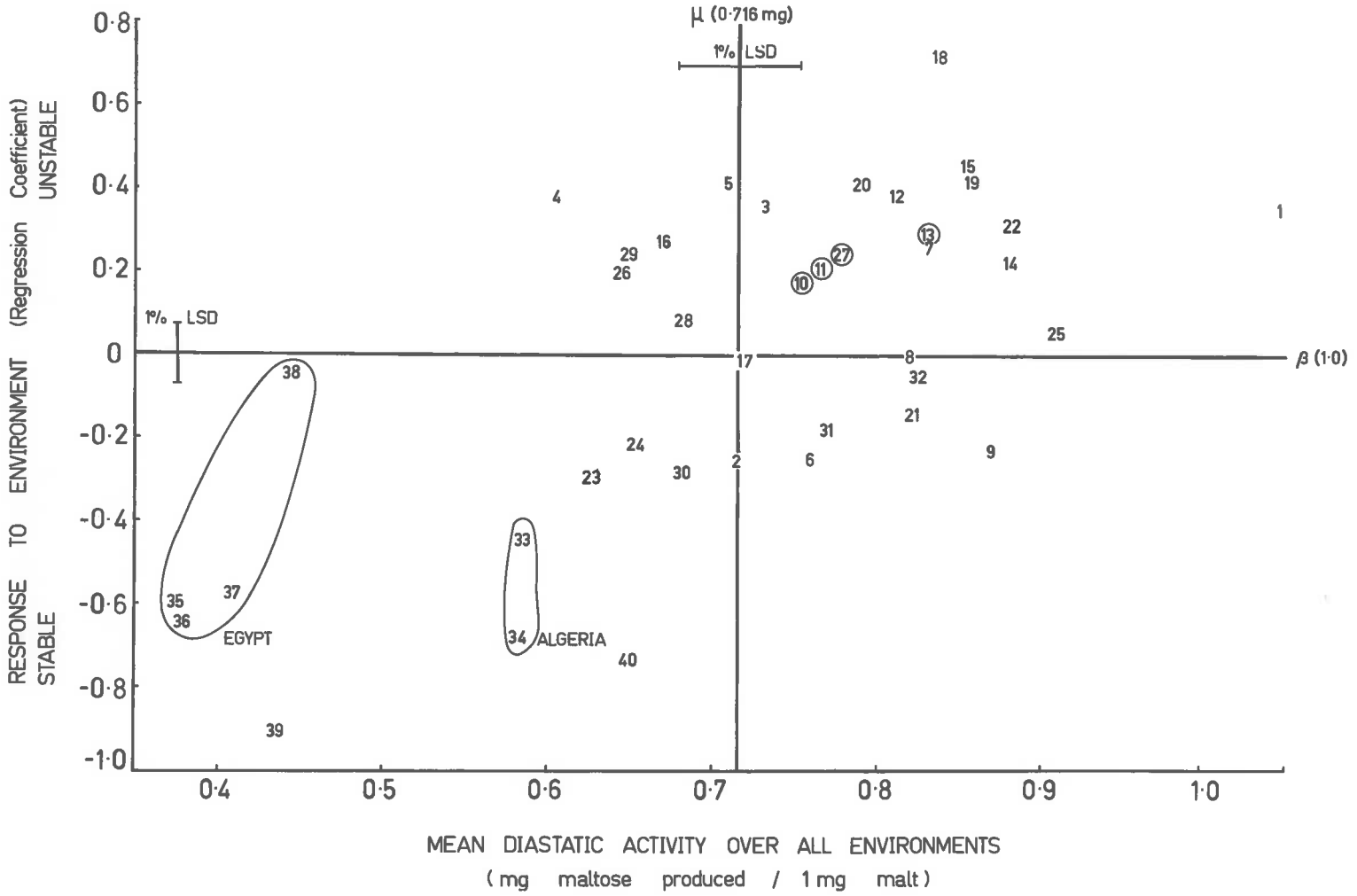
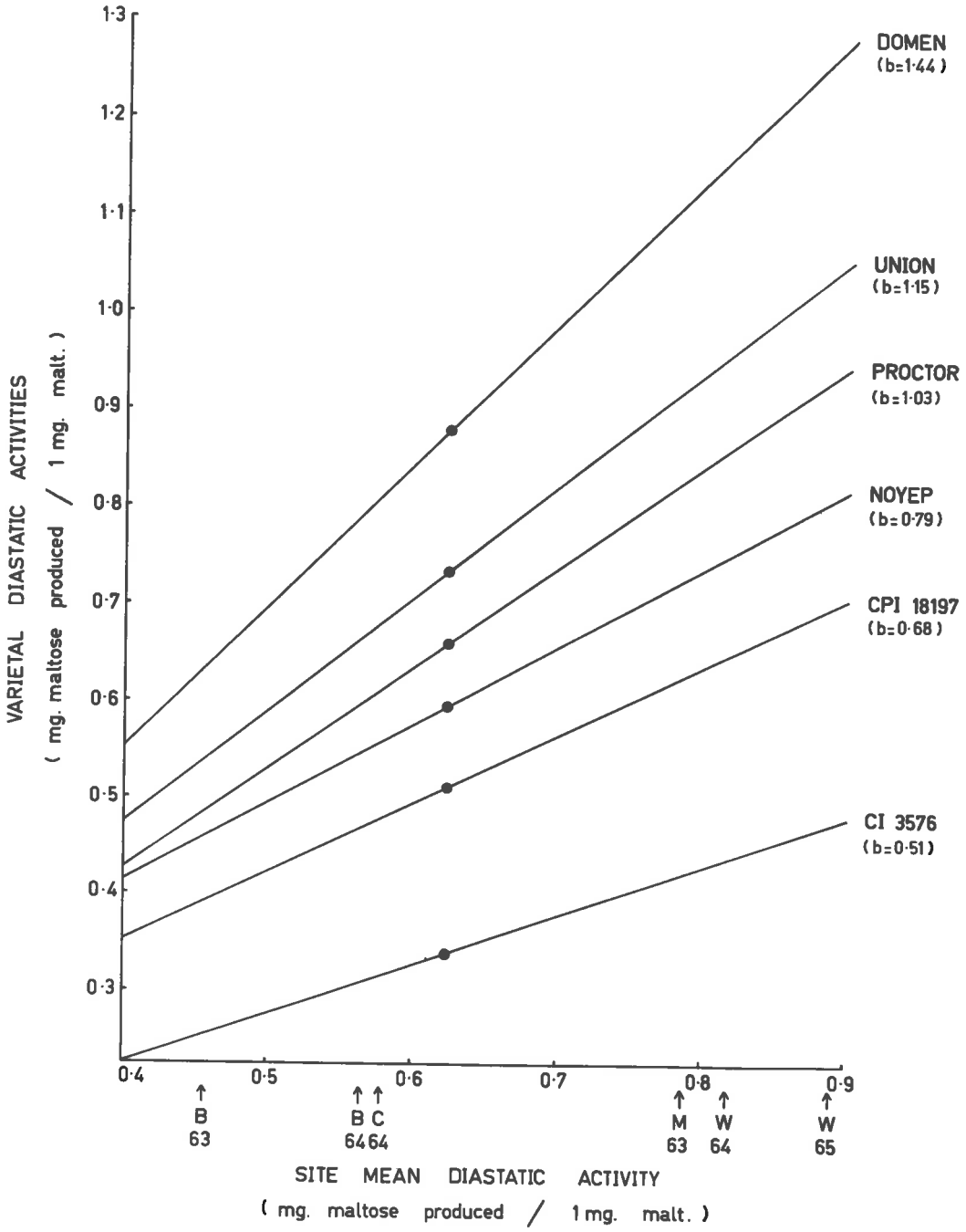

μ (0·716 mg)
1% LSD
RESPONSE TO ENVIRONMENT (Regression Coefficient)
UNSTABLE
STABLE
1% LSD
β (1·0)
0·8
0·6
0·4
0·2
0
-0·2
-0·4
-0·6
-0·8
-1·0
0·4
0·5
0·6
0·7
0·8
0·9
1·0
EGYPT
ALGERIA
MEAN DIASTATIC ACTIVITY OVER ALL ENVIRONMENTS
(mg maltose produced / 1 mg malt)

FIGURE 16

The relation between site mean diastatic activity and the individual diastatic activities of 6 varieties over 6 sites.


VARIETAL DIASTATIC ACTIVITIES
(mg. maltose produced / 1 mg. malt.)
1·3
1·2
1·1
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
DOMEN
(b=1·44)
UNION
(b=1·15)
PROCTOR
(b=1·03)
NOYEP
(b=0·79)
CPI 18197
(b=0·68)
CI 3576
(b=0·51)
0·4
0·5
0·6
0·7
0·8
0·9
B 63
B C 64 64
M W 63 64
W 65
SITE MEAN DIASTATIC ACTIVITY
(mg. maltose produced / 1 mg. malt.)

considered, they ranked in a similar order. Hence performance in one environment was predictive of relative performance in other environments.

The scatter diagram of means and regression coefficients (Fig. 15) shows that there was a wide range of values in both indices whilst the relationship between the two is quite evident. Varieties with a low mean activity tended to be insensitive to environmental change whereas those with a high mean activity were sensitive. The former included all the Mediterranean varieties again emphasising that these varieties have not been selected for malting quality. Of the Continental varieties Kankyo (23) and Hanna (24) were intermediate in performance, Compana (26) was again similar to the Prior types (28, 29), Goldfoil (25) with above average activity showed its European origin. Long Outer Glume (27) was somewhat anamlous with above average performance in both indices, however it was also rather sensitive in the case of malt extract. The South Australian varieties (28-30) had average diastatic activity as did the Scandinavian ones (2-5). The remaining European varieties had a high level of activity combined with sensitivity to environmental change except for Delta (6), Impala (9) and Union (21) which were more stable in performance (Appendix 6).

(k) Predicted extract and Relative extract

In addition to the malt characters already considered two derived characters were calculated from them. The first of these, predicted extract, was calculated from Bishop's equation (page 86), whilst the second is the difference between the extract predicted and malt extract. Because predicted extract is an empirical estimation

of malt extract, it's values were of a similar magnitude and the analysis of variance (Table 19) is directly comparable to that for malt extract (Table 17). Total variation was smaller for predicted extract although the proportion due to environment was somewhat larger. The reduced variation was reflected in the reduced spread of results. Environments ranged from 66.6% at Waite 1965 to 74.5% at Clinton 1964; genotypes from 65.4% for CPI. 18198 to 75.7% for Beka (cf. malt extract, page 110). The 5% level LSD for varietal means at 1.25% is also slightly lower (Appendix 7). Genotype-environment interaction and its two components were significant. CPI. 18198 (34) and CI. 5611 (39) with generally inconsistent results were the only varieties with significant deviation mean squares. The graph (Fig. 17) of varietal means and regression coefficients is unique amongst those presented in this study in having a negative, although non-significant association between the two indices ($r = -.31$). Compared to that for malt extract (Fig. 12, page 111) the most obvious feature of the distribution is an alteration in varietal response to environmental change. Those with a low extract, from North Africa, showing a considerable shift from insensitive to sensitive response, whilst at the high extract level the shift to insensitivity was considerably less. This indicates that although grain nitrogen and insoluble carbohydrate content in the North African varieties were quite sensitive to environmental change malt extract was not. This discrepancy was probably due to an additional factor or factors which give these varieties their inherently low extractability. It also suggests that this derived character should be used with caution in selection, because of the tendency to overestimate certain types of

TABLE 19

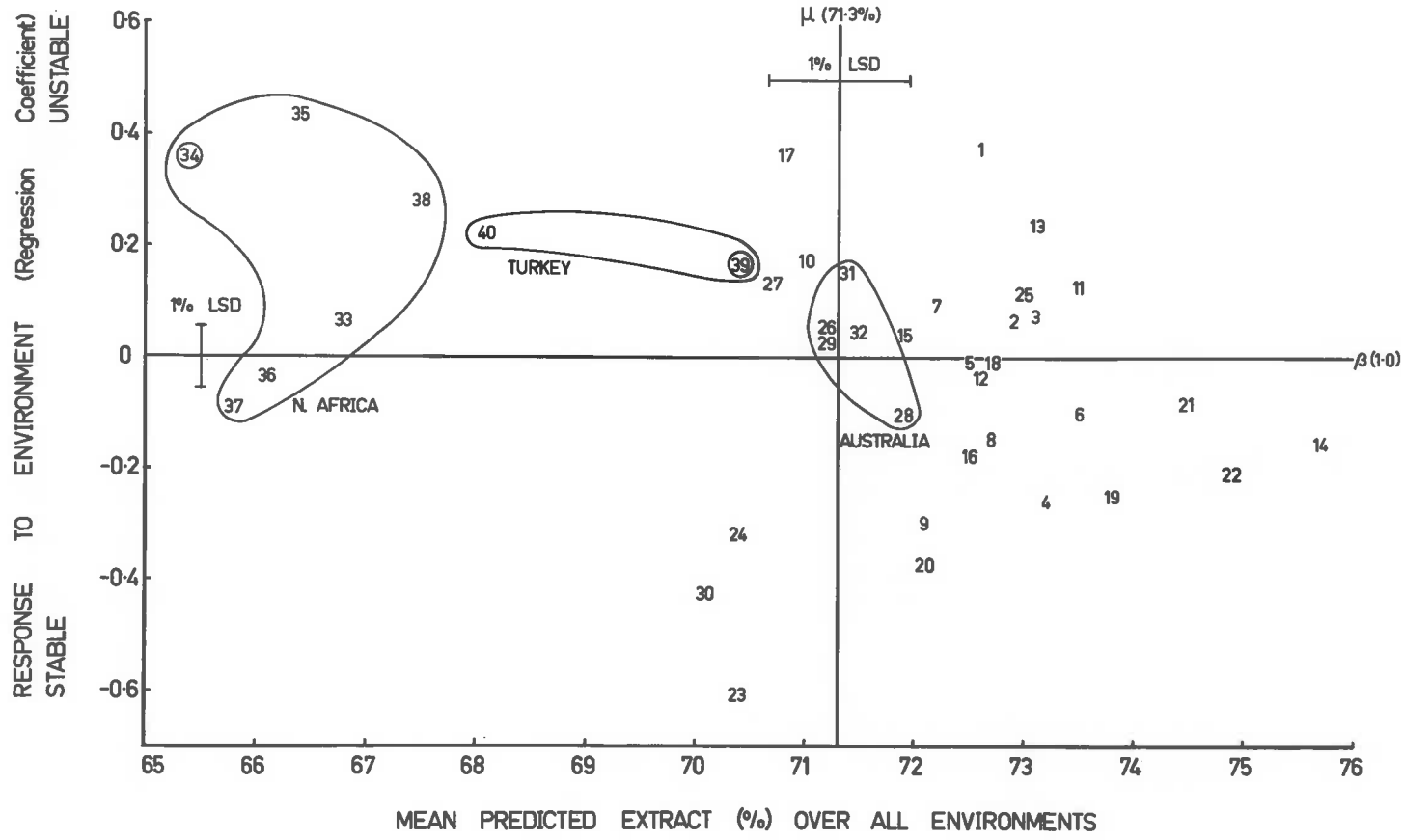
Mean squares from Analysis of Variance of two derived characters for 40 varieties grown in six trials

	D.F.	PREDICTED EXTRACT Mean Squares	RELATIVE EXTRACT Mean Squares
Environments	5	630.120 ***	110.710 ***
Replicates within environments	6	9.285 ***	7.614 ***
Genotypes	39	77.609 ***	68.058 ***
Genotype: environment interaction	195	2.942 ***	4.377 ***
Linear regressions	39	4.264 *	2.467 N/S
Deviations from regressions	156	2.606 **	4.855 ***
Residual	234	1.372	1.632

For linear regressions variance ratios were calculated against the deviations mean squares.
For all other components of variation the residual mean squares were used.

FIGURE 17

The relation between mean predicted extract over 6 sites and the stability of predicted extract for 40 varieties.


RESPONSE TO ENVIRONMENT (Regression Coefficient)
UNSTABLE
STABLE
0·6
0·4
0·2
0
-0·2
-0·4
-0·6
μ (71·3%)
1% LSD
1% LSD
β (1·0)
TURKEY
N. AFRICA
AUSTRALIA
65
66
67
68
69
70
71
72
73
74
75
76
MEAN PREDICTED EXTRACT (%) OVER ALL ENVIRONMENTS

variety.

The analysis of variance for relative extract (Table 19) showed that although the genotype-environment interaction was significant this could only be attributed to deviations from linear regressions; consequently a scatter diagram was not plotted. Both genotypic and environmental differences were significant (Appendices 7 and 8). Since the grand mean was negative (- 2.14%) prediction of extract had generally over-estimated that obtained. In other words, the standard malting method applied to the material under study did not develop the full extract potential of all the varieties which is hardly surprising in view of the diversity of material. However, it is encouraging that 18 varieties were not significantly different, at the 1% level, from a relative extract of zero. These included four Australian varieties and Beka; malting types adapted or nearly adapted to the conditions under which the trials were grown. The varieties which showed the greatest discrepancy between extracts were those from Egypt, other than Glaucous Head Sinai, followed by Hanna and the two Turkish varieties. Of the non-malting varieties only CPI. 18198 was not significantly different from zero whilst a few of the reputed malting varieties were significantly lower. There is thus a strong association between malt extract and relative extract ($r = .88^{***}$) which supports Whitmore's (1963) contention that relative extract is an important guide to malting potential.

4. Relative genetic variability

Heritability was originally conceived for genetic studies of animals and cross pollinated plants. In a self pollinated crop like barley heritability cannot have the same meaning but it is a useful

statistic to calculate as an illustration of the relative magnitude of the effects of genotype and environment. The appropriate variance components and heritability estimates were calculated, for all except the two derived characters, as set out in Table 12 (page 88a).

Data for yield were available from four replicates at 15 sites; for thousand grain weight and grain nitrogen content from four replicates at 11 sites and for the other characters from two replicates at six sites. Variance components were calculated for all characters, from the data of the six sites which were micro-malted, and for the first three characters from the full set of results.

In addition, since such comprehensive data are not normally available it was decided to vary either the number of sites or the number of varieties analysed. This was done in order to determine first if a reduced number of sites was adequate to test the heritabilities of malting quality characters. A subset of three sites (Bundaleer 1963, 1964, Minlaton 1963) was chosen since this quantity of data would be more nearly comparable to that normally available in a breeding programme, and the material from the three sites was representative of that which would be used in malting quality selection. Secondly to determine the effect of reducing the range of genotypes a subset was chosen comprising 25 varieties (22 from Europe, plus two Victorian and Portugal 2-row), with fairly similar malting qualities; the same subset was subsequently used in other analyses.

The respective subsets were 1. two replicates of 40 varieties at each of three sites and 2. two replicates of 25 varieties at each of six sites. The data for steep time and malt loss were not included in the subsets.

The relevant variance components, grand means ($\bar{x}$) and heritability estimates (h^2) are set out in Tables 20 and 21. Some idea of the expected genetic progress can be obtained if a selection differential of 5% ΔG is considered as an example of possible selection intensity. Heritability is then expressed as $\Delta G / 2.06 \sigma ph$ (Hanson 1963).

The three variance components provide a direct comparison of the relative magnitude of the components due to genotype, genotype-environment interaction and experimental error. Heritability or relative genetic variability enables a comparison to be made between characters. In this context heritability is the ratio of genotypic to phenotypic variance among the varietal means. In estimating the phenotypic variance

$$\sigma^2_{Ph} = \sigma^2_g + \sigma^2_{ge/e} + \sigma^2_{res/er}$$

the components for genotype-environment interaction and error are divided by the appropriate number of environments and replications involved (Table 12, page 88a).

The various estimates for each character are presented in table 20 (40 varieties) and table 21 (25 varieties). The genetic component was the largest for all characters except yield and grain nitrogen. For the other characters, with one minor exception the error component was larger than that for interaction and in some cases approached the magnitude of the genetic component.

The effect on the estimates of heritability of different numbers of environments or varieties may be seen from the two tables. Thus, for example, with thousand grain weight reducing the number of sites although leading to some increase in genetic variance is accompanied

TABLE 20

Variance components, means, genetic advance and heritabilities of grain and malt characters for 40 barley varieties at varying numbers of sites.

	Sites	$\sigma^2 g$	$\sigma^2 ge$	$\sigma^2 res$	$\bar{X}$	ΔG	h^2 *
Yield	15	902.88	3214.50	3594.00	268.4	54.21	.767
	6	437.00	3404.00	3446.00	327.5	25.05	.338
	3	1370.50	3286.00	3696.00	402.75	50.86	.445
Thousand Grain Weight	11	20.283	3.949	5.839	36.81	9.17	.976
	6	26.025	3.549	3.562	39.37	10.33	.967
	3	28.175	3.595	4.610	39.69	10.57	.935
Grain Nitrogen Content	11	.0040	.0118	.0273	2.11	.11	.703
	6	.0070	.0051	.0117	1.84	.15	.794
	3	.0089	.0026	.0136	1.81	.17	.741
Insoluble Carbohydrate	6	.928	.106	.137	8.01	1.95	.970
	3	.912	.060	.151	7.94	1.92	.953
Steep Time	6	36.721	18.741	27.136	48.9	11.66	.872
Malt Loss	6	.9358	.0835	.6010	8.54	1.93	.936
Malt Extract	6	18.604	1.810	1.857	69.16	8.78	.976
	3	18.150	1.290	1.510	70.26	8.62	.964
Cold Water Extract	6	3.066	.262	.507	17.78	3.56	.973
	3	3.801	.217	.459	18.15	3.94	.962
Wort Nitrogen	6	.0040	.0007	.0010	.527	.127	.952
	3	.0040	.0003	.0009	.513	.126	.942
Diastatic Activity	6	.0225	.0047	.0047	.716	.301	.951
	3	.0222	.0026	.0039	.670	.297	.936

* h^2 (heritability) calculated as $\Delta G / 2.06\ \sigma ph$. (See also Table 12, page 88a).

TABLE 21

Variance components, means, genetic advance and heritabilities of grain and malt characters for 25 barley varieties at six sites.

	$\sigma^2 g$	$\sigma^2 ge$	$\sigma^2 res$	$\bar{X}$	ΔG	h^2 *
Yield	560.92	2215.50	2887.00	333.1	33.77	.479
Thousand Grain weight	4.052	2.155	2.500	36.00	3.88	.877
Grain Nitrogen content	.0049	.0028	.0118	1.79	.13	.771
Insoluble Carbohydrate	.170	.045	.119	7.47	.81	.907
Malt Extract	1.464	.835	1.400	71.50	2.30	.851
Cold Water Extract	.684	.176	.505	18.79	1.62	.906
Wort Nitrogen	.0014	.0005	.0009	.549	.073	.900
Diastatic Activity	.0069	.0035	.0052	.803	.160	.872

* h^2 (heritability) calculated as $\Delta G/2.06 \sigma ph$ (See also Table 12, page 88a)

by a slight reduction in heritability which nonetheless is at a very high level. On the other hand reduction in the number of varieties brings about a considerable reduction in genetic variance but only a small reduction in heritability.

Insoluble carbohydrate and the malt characters showed a similar pattern of results to the thousand grain weights. For all these characters reduction either in the number of sites or of the number of varieties had only had a slight effect on the relative genetic variability, even when the genetic variance was considerably reduced by utilizing a subset of varieties with fairly similar malting characters. In other words the varieties in the subset were affected by the environment in a similar way to the remaining varieties and the heritability of the characters was relatively unchanged. Thousand grain weight, insoluble carbohydrate and all the malt characters are therefore highly heritable. Since this implies that these characters are relatively predictable across environments testing at one or possibly two sites might be sufficient for their selection in segregating material.

For grain nitrogen the reduction in sites analysed increased the genetic variance considerably whereas reduction of the number of varieties only reduced the variance to a level similar to that for all varieties over eleven trials. Heritability of the character was somewhat inconsistent and at a lower level than for the other characters. However, since the error component was in all cases larger than that for interaction it seems likely that increased replication rather than increasing the number of trial sites would be advisable in selecting for grain nitrogen.

In contrast, yield showed a considerable variation in heritability from a fairly high value when fifteen sites were analysed to quite low values for six and three sites, or when fewer varieties were involved. As all the variance components showed considerable variation there appear to be complex environmental influences and genotype-environment interactions involved. As a result yield was not predictable across environments and would be difficult to select unless a large number of sites was used.

5. Character interrelationships

The data obtained from the six trials in which grain samples were micromalted were used to estimate the correlations between all possible pairs of the ten characters. The correlations for relative extract were also calculated to determine whether it provided additional information. Variance and covariance results were used to calculate environmental, genotypic and phenotypic correlations. Since the genotypic and phenotypic values showed a general agreement in sign and magnitude only the latter will be presented.

Partial correlations involving three variables were calculated in a number of instances to aid the interpretation of the results. They are referred to at appropriate points in the text.

(a) Environmental associations

These were calculated from the site means of each variable; the resultant correlation matrix is set out in Table 22. Since only six sites were involved the correlation values need to be large to reach significance.

Although a significant positive correlation was found between yield and thousand grain weight when 11 sites were considered

TABLE 22

Correlation matrix of the site means of eleven grain and malt variables

	Thousand Grain Weight	Grain Nitrogen	Insoluble Carbo-hydrate	Steep Time	Malt Loss	Malt Extract	Cold Water Extract	Wort Nitrogen	Diastatic Activity	Relative Extract
Yield	.350	-.300	-.593	.306	.834**	.556	.645	-.193	-.433	.815*
Thousand Grain Wt.		-.342	-.604	.614	.324	.518	.459	-.077	-.289	.581
Grain Nitrogen			.541	-.301	.101	-.932***	-.513	.678	.856**	-.428
Insoluble Carbohydrate				-.670	-.526	-.707*	-.494	.279	.454	-.594
Steep Time					.309	.418	.569	.232	.024	.359
Malt Loss						.218	.297	.012	-.091	.698
Malt Extract							.671	-.575	-.820*	.717*
Cold Water Extract								.119	-.282	.710*
Wort Nitrogen									.910**	-.163
Diastatic Activity										-.443

n = 6, P > .05 = .707 >.01 = .834 >.001 = .925

(Table 13, page 94a) this was not the case for six sites. As pointed out in Materials and Methods only eight of the 11 sites produced sufficient seed for micro-malting and the six were chosen to provide a range of grain nitrogens. The sites rejected were low in yield and produced thin grains in contrast to the more even yield and grain size of the sites retained. This could account for the good correlation between these characters over 11 sites but not for six.

On the other hand the negative association between yield and grain nitrogen content was only slightly reduced in the six site data although in neither case was it significant. Similarly with the weak association between grain size and nitrogen content.

The only characters significantly associated with yield were malting loss and relative extract. This indicates that material from high yielding sites malted more rapidly under the standard micro-malting schedule employed, and that its greater respiration and growth led to greater losses in the six day germination period. This is substantiated by the relatively good but non significant positive correlations between yield and the two extract variables. In the South Australian environment high yields in cereals are produced in seasons with adequate spring rainfall, under conditions which permit grain filling to proceed without restriction due to moisture stress. The present data suggest that these conditions also produce a barley grain with greater maltability and extractability. This deduction is supported by the negative although not significant association of yield with insoluble carbohydrate content. In other words conditions which increase yield tend to decrease the relative amount of insoluble carbohydrates and increase the predictability of the extract.

Conversely a restriction in yield alters the proportions of insoluble carbohydrate and grain nitrogen, on which the prediction is based, presumably by a restriction in the deposition of extractable carbohydrate.

Grain size showed no significant correlations with other variables although it did have a relatively good association with insoluble carbohydrate, malt extract and relative extract probably for the same reasons concerning grain filling. It also showed some association with steep time, larger grains tending to take longer to absorb water, which is likely to be a reflection of the greater distance water would have to penetrate in plumper grains.

Grain nitrogen content showed a highly significant negative correlation with malt extract and a significant positive association with diastatic activity. Similar but non significant associations were apparent with cold water extract and wort nitrogen. Since these results are in agreement with many previous findings they are not unexpected.

Insoluble carbohydrate content was also significantly correlated with malt extract but not significantly with cold water extract or with the other variables.

Steep time was not significantly associated with any variables whilst malt loss was only correlated with relative extract although the coefficient just fails to reach 5% significance. It seems reasonable that material in which malt extract reaches or exceeds that predicted will have a higher malt loss.

The significant correlations between malt extract and grain nitrogen and insoluble carbohydrate have already been mentioned.

Malt extract was also negatively correlated with diastatic activity which was itself positively correlated with grain nitrogen. However, since the partial correlation, independent of grain nitrogen, between malt extract and diastatic activity was negligible ($r = -.12$) they are only associated through their dependence on grain nitrogen. Similarly the partial correlation between malt extract and wort nitrogen, independent of grain nitrogen, was also small ($r = .22$). Consequently conditions promoting high or low levels of grain nitrogen produce a parallel effect in enzyme activity but an inverse response in extract. Although the correlation of malt extract and relative extract is that of a measured variable and its derivative it does indicate that high extracting material is more accurately predicted. The association between malt extract and cold water extract although not quite significant would also explain the latter's correlation with relative extract. The lack of association between cold water extract and wort nitrogen and diastatic activity would seem only to indicate that these measurements are not associated, since endosperm modification during malting, which cold water extract is considered to measure, must be dependent upon both proteolytic and amylolytic activity.

That wort nitrogen and diastatic activity were strongly correlated was to be expected since they represent the two above mentioned aspects of enzyme activity. Whilst a partial correlation between them, with grain nitrogen held constant, remains significant ($r = .87^{**}$), showing the association to be independent of grain nitrogen.

(b) Varietal associations

These were calculated from the varietal means of each variable. The resultant correlation matrix is set out in Table 23. With 40 varieties involved the value of the correlation necessary to reach significance is quite low but comment is generally restricted to coefficients greater than .5.

Maturity has been included in the matrix to provide information on its effect on grain and malt quality. It should, however, be pointed out that varietal maturity was estimated from observations at three sites; it is not, therefore, possible to subject it to the same analysis of variance and adaptation as the other variables, nor can it be included in the multivariate analysis. Maturity showed a fairly strong negative correlation with thousand grain weight, a somewhat smaller negative correlation with insoluble carbohydrate and a positive association with three malt characters, malt extract, cold water extract and diastatic activity. Thus the earlier maturing varieties, those better adapted to South Australian conditions, tended to have larger grains with a high level of insoluble carbohydrate and to be relatively low in extractability and enzyme activity. This pattern of associations is substantiated in subsequent paragraphs. Fortunately the correlations with maturity are not so large as to preclude the possibility of combining, by hybridization and selection, early maturity with higher levels of malting quality.

The lack of association between yield and, with one exception, the other characters would seem to reflect the diversity of the 40 varieties. It does suggest there should be no difficulty in combining high yield and good malting quality in varieties adapted to Australian

TABLE 23

Correlation matrix of the varietal means of maturity and eleven grain and malt variables

	Yield	Thousand Grain Weight	Grain Nitrogen	Insoluble Carbo-hydrate	Steep Time	Malt Loss	Malt Extract	Cold Water Extract	Wort Nitrogen	Diastatic Activity	Relative Extract
Maturity	.052	-.714***	-.338*	-.610***	.118	.363*	.552***	.524***	.243	.506***	.361*
Yield		-.102	-.338*	.004	-.184	.001	.046	.012	-.145	-.081	-.005
Thousand Grain Wt.			.513***	.812***	-.152	-.563***	-.708***	-.732***	-.453***	-.723***	-.418**
Grain Nitrogen				.480*	-.189	-.253	-.532***	-.404**	-.144	-.412**	-.260
Insoluble Carbohydrate					-.519***	-.695***	-.891***	-.684***	-.658***	-.805***	-.592***
Steep Time						.275	.536***	.068	.437**	.323*	.463**
Malt Loss							.785***	.736***	.758***	.733***	.734***
Malt Extract								.802***	.828***	.859***	.877***
Cold Water Extract									.806***	.852***	.737***
Wort Nitrogen										.796***	.882***
Diastatic Activity											.730***

n = 40 P > .05 = .304 > .01 = .393 > .001 = .490

conditions. The only significant association was with grain nitrogen and, as has commonly been found, this association was negative.

Thousand grain weight was significantly correlated with all characters except yield and steep time. The strongest correlation, with insoluble carbohydrate, was positive as was the lesser association with grain nitrogen. In other words, at the varietal level an increase in grain size was allied with an increase in insoluble material and a tendency towards a higher nitrogen content. The former association is illustrated in Figure 18 from which it is apparent that the small grained European varieties contain less insoluble material but that as grain size increases through the Australian and Continental varieties to those from North Africa, the level of insoluble carbohydrate increases. The same trend is evident, although less clear cut, for the association with grain nitrogen but as has been mentioned above the varietal range in this character was not large.

All other correlations involving thousand grain weight were negative. The associations with malt extract, cold water extract and diastatic activity were strong, and, as illustrated for the latter (Fig. 19), were almost the reverse of the association with insoluble carbohydrate. Compared to other varieties, therefore, those from Europe are smaller grained, lower in insoluble carbohydrate and grain nitrogen, and with a higher extractability and enzyme activity.

The correlations with insoluble carbohydrate had a similar pattern to those with thousand grain weight. The partial correlations involving these two characters are presented in Table 24.

FIGURE 18

The relation between grain size and insoluble carbohydrate content for 40 varieties.

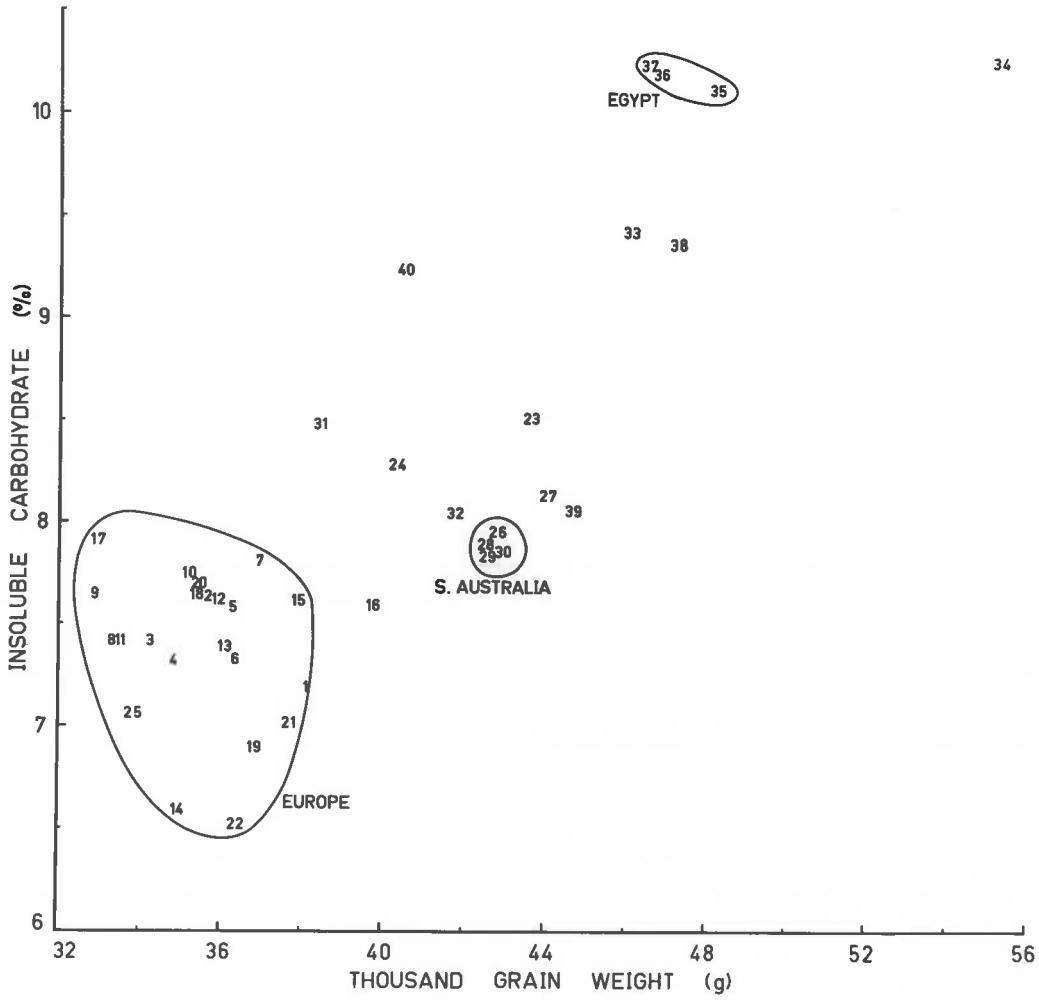

INSOLUBLE CARBOHYDRATE (%)
10
9
8
7
6
32
36
40
44
48
52
56
THOUSAND GRAIN WEIGHT (g)
EGYPT
S. AUSTRALIA
EUROPE

FIGURE 19

The relation between grain size and diastatic activity for 40 varieties.

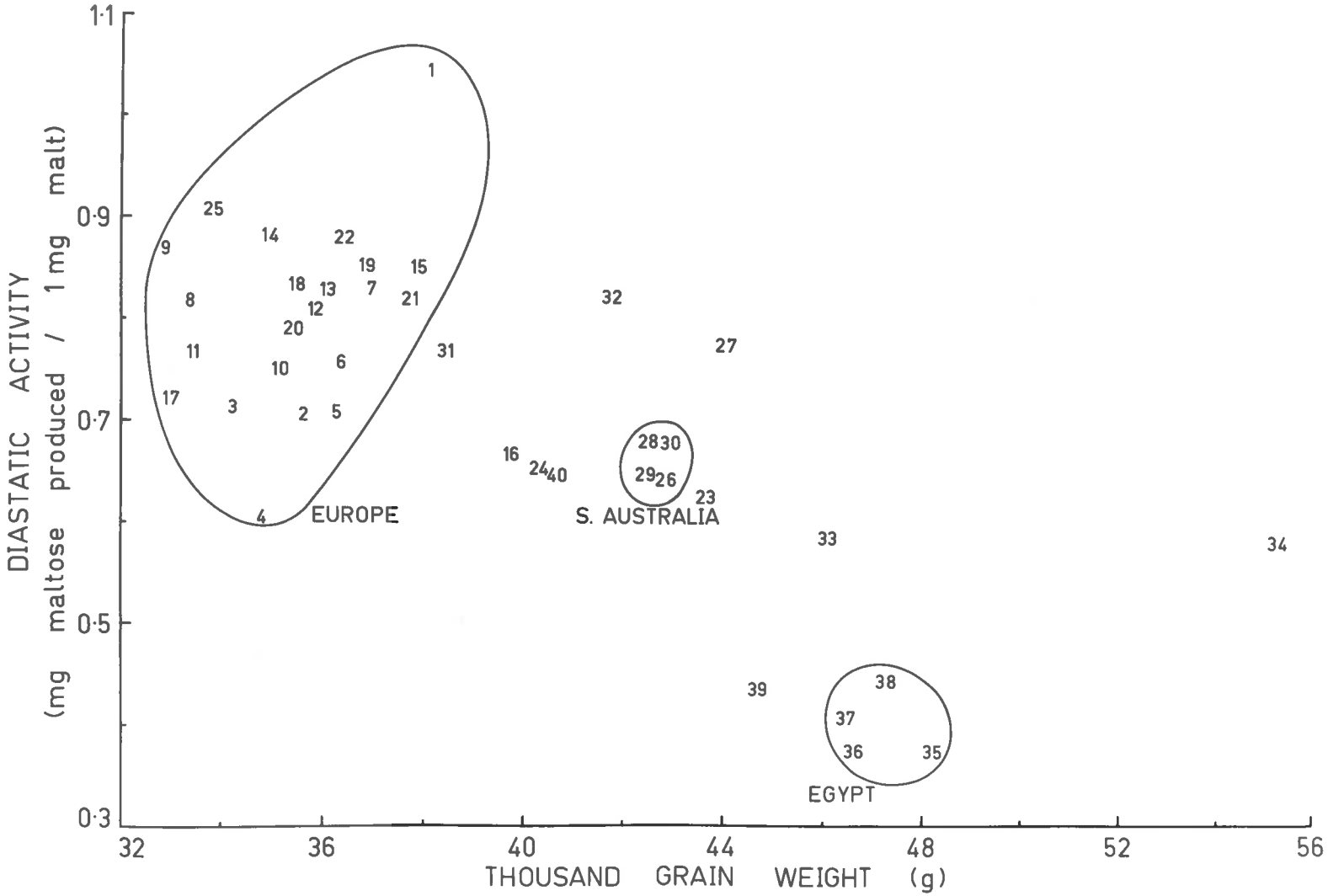

DIASTATIC ACTIVITY
(mg maltose produced / 1 mg malt)
1·1
0·9
0·7
0·5
0·3
32
36
40
44
48
52
56
THOUSAND GRAIN WEIGHT (g)
EUROPE
S. AUSTRALIA
EGYPT
1
25
14
22
9
19
15
18
13
7
21
8
12
32
20
27
11
31
10
6
17
3
2
5
4
16
24
40
28
30
29
26
23
33
34
39
38
37
36
35

TABLE 24

Partial correlation coefficients involving thousand grain weight and insoluble carbohydrate

		Malt Loss	Malt Extract	Cold Water Extract	Wort Nitrogen	Diastatic Activity
Insoluble Carbohydrate held constant.	Thousand Grain Wt.	.003	.058	-.226	.184	-.200
Thousand grain weight held constant.	Insoluble Carbo-hydrate.	-.492***	-.765***	-.225	-.557***	-.541***

In the first line of the table it is apparent that all the malt characters lose their association with grain size when partial correlations are calculated. In contrast, as is evident from the second line of the table the only correlation that has been reduced to non-significance is that with cold water extract, this malt character may thus be fairly equally dependent on both grain characters. The other partial correlations with insoluble carbohydrate remain significant. The main grain character determining varietal malt quality is therefore insoluble carbohydrate. An important inference is that it should be possible, using these 40 varieties as parents, to select lines with a grain size larger than that of the European varieties but with equivalent malting quality provided concurrent selection is made for low insoluble carbohydrate level.

Continuing with the results in table 23 it is evident that grain nitrogen, the most important factor in the environmental associations was of lower overall significance at the varietal level. It's

largest coefficient was a negative one with malt extract. Such an association is in agreement with those mentioned above, and a graph (Fig. 20) illustrates a somewhat similar arrangement of varieties except that three of those from Egypt (35, 36, 37) fall outside the main trend. If these are omitted from the calculation the correlation is considerably strengthened ($r = -.73^{***}$). Thus at both the environmental and varietal level the grain nitrogen content of the grain is an important determinant of the extractability of the malt.

Steep time showed significant associations with insoluble carbohydrate and malt extract, but the partial correlation with the latter ($r = .19$) indicates that the association is due to their common dependence on insoluble carbohydrate. What is less readily explicable is that despite the correlation between insoluble carbohydrate and thousand grain weight the latter is not associated with steep time. In addition, it is not easy to see why increasing amounts of insoluble carbohydrate should lead to a more rapid uptake of water in the steep. However, the correlation ($r = -.52^{***}$) is not large enough to be the only factor involved, although none of the characters measured seems to be implicated.

The remaining characters which are different aspects of malt quality, are all closely interrelated. This is not surprising, varieties with a rapid breakdown of endosperm during malting and mashing would be expected to show high values of all the characters measured. The disadvantage of this parallel effect is that it is desirable to restrict malt loss in order to maximise the amount of malt produced. Whilst in addition, the brewer specifies an optimum

FIGURE 20

The relation between grain nitrogen content and malt extract for 40 varieties.

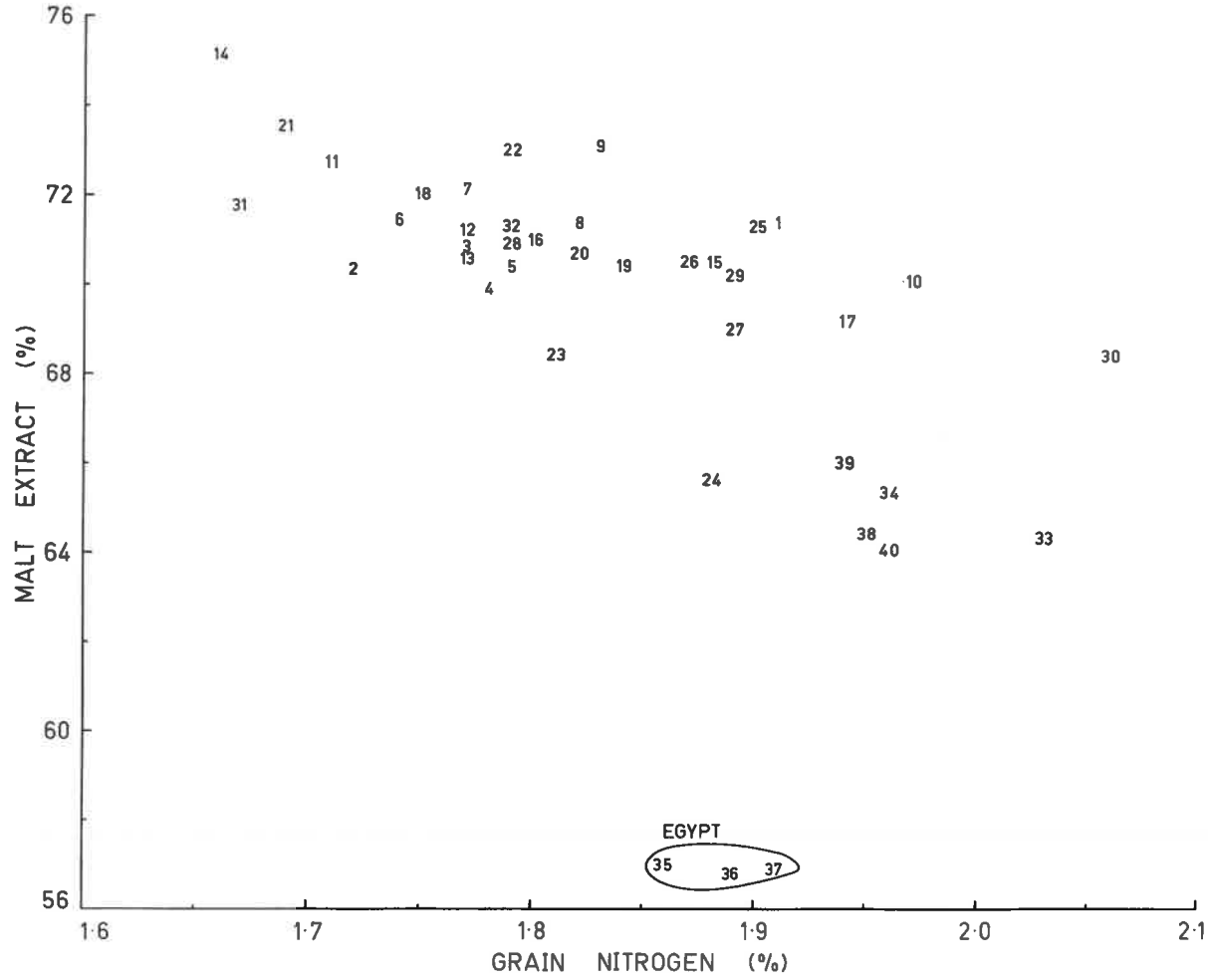
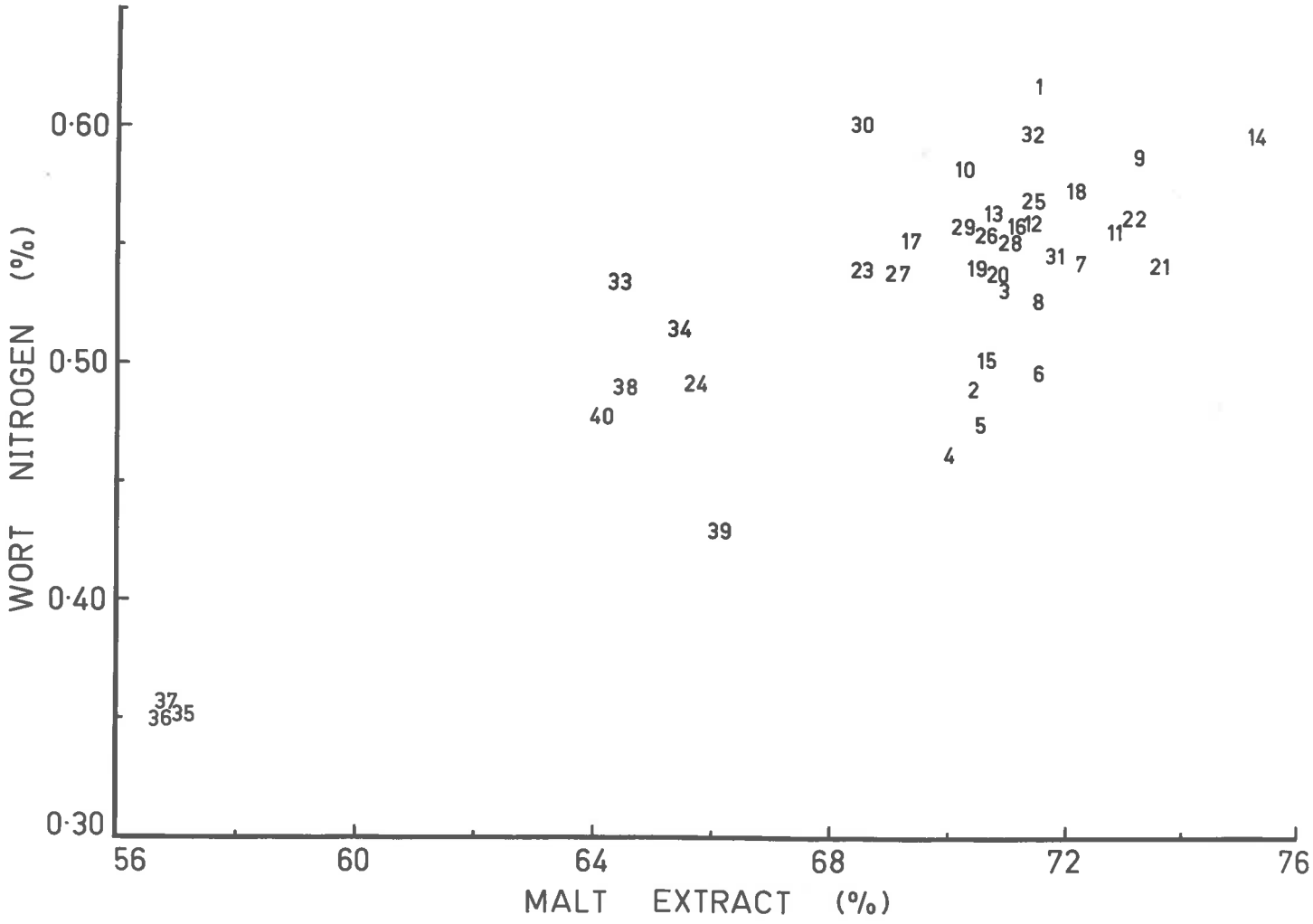

76
72
68
64
60
56
MALT EXTRACT (%)
1·6
1·7
1·8
1·9
2·0
2·1
GRAIN NITROGEN (%)
14
21
11
22
9
31
18
7
6
12
32
8
25
1
3
28
16
13
5
20
19
26
15
2
29
4
10
17
27
23
30
39
24
34
38
40
33
EGYPT
35
36
37

FIGURE 21

The relation between malt extract and wort nitrogen for 40 varieties.


WORT NITROGEN (%)
0·60
0·50
0·40
0·30
56
60
64
68
72
76
MALT EXTRACT (%)
1
30
32
14
9
10
18
25
13
29
26
16
12
22
11
17
28
31
7
23
27
19
20
21
3
33
8
34
15
6
38
24
2
40
5
4
39
37
36
35

rather than high levels of wort nitrogen. To satisfy these requirements it will be necessary to select material that deviates, as far as possible, from these correlations. The plot of varietal wort nitrogen on malt extract (Fig. 21) shows that although there are some deviates in the right direction, high extract and intermediate wort nitrogen, the advantage they confer is not large. Fortunately a reduction in wort nitrogen may not lead to a reduction in diastatic activity since the partial correlation between these two characters, with malt extract constant, is small (r = .30).

(c) Associations involving coefficients calculated in the adaptation analysis

The varietal means and regression coefficients calculated for each character in the adaptation analysis were presental in section 3, starting at page 99. It is useful to examine the interrelationships between means and regression coefficients (Table 25) and between the regression coefficients of the different characters (Table 26). In the case of the latter a positive correlation between two characters indicates that they showed a similar response to environmental change.

Attention has been drawn to the strong correlation between maturity and the response coefficient calculated for grain nitrogen content over 11 sites (Fig. 11, page 107). When the coefficient was calculated from the six site data the association was not so clear cut but is still significant at the .1% level. Maturity also showed correlations of a similar magnitude with the response coefficients for grain yield, malt extract and wort nitrogen and lesser associations with the other two malt characters (Table 25). The maturity of a variety under South Australian conditions, is therefore, an important

TABLE 25

Matrix of correlations between varietal means and environmental response coefficients over six sites

		Response to Environmental Change (Regr. Coefficient)						
		Yield	Thousand Grain Weight	Grain Nitrogen	Malt Extract	Cold Water Extract	Wort Nitrogen	Diastatic Activity
VARIETAL MEANS	Maturity	.506***	-.102	.597***	.677***	.338*	.549***	.419**
	Yield	.352*	.249	.138	-.044	-.110	.177	.041
	Thousand Grain Weight	-.606***	.209	-.279	-.506***	-.364*	-.735***	-.613***
	Grain Nitrogen	-.546***	-.161	.010	-.231	-.152	-.490**	-.405**
	Insoluble Carbohydrate	-.515***	.182	-.121	-.495**	-.254	-.665***	-.700***
	Steep Time	.268	.252	-.140	.122	-.205	.223	.342*
	Malt Loss	.462**	-.103	-.001	.317*	.264	.416**	.560***
	Malt Extract	.633***	.036	.121	.532***	.321*	.612***	.678***
	Cold Water Extract	.619***	-.078	.360*	.649***	.535***	.622***	.601***
	Wort Nitrogen	.455**	.025	.132	.467**	.349*	.468**	.557***
	Diastatic Activity	.635***	-.018	.206	.559***	.357*	.713***	.660***

n = 40, P > .05 = .304, > .01 = .393, > .001 = .490

TABLE 26

Matrix of correlations between environmental response coefficients over six sites

Response to Environmental Change (Regr. Coefficient)	Response to Environmental Change (Regr. Coefficient)	Thousand Grain Weight	Grain Nitrogen	Malt Extract	Cold Water Extract	Wort Nitrogen	Diastatic Activity
	Yield	.185	.393*	.500**	.249	.617***	.464**
	Thousand Grain Weight		.153	.033	-.084	.123	-.020
	Grain Nitrogen			.663***	.243	.432**	.142
	Malt Extract				.521***	.420**	.456**
	Cold Water Extract					.100	.237
	Wort Nitrogen						.562***

n = 40, P > .05 = .304, > .01 = .393, > .001 = .490

determinant of the relative sensitivity, in several characters, of its response to environmental change. Thus the late varieties were more sensitive than the early varieties and would be expected to vary more in yield and grain quality between sites and/or years.

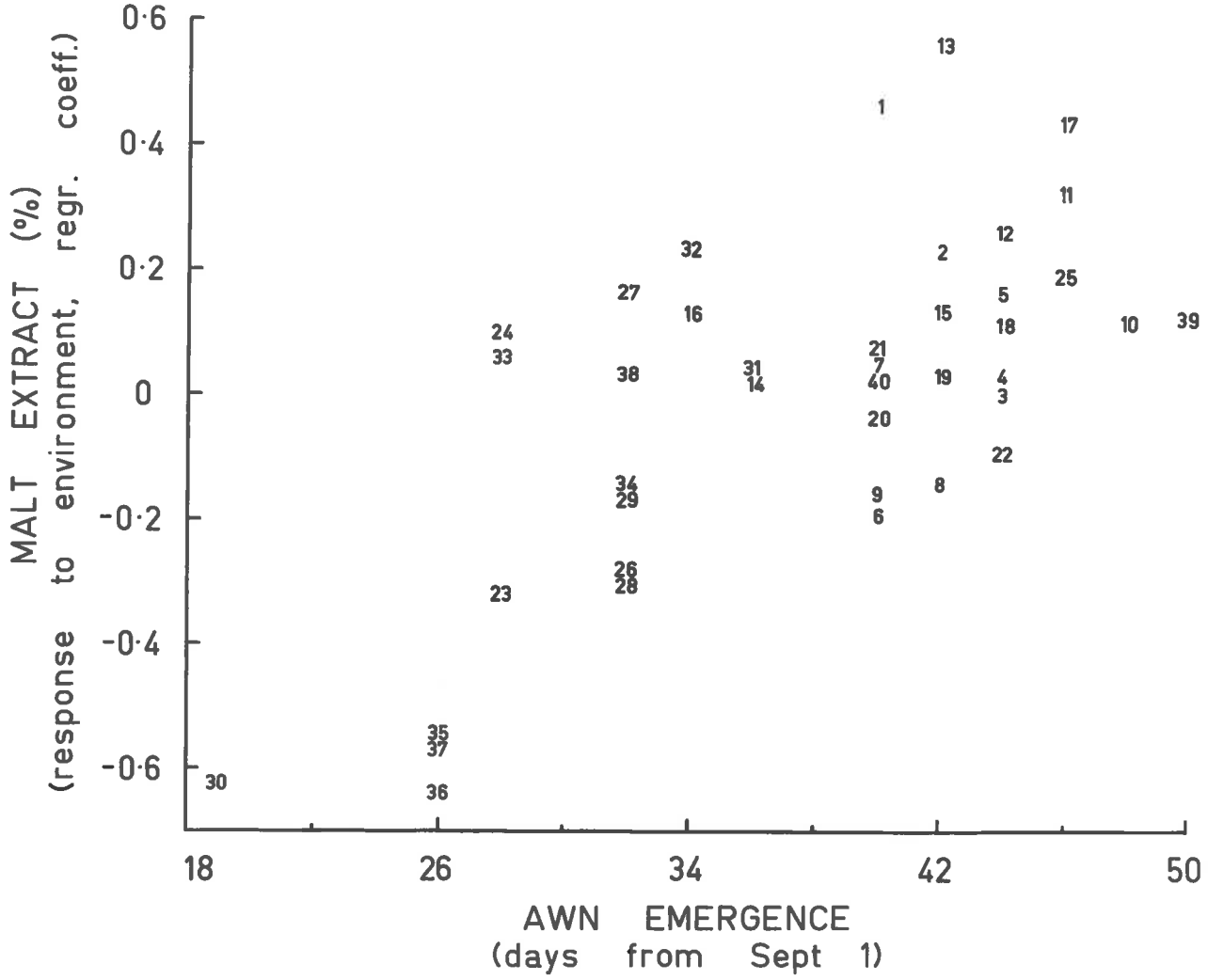
The relation between maturity and the malt extract response (Fig. 22) had a similar pattern to that between maturity and grain nitrogen response. In both cases the later maturing European varieties were the most sensitive. It is not surprising then that the two types of response are also relatively highly correlated (Table 26). However if the same correlation is calculated independently of maturity it remains significant ($r = .44^{***}$), although somewhat reduced indicating that the two responses are not entirely associated through maturity and other factors must be involved. On the other hand the lesser association between grain and wort nitrogen responses is reduced to non-significance ($r = .16$) when maturity is held constant.

Neither varietal yields nor steep time show strong associations with the response coefficients of any character (Table 25). However, the sensitivity of yields to environmental change is allied to those for malt extract, wort nitrogen and diastatic activity (Table 26).

Attention has already been drawn to the strong association between thousand grain weight and insoluble carbohydrate and their parallel influence on other characters. The common effect extended to the response coefficients, particularly those for malt extract, wort nitrogen and diastatic activity whilst the response for cold water extract was less influenced (Table 25). The environmental response of yield was also associated with these two characters although mean varietal yield was not. In other words, the non European varieties

FIGURE 22

The relation between maturity and malt extract stability for 40 varieties.


MALT EXTRACT (%)
(response to environment, regr. coeff.)
0·6
0·4
0·2
0
-0·2
-0·4
-0·6
18
26
34
42
50
AWN EMERGENCE
(days from Sept 1)
13
1
17
11
12
2
25
32
5
27
16
15
18
10
39
24
33
21
7
40
38
31
14
19
4
3
20
22
34
29
9
6
8
26
28
23
35
37
36
30

with large grains and/or an above average level of insoluble carbohydrate, tended to be relatively insensitive to environmental change in malt extract, wort nitrogen, diastatic activity and yield but not necessarily to be high or low in yielding ability. Interestingly the environmental response of grain size was not significantly correlated with any other character or response (Table 26) whilst the response of insoluble carbohydrate could not validly be calculated since the linear component of the genotype-environment interaction was not significant.

Grain nitrogen mean showed a reasonable correlation with the environmental response for yield, wort nitrogen and diastatic activity and these were all negative (Table 25). Thus the varieties which were more stable in yield also tended to be more stable in the other two characters and to have a higher grain nitrogen content. The environmental response of grain nitrogen was quite highly correlated with that of malt extract probably reflecting the correlation between the environmental and varietal means of the two characters (Table 26). As with the latter the removal of the values for the three Egyptian varieties (35, 36, 37) improved the correlation of the response coefficients ($r = -.73^{***}$). On the other hand, the responses of grain nitrogen and wort nitrogen show some association although their varietal means do not, and that of their environmental means just fails to reach significance.

The means of malt loss and the four malt characters all showed a similar pattern of associations with the response coefficients for the various characters (Table 25). The responses for yield, malt extract, cold water extract, wort nitrogen and diastatic activity were

positively associated with the malt characters, although the largest correlation was .71 and the majority were only of the order of .5 and .6. It seems then, with regard to the malt characters, the better varieties tend to be those which are more sensitive to environmental change both in the same characters and in yielding ability. This further emphasises that the European varieties, which have the best quality in the set studied, are not well adapted to South Australian cereal growing conditions. This is illustrated, for example, in Figure 23 which presents the relationship between the yield response coefficient and mean malt extract.

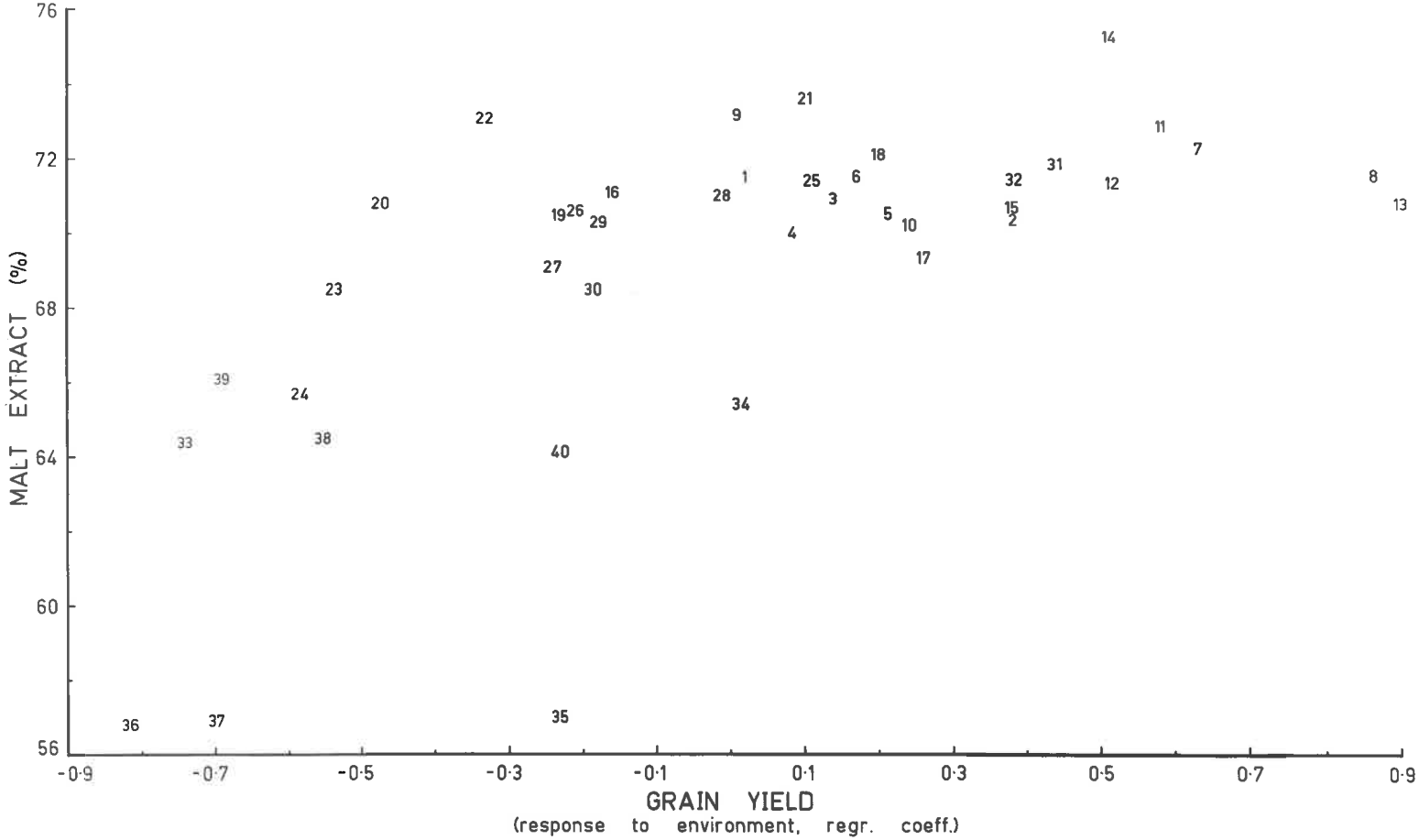
As might be expected the response coefficients of the malt characters were all more or less associated although those of cold water extract were not related to those of wort nitrogen and diastatic activity (Table 26). In fact the only associations of any size involving cold water extract response were those with malt extract response and mean cold water extract. It should be pointed out, however, that in the analysis of variance of this character the linear component of genotype-environment interaction was just below significance at the 5% level; too much weight should not, therefore, be put on figures for this character's response to environmental change. All aspects of malt extract, wort nitrogen and diastatic activity were relatively highly correlated indicating their considerable interdependence.

(d) Multiple associations from stepwise regression analysis

Multiple regressions were used to obtain further information on character interrelationships not available from a simple correlation matrix. The analysis was applied separately to the site and varietal

FIGURE 23

The relation between yield stability and malt extract for 40 varieties.


MALT EXTRACT (%)
76
72
68
64
60
56
-0·9
-0·7
-0·5
-0·3
-0·1
0·1
0·3
0·5
0·7
0·9
GRAIN YIELD
(response to environment, regr. coeff.)
14
21
22
9
11
7
18
1
25
6
31
32
8
12
16
28
3
20
19
26
29
5
15
2
13
4
10
27
17
23
30
39
24
34
33
38
40
36
37
35

means of the ten characters measured; relative extract was not included. The dependent variable was varied to include, in turn, each of the five malt characters. In the first instance the remaining nine variables were designated as independent and subsequently only the five grain characters were included as independent variables.

In the programme employed for this analysis the multiple regressions are used to calculate the proportion of the variance of each dependent variable that could be accounted for by the independent variables (i.e. r^2 rather than the correlation coefficient). It is these proportions that are considered below, first for the results obtained from all 40 varieties and second for those from the 25 variety subset.

The results obtained when all variables were included are given in Table 27. It is apparent that, in most cases, one independent variable accounts the major proportion of the variation in each dependent variable.

Thus, for malt extract, 87% of the variation between sites can be accounted for by differences in grain nitrogen and 79% of the variation between varieties by insoluble carbohydrate differences. This serves to further emphasise the influence on malt quality of grain nitrogen at the environmental level and, at least in this set of varieties, of insoluble carbohydrate at the varietal level.

As might be expected from the simple correlations that were considered previously malt extract, cold water extract, wort nitrogen and diastatic activity were closely interrelated. Thus 83% of the environmental variation in cold water extract was due to malt extract and wort nitrogen combined. The same variation in wort nitrogen and

TABLE 27

The proportion of the variance in five malt characters accounted for by ten quality characters from 40 varieties

	Site Means		Variety Means	
Malt Loss	Yield	69.5	Malt Extract	61.5
	Grain Nitrogen	13.4	Grain Nitrogen	3.8
			Steep Time	4.0
Malt Extract	Grain Nitrogen	86.9	Insoluble Carbohydrate	79.4
	Malt Loss	9.9	Wort Nitrogen	10.3
			Grain Nitrogen	4.4
Cold Water Extract	Malt Extract	45.0	Diastatic Activity	72.5
	Wort Nitrogen	38.0	Steep Time	4.8
	Diastatic Activity	9.6	Malt Extract	9.1
			Wort Nitrogen	3.9
Wort Nitrogen	Diastatic Activity	82.7	Malt Extract	68.5
	Cold Water Extract	15.4	Grain Nitrogen	12.2
			Cold Water Extract	4.9
			Thousand Grain Weight	4.9
Diastatic Activity	Wort Nitrogen	82.7	Malt Extract	73.7
	Cold Water Extract	15.5	Cold Water Extract	7.5

diastatic activity was mainly accounted for by each other with a smaller amount due to cold water extract. Varietal variation in malt extract accounted for 69% of that in wort nitrogen and 74% in diastatic activity, whilst 73% of the variation in cold water extract was also due to the latter character.

Nearly 62% of the varietal variation in malt loss could also be accounted for by that in malt extract but environmental variation in the same character was due mainly to yield differences and to a lesser extent grain nitrogen differences.

If only the five grain characters are included as independent variables the results of the analyses (Table 28) again strongly emphasise the environmental importance of grain nitrogen and the varietal importance of insoluble carbohydrate. Cold water extract was the only malt character not under the major influence of these two grain characters, being more dependent environmentally on yield and varietally on grain size. From a consideration of the partial correlations in Table 24 (page 127a) it has already been deduced that cold water extract might be dependent on both insoluble carbohydrate and thousand grain weight in contrast to the other malt character's strong association with the former. This subsequent evidence points to grain size as having the more important influence. The environmental influence of yield both on cold water extract and malt loss has already been covered under 5(a) (page 121) where it was suggested that conditions promoting high yields also produced a grain of greater maltability and extractability.

With regard to varietal differences in malting quality insoluble carbohydrate occupies a dominant position as an independent variable.

TABLE 28

The proportion of the variance in five malt characters accounted for by five grain characters from 40 varieties

	Site Means		Variety Means	
Malt Loss	Yield	69.5	Insoluble Carbohydrate	48.3
	Grain Nitrogen	13.4		
Malt Extract	Grain Nitrogen	86.9	Insoluble Carbohydrate	79.4
	Yield	8.5		
Cold Water Extract	Yield	41.6	Thousand Grain Weight	53.5
Wort Nitrogen	Grain Nitrogen	46.0	Insoluble Carbohydrate	43.3
	Steep Time	20.9		
Diastatic Activity	Grain Nitrogen	73.2	Insoluble Carbohydrate	64.8

This is illustrated in Figure 24 where malt extract is plotted against this variable, from which it is apparent that the North African and other non-malting varieties are generally high in non-extractable material. With 40 varieties (Table 20, page 119a) the mean value for insoluble carbohydrate was 8.01% and the genotypic variation .928; whilst for the 25 variety subset (Table 21, page 119b) the values were 7.47 and .170 respectively. The stepwise regression procedure was, therefore, carried out on the data from this subset of varieties to see whether the importance of this variable was altered when only malting varieties were considered.

The results of the analysis are presented in Tables 29 and 30.

For malt loss insoluble carbohydrate remained the most important independent variable whether all ten characters or only the five grain ones were entered in the analysis. But, the proportion of the variation involved was only half that which could be accounted for when the full set of varieties were analysed.

Up to 67% of the varietal differences in malt extract were due to differences in grain nitrogen and diastatic activity and up to 48% could be accounted for by grain nitrogen and insoluble carbohydrate if only the grain characters were considered. In the subset of malting varieties the relative importance of insoluble carbohydrate is, therefore, reduced and that of grain nitrogen increased. Tables 20 and 21 show that the genotypic variance of the latter is less affected by a reduction in the number of varieties analysed than is the former. However, because the variation in grain nitrogen is small and because it only accounts for one third of the varietal differences in malt extract it would not be feasible to use it as a criteria of malting

FIGURE 24

The relation between insoluble carbohydrate content and malt extract for 40 varieties.

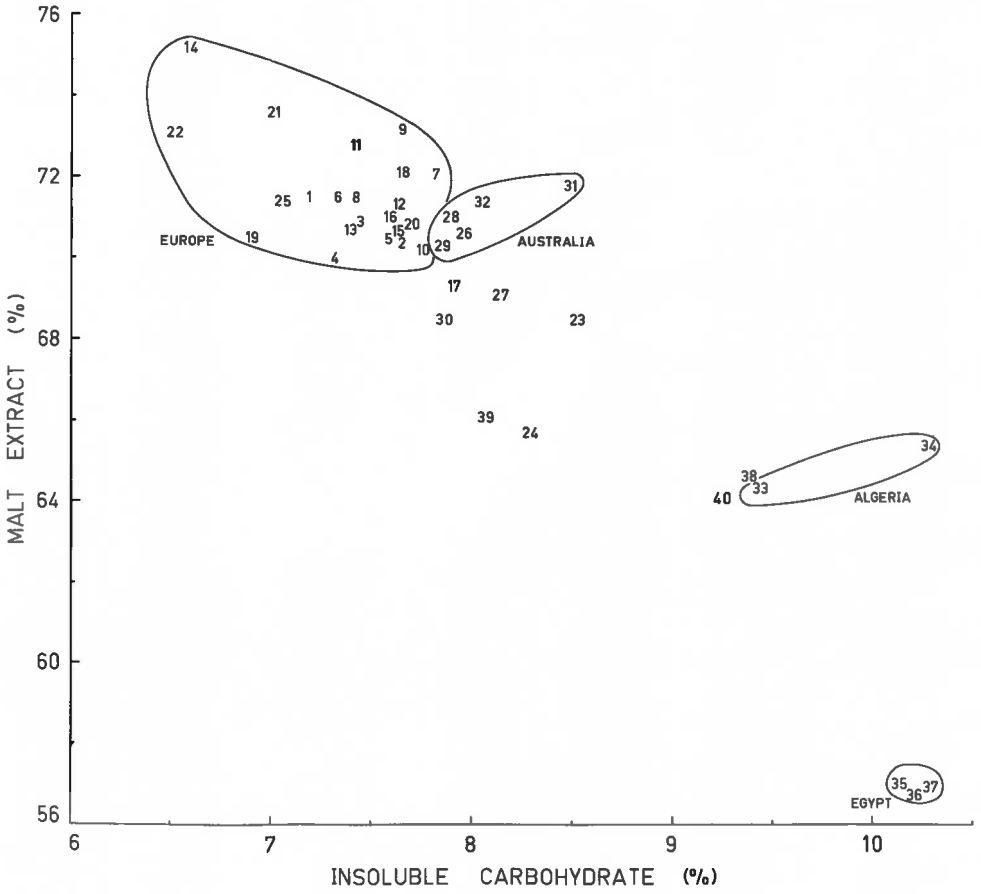

76
72
68
64
60
56
MALT EXTRACT (%)
6
7
8
9
10
INSOLUBLE CARBOHYDRATE (%)
EUROPE
AUSTRALIA
ALGERIA
EGYPT
14
21
22
9
11
18
7
25
1
6
8
12
31
32
16
3
13
15
20
28
5
2
10
29
26
19
4
17
27
30
23
39
24
34
38
33
40
35
36
37

TABLE 29

The proportion of the variance in five malt characters accounted for by ten quality characters from 25 varieties

	Variety Means	
Malt Loss	Insoluble Carbohydrate	24.0
Malt Extract	Grain Nitrogen	31.7
	Diastatic Activity	35.0
	Malt Loss	16.0
Cold Water Extract	Wort Nitrogen	62.3
	Steep Time	11.8
Wort Nitrogen	Cold Water Extract	62.3
	Thousand Grain Weight	8.8
	Malt Loss	10.0
Diastatic Activity	Wort Nitrogen	43.0
	Insoluble Carbohydrate	10.4

TABLE 30

The proportion of the variance in five malt characters accounted for by the five grains characters from 25 varieties

	Variety Means	
Malt Loss	Insoluble Carbohydrate	24.0
Malt Extract	Grain Nitrogen	31.7
	Insoluble Carbohydrate	16.1
Cold Water Extract	Not Significant	
Wort Nitrogen	Not Significant	
Diastatic Activity	Not Significant	

quality in this type of material.

The remaining three variables show a close interdependence as was the case when 40 varieties were analysed. The relationships were somewhat different; malt extract was not involved, and a small proportion of the variation (about 10%) in each character was due to a grain character. In contrast, when the five latter were entered into the analysis by themselves (Table 30) the F level was too low for a meaningful analysis to be made. In other words the correlations between the grain characters and these three malt characters were not significant.

6. Principal component analysis

The relevant theory and terminology concerning this analysis has been reviewed earlier (pages 63-67).

Eleven variables were studied by principal component analysis: these included the ten characters measured directly and the derived variable relative extract. Predicted extract was not included since it did contribute to the total variation. The 11 x 11 matrix of correlation coefficients was transformed to a matrix of 11 principal components. The latent roots show that five components accounted for 87% of the total variation (Appendix 9). Although the remaining components were found to be distinguishable from zero by means of the test suggested by Holland (1969), this is chiefly because of the large number of degrees of freedom. Since no other satisfactory test is available it was necessary to make an arbitrary choice of components to be interpreted; selection of those accounting for approximately 90% of the total variation has general acceptance.

The eigen vectors (the values assigned to each variable) of the

first five components were converted to component loadings (multiplied by the square root of the appropriate latent root) (Table 31). This weights them according to their importance and enables comparisons to be made between the loadings of a variable on each component as well as those of each variable on a single component; a considerable aid to interpretation. When more than one component has a high loading on a variable, then each component involved influences the variable in proportion to the magnitude and sign of the loading. Loadings are comparable to standardized partial regression coefficients of the principal components on the variables. Since there is no satisfactory test of significance for component loadings only those greater than .30 were interpreted.

The first component, accounting for nearly half the total variation, showed high loadings on all but two characters, yield and grain nitrogen. Grain size and insoluble carbohydrate had positive loadings whilst all the malting characters had negative loadings. Since the highest loadings were on malt extract, cold water extract and relative extract it is appropriate to designate this component 'extractability'. The contrast shows that high extractability was negatively associated with large grain and high levels of insoluble carbohydrate. But, significant negative loadings for steep time, malting loss, wort nitrogen and diastatic activity indicate that all these characters were associated with extractability. The first component was therefore a general component that accounted for all the interdependent malting quality characters.

The second component had high loadings on grain nitrogen, diastatic activity and wort nitrogen which contrast with somewhat

TABLE 31

Component loadings on first five components of a matrix of 11 principal components

Variable \ Component		1	2	3	4	5
Yield		-.217	-.543	.238	.556	.422
Thousand Grain Weight		.526	-.274	.694	-.043	-.177
Grain Nitrogen		.221	.847	.286	.215	.139
Insoluble Carbohydrate		.788	-.030	.242	.271	-.371
Steep Time		-.436	-.179	.547	-.588	.261
Malting Loss		-.714	.030	.195	.349	.180
Malt Extract		-.845	-.469	-.094	-.134	-.125
Cold Water Extract		-.847	-.091	-.114	.173	-.246
Wort Nitrogen		-.620	.623	.283	-.021	-.144
Diastatic Activity		-.582	.716	-.012	-.011	.043
Relative Extract		-.767	-.177	.257	.144	-.404
Proportion of total variance		.40	.21	.11	.09	.06
Percentage of total sum of squares	environment	9.57	74.76	25.90	37.08	18.86
	genotype	81.62	8.37	44.76	32.23	38.31

lower loadings on yield and malt extract. This component demonstrates the well established associations between the nitrogen characters on one hand, yield and extract on the other, and can, therefore, be termed 'grain-nitrogen'.

Thousand grain weight and steep time were the only major variables on which the third component was loaded; it can thus be designed 'Grain size'. This component points to an association between these two characters which was not apparent from their original correlation ($r = .10$). However, the within variety correlation of these two characters was almost significant ($r = .61$), the within site correlation was not ($r = -.15$). The component loadings on these characters therefore reflect the environmental influence on their association.

The fourth and fifth components reveal additional unexpected associations. The former had a loading on yield allied with a small one on malting loss and contrasting with one on steep time. In other words high yield was associated with increased malt loss, as previously deduced in 5(a) (page 121), and rapid water uptake. Within the context of the malting method employed rapid water uptake would be likely to mean increased rate of germination and hence increased malt loss. The relationship between yield and water uptake was unexpected but may imply that high yield had influenced either the constitution of the endosperm or its covering layers so as to afford a more rapid entry of water during steeping. (Compare Anderson et al. (1941) who found a positive association between grain size and rate of water uptake.) The fifth component had a small positive loading on yield contrasting with negative loadings on insoluble

carbohydrate and relative extract. This suggests that increases in yield may cause a reduction in insoluble material in the grain.

In order to further the interpretation of the components a score for each of the first five components was calculated for each of the original 480 entries (40 varieties x 6 sites x 2 replications). The resultant data, for each component, was subjected to an analysis of variance (Appendix 10).

For the first, or 'extractability', component a very high proportion of the total sums of squares was attributable to genotypes indicating that variability in this direction was chiefly an inherited characteristic. On the other hand the second, or 'grain nitrogen', component had most of its variation attributable to differences between sites and was thus mainly influenced by the environment. It can be seen that components one and two are both loaded on malt extract, with nitrogen and diastatic activity. This is in agreement with previous deductions that these three characters although inherited are strongly influenced by the environment via the grain nitrogen content. The remaining three components had an intermediate partitioning of variation; genetic and environmental influences were of a similar magnitude.

The high heritability of the first component suggests an additional use for the analysis that has not previously been considered. As already pointed out the components are linear functions of the original variables, the component scores were obtained from this function. Each variety can be described in terms of any component; where the score is highly heritable it could provide a useful selection criterion for the variety. The average first component

scores for each variety (Table 32) rank the varieties very close to their appropriate position with regard to maltability. Thus component loading provides an objective method of deriving a selection index without recourse to arbitrary weighing of variables. However, three problems could arise. First, the use of an excessive number of variables would be undesirable in a selection programme. Hence the initial principal component analysis might be used to select variables easy to measure and with high loadings. A further analysis of the reduced set would then be used to derive the selection index. Second, variables in which an optimum rather than a maximum or minimum value was required would have to be scaled accordingly. Third, a selection index derived from a set of varieties might not be appropriate for hybrid lines, but providing the parent varieties and only their close relatives occurred in the original set, it is unlikely that too much difficulty would be encountered.

Further light can be thrown on the influence of environment on the second component. The original principal component analysis was carried out on a correlation matrix derived from all 480 cases (40 varieties x 6 sites x 2 replicates). Additional analyses were performed on correlation matrices derived from the 40 variety means and the six site means i.e. the genotypic and environmental matrices; the loadings of the first two components in each analysis are presented in Table 33.

Averaging over sites eliminated the environmental effect. Compared to the original analysis (Table 31) component 2 was still loaded on grain nitrogen but only slightly on wort nitrogen and insignificantly on diastatic activity; it was also more heavily loaded

TABLE 32

40 varieties ranked according to their mean score on the first component

(LSD 1% = .54)

Variety	Mean Score
Beka	- 2.64
Juliane	- 1.96
Impala	- 1.93
Domen	- 1.71
Goldfoil	- 1.60
Union	- 1.54
Proctor	- 1.38
Emir	- 1.33
Morgenrot	- 1.31
G/Spratt	- 1.16
Baldric	- 1.11
Boa Fe	- 1.09
Resibee	- 1.09
Cambrinus	- 1.09
Haisa II	- 0.96
Maythorpe	- 0.94
Rika	- 0.88
Research M.R.	- 0.84
Piroline	- 0.72
Portugal 2-Row	- 0.65

Variety	Mean Score
Ceres	- 0.57
Delta	- 0.54
Priors	- 0.30
Rigel	- 0.26
Freja	- 0.20
Prior A	- 0.17
Compana	- 0.11
Noyep	- 0.02
Bonus	+ 0.11
Long Outer Glume	+ 0.23
Kankyo	+ 0.31
CPI. 18197	+ 1.45
Hanna	+ 1.55
W. Smyrna	+ 2.00
CPI. 18198	+ 2.13
G.H. Sinai	+ 2.28
CI 5611	+ 2.44
Retu	+ 5.17
CI 3576	+ 5.19
Waite 775	+ 5.24

TABLE 33

Loadings on First two Components from Principal Component Analysis of Genotype Matrix

Variable \ Component	1	2
Yield	- .001	.771
Thousand Grain Wt.	.764	- .366
Grain Nitrogen	.488	- .645
Insoluble Carbohydrate	.891	- .078
Steep Time	- .458	- .396
Malting Loss	- .840	- .088
Malt Extract	- .977	.011
Cold Water Extract	- .877	.099
Wort Nitrogen	- .869	- .341
Diastatic Activity	- .921	- .017
Relative Extract	- .849	- .231
Proportion of total variance	.60	.73

Loadings on First two Components from Principal Component Analysis of Environmental Matrix

Variable \ Component	1	2
Yield	.775	.295
Thousand Grain Wt.	.657	.259
Grain Nitrogen	- .753	.555
Insoluble Carbohydrate	- .831	- .144
Steep Time	.554	.497
Malting Loss	.527	.552
Malt Extract	.927	- .295
Cold Water Extract	.732	.306
Wort Nitrogen	- .436	.820
Diastatic Activity	- .709	.678
Relative Extract	.846	.261
Proportion of total variance	.52	.22

on yield and steep time. Component 1 showed an increased loading on grain nitrogen and a negligible loading on yield. In other words the removal of the environmental effect had destroyed the positive relationship between grain nitrogen and wort nitrogen and diastatic activity. However, the first component is loaded on all characters except yield and here grain nitrogen with positive sign is in contrast with the malt characters which all have negative sign. In other words varieties with high grain nitrogen have low values for all the malt characters.

When the results are averaged over varieties the second component remains loaded on grain nitrogen, wort nitrogen and diastatic activity; it also shows an increased loading on steep time and malting loss. In addition the first component also has negative loadings on grain nitrogen, wort nitrogen and diastatic activity as well as insoluble carbohydrate. When the genotypic effect is removed the relationship of these three characters is enhanced and they are distinguished from the other malt characters by the sign of the loading. In other words at sites where the grain produced has a high nitrogen content the malts are characterised by increased levels of wort nitrogen and diastatic activity.

7. Discriminant Analysis

A stepwise discriminant analysis was applied to the data for 11 characters from, in the first case, all 40 varieties and subsequently the 25 variety subset. For each character the ratio of the between population to the within population variation provided a yard stick on which to evaluate that character for it's discriminatory ability between varieties.

The value of F required for a character to be entered in the analysis was set at 3.0 (see Materials and Methods, 4(e), page 90 for method of determining appropriate F value). The order in which the characters entered the analysis together with their F value at that stage are listed in Table 34. The remaining three characters had F values less than 3.0 indicating that most of the between population variation was accounted for by the first eight characters.

Insoluble carbohydrate provided the greatest discrimination between populations, in other words for this character the ratio of between population to within population variances was largest. The other seven characters were of progressively lesser importance. Of the three characters having a low and non significant discriminating value yield and grain nitrogen originally had very low F values, i.e. a small between to within population variance ratio. The discrimination contributed by malt extract was reduced to insignificance by the inclusion of the other, correlated characters. Thus relative extract, a linear function of malt extract, entered the analysis earlier and contributed the discriminatory variance that would have been attributed to malt extract.

When the eight characters were entered in the analysis the eight uncorrelated, canonical axes were derived. The latent roots of these axes and the cumulative proportion of the total variance accounted for by each axis progressively are given in Appendix 11. Since the first two axes accounted for 84% of the total variation a good approximation to the distribution of the 40 populations can be obtained by plotting each variety in terms of its coordinates on these two axes (Fig. 25).

TABLE 34

Order in which variables entered a stepwise discriminant analysis of 40 varieties

Variable	Original F	F at entry to analysis
Insoluble Carbohydrate	44.332	44.332
Thousand Grain Wt.	33.298	22.717
Relative Extract	16.322	18.609
Cold Water Extract	22.217	10.987
Steep Time	7.127	5.471
Diastatic Activity	11.079	5.546
Wort Nitrogen	9.954	7.234
Malt Loss	9.428	4.963
Yield	1.145	2.525
Grain Nitrogen	.753	2.775
Malt Extract	15.236	2.769

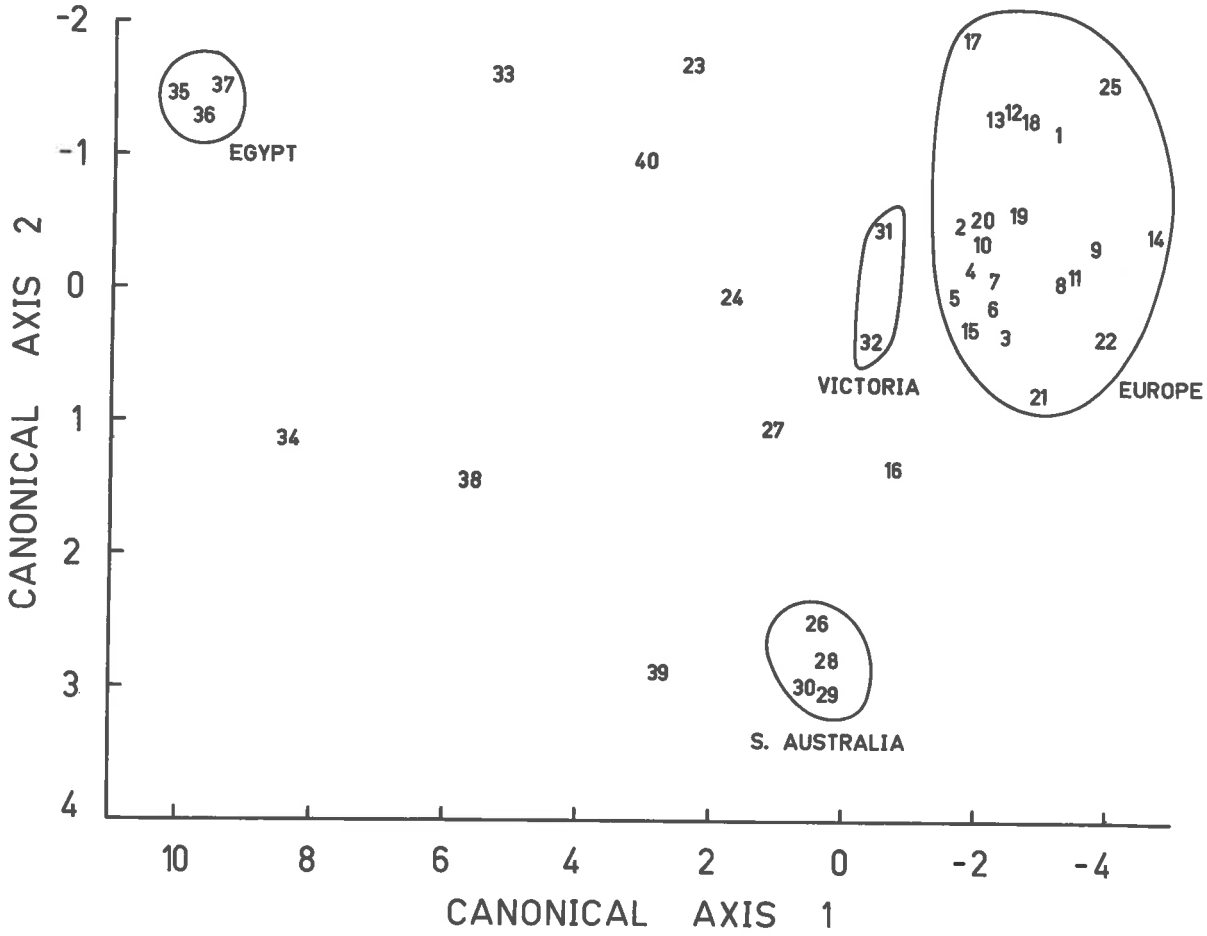
TABLE 35

Loadings on first three canonical axes of a discriminant analysis of 40 varieties

Variable \ Axis	1	2	3
Thousand Grain Wt.	3.035	- 1.371	- .803
Insoluble Carbohydrate	3.629	.291	- .817
Steep Time	- 1.032	- .874	.558
Malt Loss	.020	- .148	- .909
Cold Water Extract	- 2.658	1.388	- 1.276
Wort Nitrogen	- 1.821	- 1.243	- .795
Diastatic Activity	- 1.626	.108	- .362
Relative Extract	- 3.001	- 1.360	- .188
Proportion of total variance	.71	.13	.08

FIGURE 25

Canonical diagram for 40 varieties derived from a discriminant analysis of 8 grain and malt quality characters.


-2
-1
0
1
2
3
4
CANONICAL AXIS 2
10
8
6
4
2
0
-2
-4
CANONICAL AXIS 1
EGYPT
35 37
36
VICTORIA
31
32
EUROPE
17
25
13 12 18 1
2 20 19
10
9
14
4
7
8 11
5
6
15
3
22
21
33
23
40
24
27
34
38
16
26
28
30 29
39
S. AUSTRALIA

In the analysis the greatest spatial separation between the malting and non malting types took place on the first canonical axis, it accounted for 71% of the total variance. As in the principal component analysis the eigen vectors of each axis, when multiplied by the square root of the appropriate latent root, provide an indication of the relative importance of each character on each axis (Table 35). The two characters with the highest loadings on the first axis were insoluble carbohydrate and thousand grain weight, these contrasted in sign with relative extract, cold water extract, wort nitrogen and diastatic activity which were of lesser importance. In other words the characters which reflected the 'extractability' of the endosperm, provided the greatest discrimination between varieties and it was mainly in respect of these that the non malting varieties were differentiated from the others, thus confirming the univariate relationships discussed above. It should be noted that on this axis the Australian varieties, both from Victoria and South Australia, were separated from the European types.

The second axis accounted for a further 13% of the total variance; the most important variable was cold water extract which was contrasted with relative extract, wort nitrogen and grain size. This axis may indicate varietal differences in the action of enzymes on the endosperm during malting (i.e. modification). It is interesting that three of the Egyptian and several other non malting varieties do not differ from the European types on this axis. Varieties which do differ include the three from South Australia, Compana (26), Turk (39), Glaucous Head Sinai (38), CPI. 18198 (34) Long Outer Glume (27) and Portugal 2-row (16).

The loadings on the third axis, which only accounted for 8% of the variation, are included in Table 35 for comparison with the results in the subsequent discrimination (Table 37). On this axis all the variables except steep time had a negative loading with cold water extract the most important; this was the only axis on which malt loss showed a sizeable loading.

For a more accurate comparison of varieties the linear distance, in the eight dimensional space ($\sqrt{D^2}$), was calculated for each pair of varieties. (See Appendix 16 ~~in back pocket~~). The 780 distances ranged from 0.55 to 14.84, and of these 742 were significant at the .1% level. [Significant distances, by the method of Whitehouse (1969), were 1.49 and 1.90 at the 1% and .1% level respectively].

The distribution of the 40 varieties can be interpreted by using the table of distances in conjunction with the two dimensional canonical graph. The extreme diversity of the material under study is readily apparent, but it was also possible to delineate varieties with a similar geographic origin. At one extreme, and at a significant distance from the others, were the three Egyptian varieties; at another extreme, the large group of European varieties. The Australian varieties were a significant distance from the European group, and it was possible, in terms of the second axis, to distinguish between those from South Australia and Victoria.

Varieties, other than those already mentioned, lying outside the European area included various entries from the Mediterranean basin and North America. One of these, Compana (26), lay very close to the South Australian group and even when all dimensions were considered was not a significant distance (.76) from the group. There is no

reason to suppose that this variety is related to this group but its origin as a selection from Harlan's Composite Cross I would be obscure and it is an early maturing type similar to Chevallier. On the other hand the variety Portugal 2-row (16) was also at a distance of only 2.10 from the South Australian group and in view of the similarity of climate in the two areas might be a similar type. The other Portuguese variety, Boa Fe (17) was situated well within the European group. One particular anomaly amongst the outliers was the variety Hanna (24). This variety, selected from the Moravian land race, was well outside the modern European group. (It's anomalous character has already been mentioned, page 77). The original data showed this variety to be higher in insoluble carbohydrate and of lower extractability than other European varieties, which probably accounts for the discrimination. The remaining varieties were quite distinct, even from the Egyptian group, indicating a wide degree of variability amongst non-malting types. The discriminant analysis therefore confirms the view that the European, two row malting varieties are a small specialized group amongst the variation available in the species as a whole.

Since the European varieties were clustered on the graph and were not easily distinguished it seemed useful to attempt a greater resolution by reanalysing these varieties alone. Accordingly the data from the European subset of 25 varieties (see page 118) was subjected to a further stepwise discriminant analysis.

Table 36 provides details of the order in which the characters entered the analysis. The same eight characters were the major factors in discrimination and were similarly ranked except that relative

TABLE 36

Order in which variables entered a stepwise discriminant analysis of 25 varieties

Variable	Original F	F at entry analysis
Insoluble Carbohydrate	13.043	13.043
Thousand Grain Wt.	7.165	9.025
Cold Water Extract	4.905	6.802
Steep Time	3.489	4.529
Relative Extract	3.848	4.145
Diastatic Activity	2.998	4.855
Wort Nitrogen	3.106	5.025
Malt Loss	4.244	4.111
Yield	.911	2.341
Grain Nitrogen	.502	2.788
Malt Extract	1.241	2.785

TABLE 37

Loadings on first three canonical axes of a discriminant analysis of 25 varieties

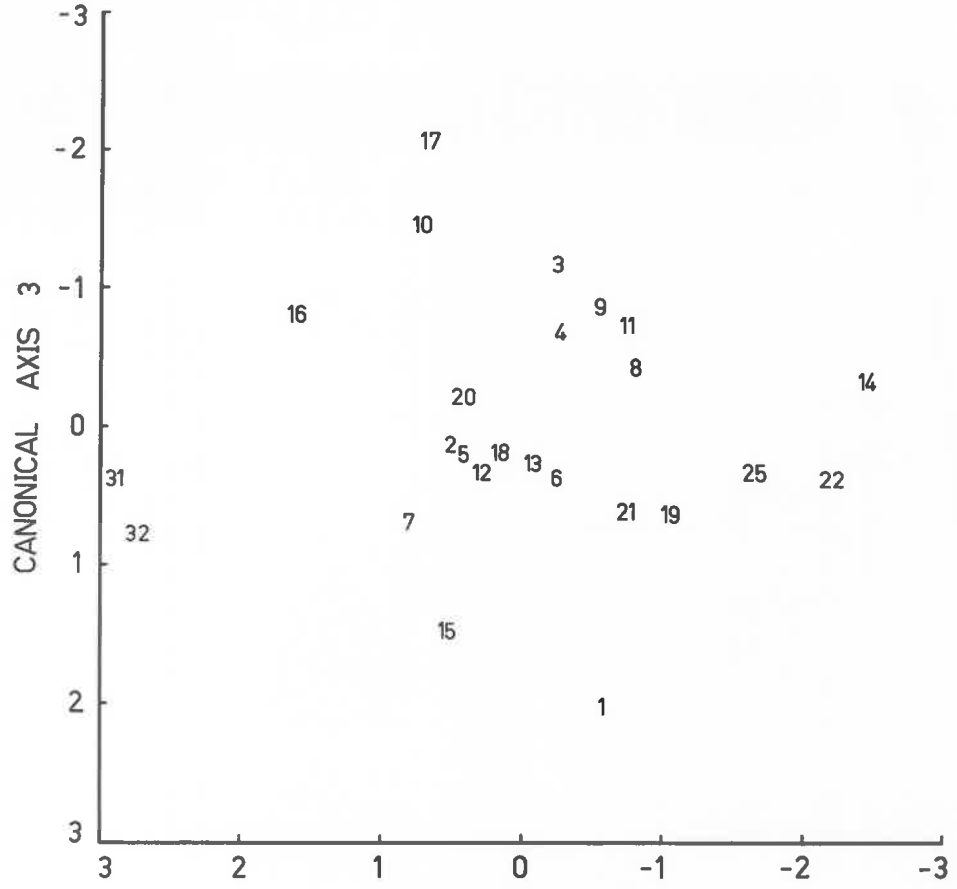
Variable \ Axis	1	2	3
Thousand Grain Wt.	.697	- 1.077	- .785
Insoluble Carbohydrate	1.007	.616	- 1.232
Steep Time	.206	- .457	.193
Malt Loss	- .025	- .326	- .189
Cold Water Extract	- 1.234	.915	- .703
Wort Nitrogen	- .968	- .409	- .585
Diastatic Activity	- 1.101	- .772	- .205
Relative Extract	.213	- .474	- .396
Proportion of total variance	.32	.23	.20

extract was displaced in importance by cold water extract and steep time. The F values for insoluble carbohydrate, grain size and relative extract were considerably reduced by the omission of 15 varieties; in this study large, husky grains were associated with non-malting types.

The eight, uncorrelated, canonical axes were derived from the data; their latent roots and cumulative proportion of the total variance are given in Appendix 12. The first two axes accounted for little more than half (55%) of the total variation, in contrast to 84% when the 40 varieties were considered. Since the third axis accounted for a further 20% of the variation Figure 26 includes a plot of the 25 varieties in two planes. The loadings of the variables on the first three axes (Table 37) were consistent with the results for 40 varieties (Table 35) although their relative magnitude tended to be different. Thus the first axis was oriented in the positive direction of insoluble carbohydrate and grain size and the negative direction of cold water extract, wort nitrogen and diastatic activity; relative extract was of less importance than in the previous discrimination. The second axis again had cold water extract and grain size in contrast, whilst wort nitrogen was reduced in importance in favour of diastatic activity. Insoluble carbohydrate and grain size were of considerable importance on the third axis but, as previously, were of the same sign as other variables except steep time. Malt loss was of negligible importance on this axis compared to the previous discrimination. Because of the agreement in sign of the malt and grain variables this third axis probably represented some factor

FIGURE 26

Canonical diagrams for 25 varieties derived from the same data as figure 25.


CANONICAL AXIS 3
-3
-2
-1
0
1
2
3
3
2
1
0
-1
-2
-3
17
10
3
16
9
4
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20
2
5
18
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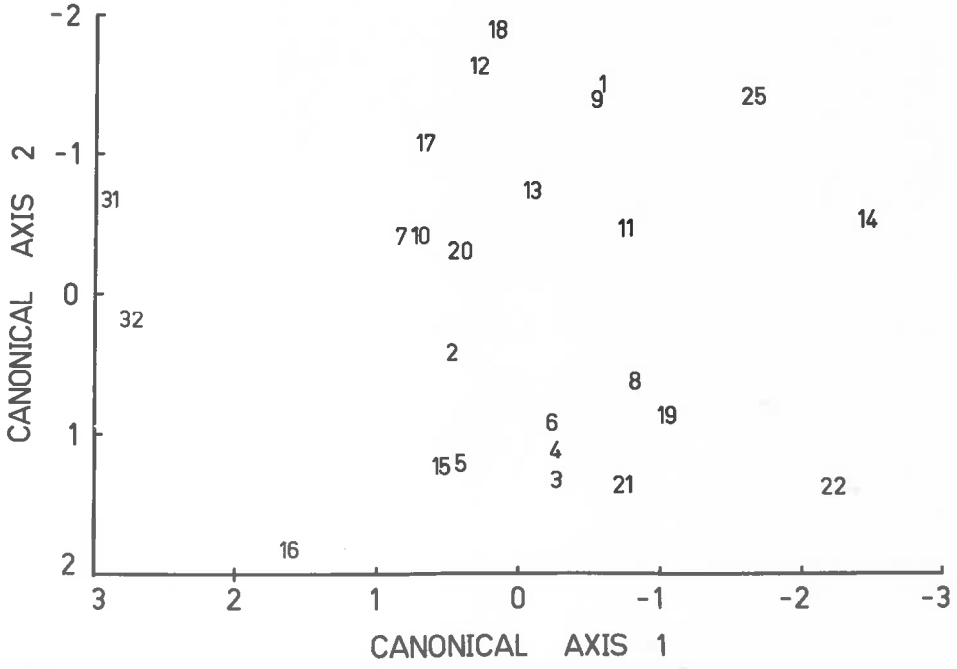
12
6
25
22
31
7
21
19
32
15
1


CANONICAL AXIS 2
-2
-1
0
1
2
3
2
1
0
-1
-2
-3
18
12
1
9
25
17
13
31
11
14
7
10
20
32
2
8
19
6
4
15
5
3
21
22
16
CANONICAL AXIS 1

other than extractability.

The distribution of varieties in the lower half of Figure 26 is somewhat similar to that in Figure 25. The two Victorian varieties (31, 32) and Portugal 2-row (16) appear in the same relation to the main European group. No strong subgrouping of the European varieties was apparent although there was a tendency for the English varieties (11, 12, 13) to have negative values for the second axis and the Scandinavian varieties (1-5) positive values. The separation on the third axis does little to aid the interpretation of the varietal discrimination. In view of the considerable intermixing of European germplasm over half a century of plant breeding it is not surprising, that one can no longer discriminate between varieties from different areas.

In contrast to the first discriminant analysis the third (20%) and fourth (11%) axes accounted for a considerably larger proportion of the total variation and thus the multidimensional discrimination was of greater importance. The 300 distances (Appendix 17 ~~in back pocket~~) ranged from 0.63 to 5.64, and of these 276 were significant at the 1% level. (Significant distances were as before 1.45 and 1.90 at the 1% and .1% levels respectively). If the same 300 comparisons are made in the first analysis, 262 are significant at the same level. A separate analysis has therefore, only slightly improved the discrimination of the European subgroup.

8. Varietal response to Gibberellic Acid

These studies are considered in three parts, a, b and c which differ in the material used and in the details of the experiments.

(a) Eight varieties and five concentrations

Eight varieties were selected to represent the range of diversity available in the complete set of 40 varieties. Those chosen were Domen (1), Proctor (11), Beka (14), Long Outer Glume (27), Prior's Chevalier (28), Resibee (32), CPI. 18197 (33) and CI. 3576 (36). Five concentrations of gibberellic acid (GA_3) (0, .001, .01, .1, 1.0 ppm) provided a range greater than that used in commercial malting. Grain of the eight varieties was obtained from plots grown at Bundaleer in 1963; 25 gram samples were micro-malted with a four day germination period as detailed under Materials and Methods (Table 11, page 81a). The kilned malts were analysed for malt extract, wort nitrogen and diastatic activity; the full results are given in Appendix 13.

The results obtained for diastatic activity will be considered first because they are clearer than those of the other two analyses. This was expected since a large part of diastase, namely alpha-amylase, is released directly from the aleurone in response to stimulus by the hormone. In Figure 27 the results for six of the eight varieties are plotted; those omitted, Domen and CPI. 18197, were essentially similar to Beka and Proctor respectively. All the varieties showed the same type of response curve, exponential without any flattening off to an asymptote, but the shape of the curve did vary between varieties. Thus in Proctor there was an almost regular increase in enzyme activity between four concentrations of GA_3 whilst Beka and Long Outer Glume showed an increasing response to increasing concentrations. The three remaining varieties in the

FIGURE 27

Diastatic activities of 6 varieties treated with varying concentrations of GA_3.

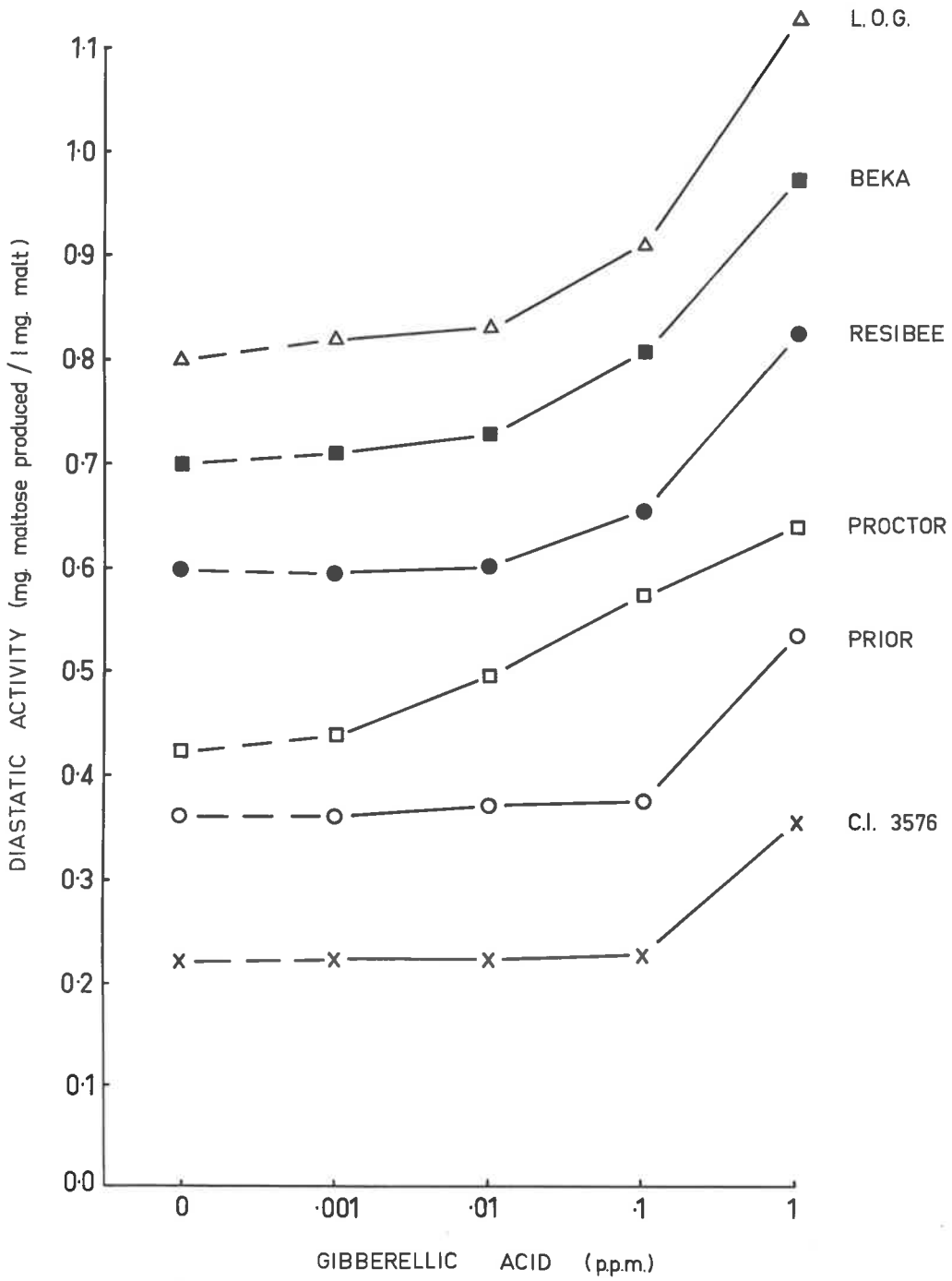

L.O.G.
BEKA
RESIBEE
PROCTOR
PRIOR
C.I. 3576
DIASTATIC ACTIVITY (mg. maltose produced / 1 mg. malt)
1·1
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0·0
0
·001
·01
·1
1
GIBBERELLIC ACID (p.p.m.)

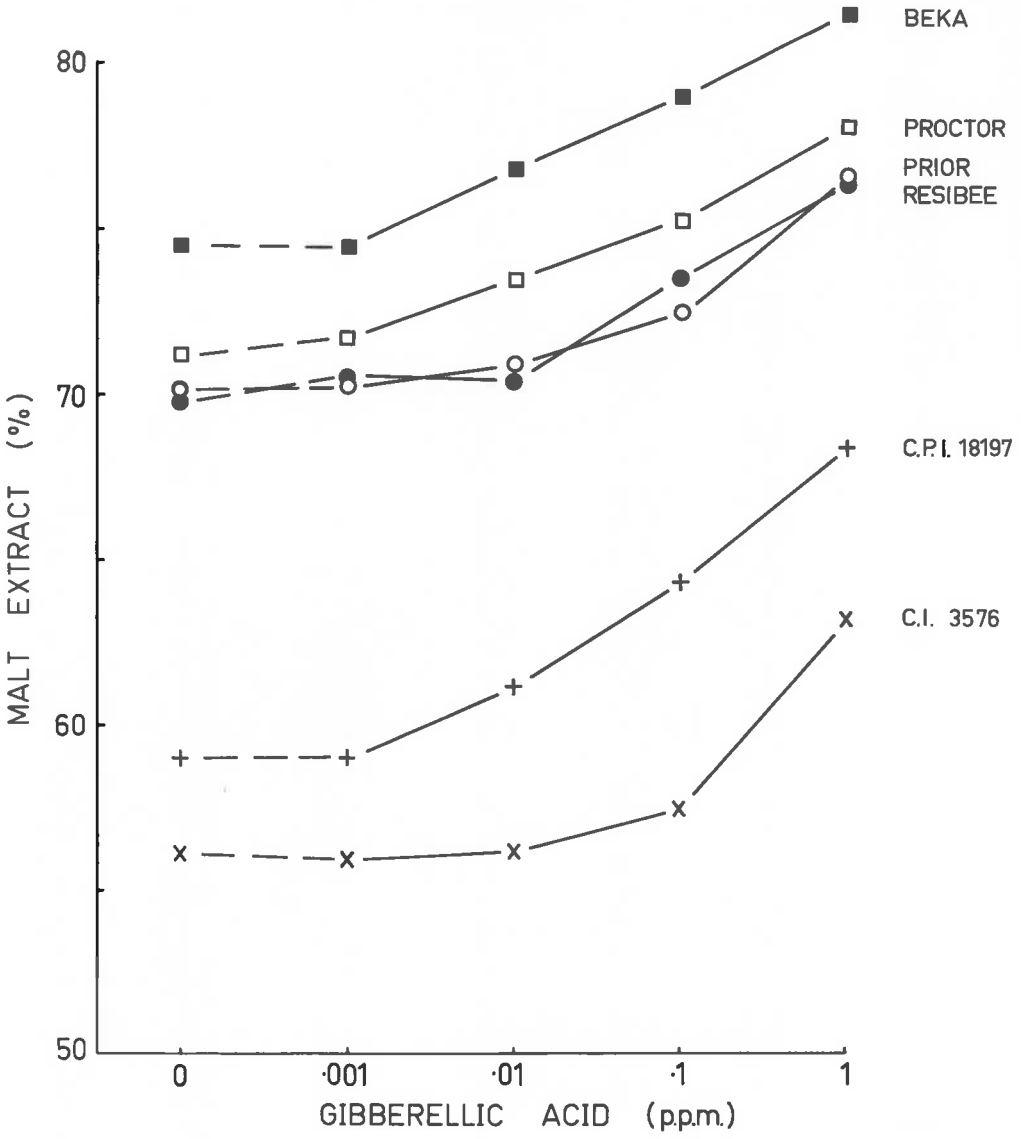
figure showed little response until an application of .1 or 1.0 ppm and it required 100 times more GA_3 to bring about a response in CI. 3576 than in Proctor. Over the range of concentrations used varietal ranking did not alter. These differences in response curve lead to different angles of slope within the range of commercial application rates (.1-1.0 ppm). Within this range, therefore, increased application had a smaller effect on those varieties with flatter slopes. This could have important implications in the selection of malting varieties with an adequate but economical response to applied GA_3.

The results for malt extract (Fig. 28) and wort nitrogen provided a similar pattern of response. As noted earlier there is a considerable contrast between the extract levels of the acceptable malting varieties and the two non malting varieties from North Africa (CPI. 18197 and CI. 3576). Beka, and to a lesser degree, Proctor gave higher extracts than the other varieties. Prior's Chevalier, Resibee, Domen and Long Outer Glume were so similar that the later two have been omitted from the graph. The main varietal rankings did not alter over the range of GA_3 concentrations, although the degree of response did vary and, with regard to extract, the two poorer quality varieties were more responsive to GA_3 than the others.

There are several ways in which varietal differences in response to GA_3 might be compared. However, the simple difference between values obtained for the water control and the highest level of GA_3 (1.0 ppm) was found to give as good a picture of the results as derived data involving all the points and the curvature of the response. The association between this difference and the value for the untreated

FIGURE 28

Malt extracts of 6 varieties treated with varying concentrations of GA_3.


BEKA
PROCTOR
PRIOR
RESIBEE
C.P.I. 18197
C.I. 3576
80
70
60
50
MALT EXTRACT (%)
0
·001
·01
·1
1
GIBBERELLIC ACID (p.p.m.)

control provides further information on varietal response.

TABLE 38

Difference between water control and GA_3 at 1.0 ppm in the malt analysis of eight barley varieties

	Domen	Proctor	Beka	Long Outer Glume	Prior's	Resibee	CPI. 18197	CI. 3576
Malt Extract (%)	5.9	7.0	6.9	5.4	6.4	6.6	9.4	7.2
Diastatic Activity (maltose equivalents)	.319	.219	.273	.328	.174	.229	.198	.135
Wort Nitrogen (%)	.211	.143	.229	.250	.174	.225	.214	.112

In Table 38 the response of the eight varieties is listed in respect of the three components of analysis. There was a considerable range of varietal response, and for both diastatic activity and wort nitrogen there were no marked discontinuities in the range. CPI. 18197 showed a far greater malt extract response than the other varieties but was not anomalous in the other two components.

For diastatic activity (Fig. 29) it is clear that response was closely dependant on the inherent level of enzyme activity ($r = .95^{**}$). The relationship for wort nitrogen was similar ($r = .78^{*}$) although Proctor was less responsive than might be expected. On the other hand the relationship for extract (Fig. 30) showed a slight inverse trend ($r = -.64$), which was largely due to the non malting varieties CI. 3576 and CPI. 18197; while within the malting varieties alone there was no relationship. This is explicable on two counts (1) in

FIGURE 29

The relation between diastatic activity and the response of diastatic activity to GA_3 in 8 varieties.

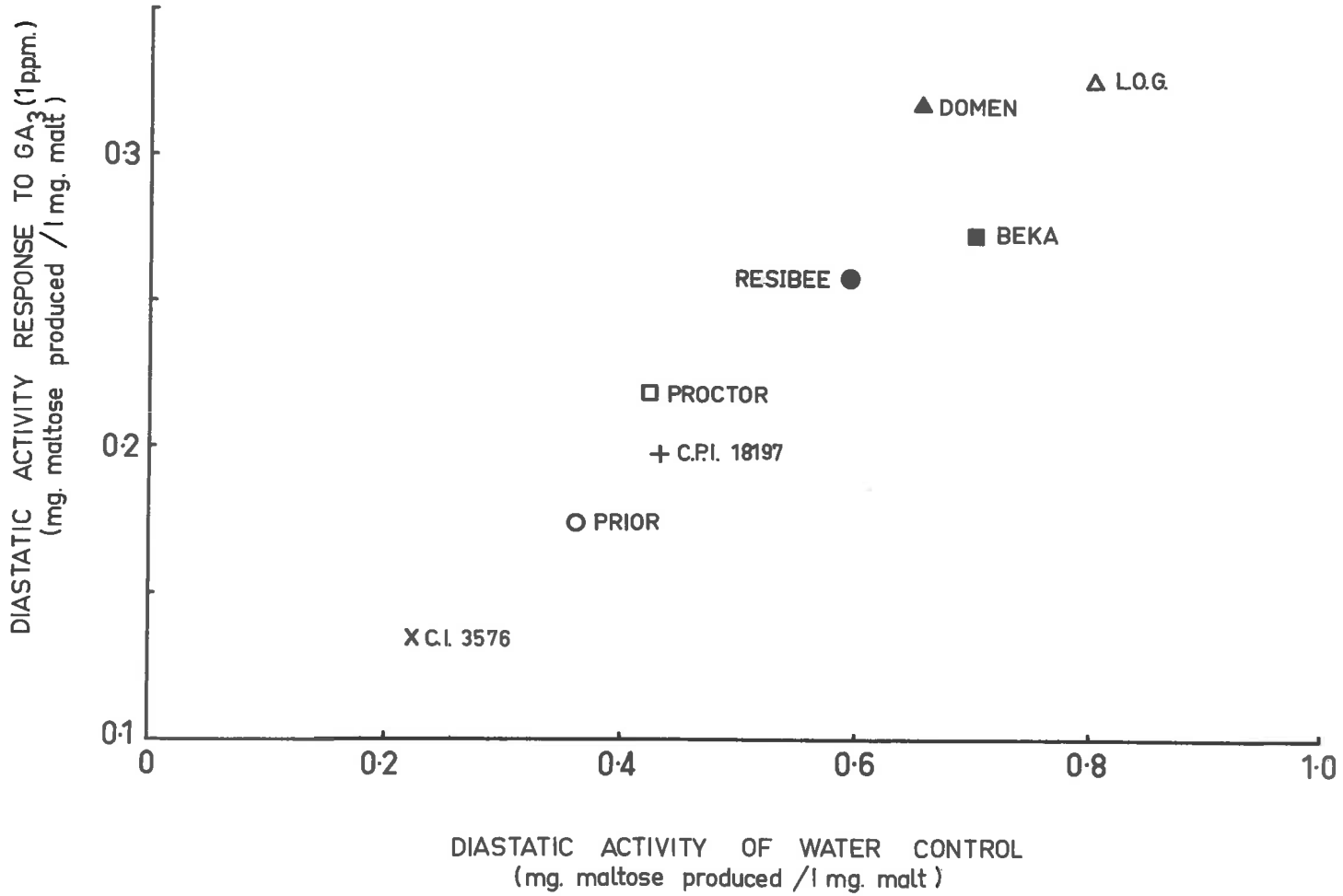
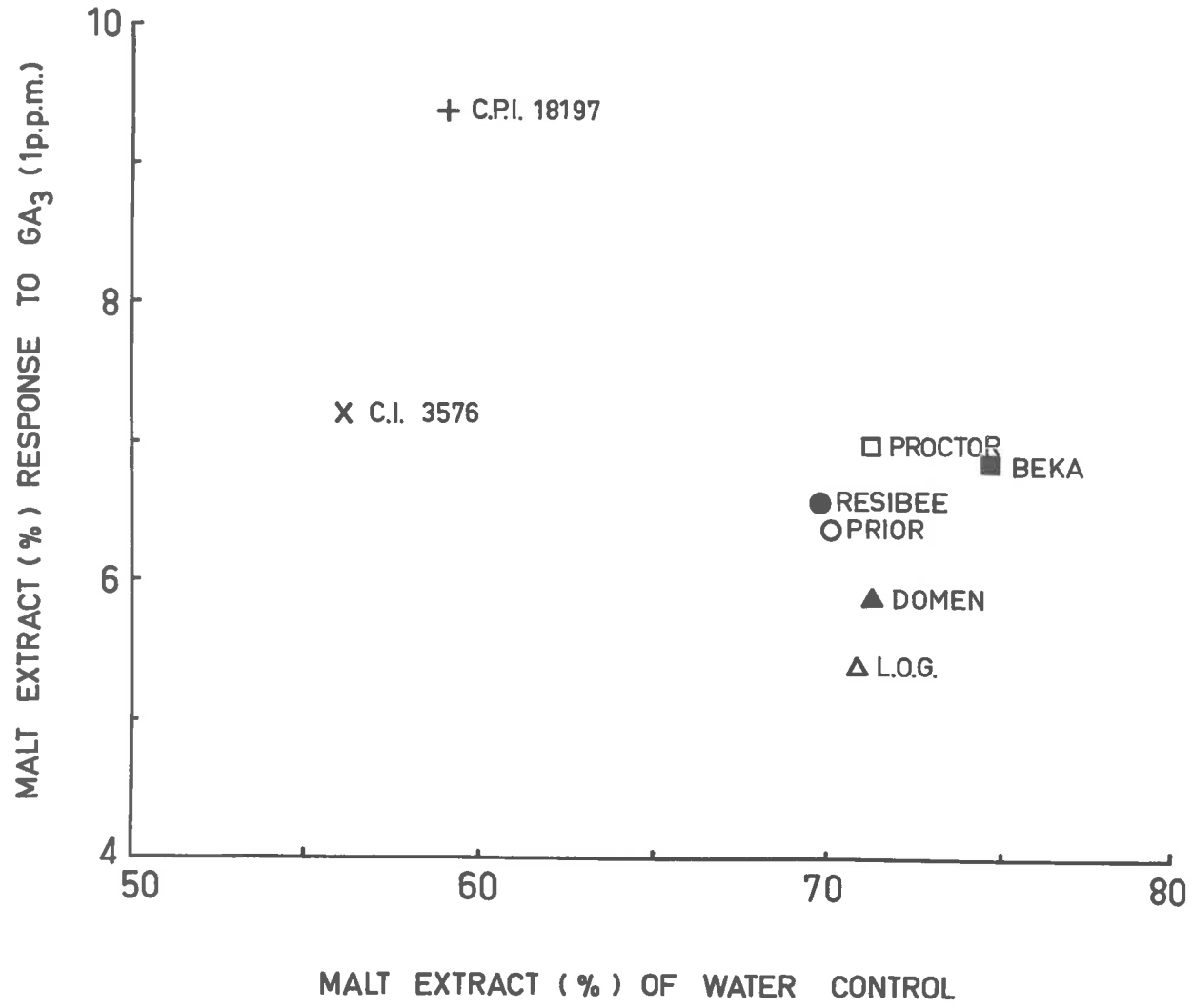

DIASTATIC ACTIVITY RESPONSE TO GA3 (1 ppm.)
(mg. maltose produced / 1 mg. malt)
0·3
0·2
0·1
0
0·2
0·4
0·6
0·8
1·0
L.O.G.
DOMEN
BEKA
RESIBEE
PROCTOR
C.P.I. 18197
PRIOR
C.I. 3576
DIASTATIC ACTIVITY OF WATER CONTROL
(mg. maltose produced / 1 mg. malt)

FIGURE 30

The relation between malt extract and the response of malt extract to GA_3 in 8 varieties.


10
8
6
4
50
60
70
80
+ C.P.I. 18197
X C.I. 3576
□ PROCTOR
■ BEKA
● RESIBEE
○ PRIOR
▲ DOMEN
△ L.O.G.
MALT EXTRACT (%) RESPONSE TO GA3 (1p.p.m.)
MALT EXTRACT (%) OF WATER CONTROL

acceptable malting varieties, extracts closely approach a ceiling value, and there is less room for improvement than in poorer quality varieties. (2) Malt extract is the end product of a complex enzyme-substrate interaction and is further removed from the original stimulus arising in the aleurone than the other two components.

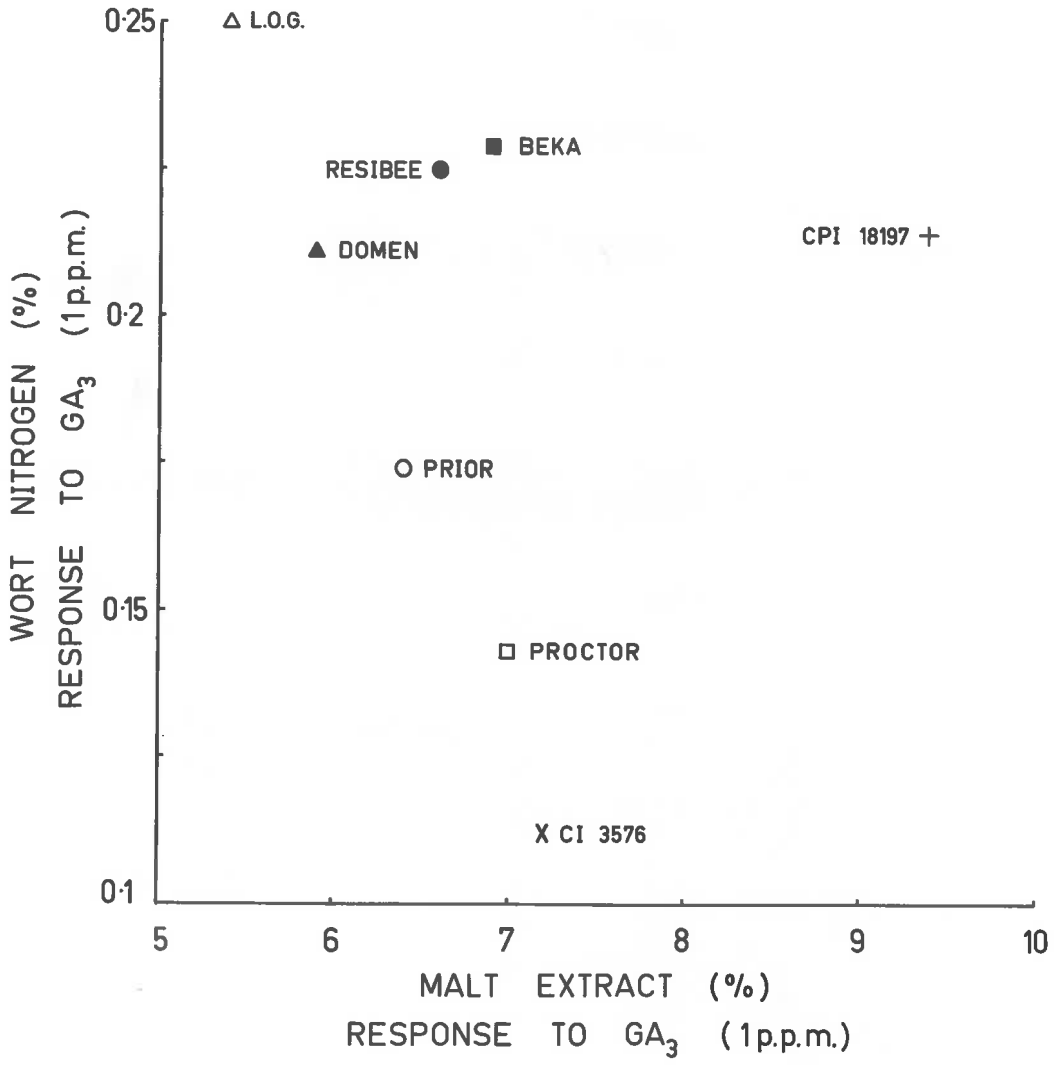
Further, if extract response is plotted against wort nitrogen response (Fig. 31) there is a slight inverse association ($r = -.20$) which just fails to reach significant if the data for CPI. 18197 are omitted from the calculation ($r = -.70$). In other words increases in extract were not solely due to increased proteolysis, as suggested by a previous report (SECOBRAH, 1961). In this experiment there was a tendency for the largest increases in extract to be associated with the smallest increases in wort nitrogen.

(b) Four varieties and fourteen concentrations

Four of the above eight varieties were chosen for a more detailed study of their response to GA_3. The varieties Long Outer Glume (27), Prior's Chevalier (28), Resibee (32) and CI. 3576 (36) although diverse in their malting quality were reasonably adapted to local growing conditions so that no difficulty was experienced in obtaining sufficient grain for malting. Grain of the four varieties was available in sufficient quantity from four trial sites, Waite 1964, Bundaleer, Waite (except Resibee) and Aldinga 1966. 25 gram samples were again micro-malted with a four day germination period and were treated with water or one of 14 concentrations of GA_3 in the range .01-2.0 ppm, (Table 11, page 81a). The kilned malts were analysed for malt extract, wort nitrogen and diastatic activity. The results from the latter are not reported as the analysis carried out with a

FIGURE 31

The relation between the response of malt extract and the response of wort nitrogen to GA_3 in 8 varieties.


0·25
0·2
0·15
0·1
△ L.O.G.
■ BEKA
RESIBEE ●
▲ DOMEN
CPI 18197 +
O PRIOR
□ PROCTOR
X CI 3576
WORT NITROGEN (%)
RESPONSE TO GA3 (1p.p.m.)
5
6
7
8
9
10
MALT EXTRACT (%)
RESPONSE TO GA3 (1p.p.m.)

Technicon Auto-Analyser according to the method of Scharoun and Saletan (1966) gave inconsistent and poorly reproducible results. For the other two components the full results are presented in Appendix 14.

For the fifteen sets of results, regressions of malt extract and wort nitrogen on the logarithm of GA_3 concentration were calculated. All the linear regressions were significantly different from zero and in a few cases the quadratic term was also significant.

Details of the means and regressions together with the average values for each variety and environment are set out in Table 39. Since the abscissae (GA_3 concentrations) were the same for all the regressions the best estimate of S^2 can be obtained from the arithmetic mean of the residual mean squares. It is thus possible to calculate least significant differences for the comparison of individual regressions and average variety and site regressions.

Considering first the mean values for malt extract, averaged over all environments, it is apparent that Resibee gave a significantly higher extract than either Prior's Chevalier or Long Outer Glume whilst CI. 3576 had a lower extract than the other varieties; a similar ranking to that in the genotype-environment investigations. Within the four environments a similar ranking occurred and although Resibee was not always significantly above Prior's Chevalier it was always better than Long Outer Glume. The four environments were distinguishable with Bundaleer 1966 giving the most extract and Waite 1964 just above the other two environments; these values followed those for grain nitrogen of 1.93, 2.10, 2.25 and 2.26 respectively. The absence of Resibee from Waite 1966 may have depressed the site mean

TABLE 39

Means and regression coefficients of two malt characters from four varieties treated with fourteen gibberellic acid concentrations.

Variety	Site		Malt Extract Mean	Malt Extract Regr. Coeff.	Wort Nitrogen Mean	Wort Nitrogen Regr. Coeff.
Long Outer Glume	Waite	1964	69.82	2.008	.710	.129
	Waite	1966	68.23	2.349	.714	.166
	Bundaleer	1966	75.43	2.800	.814	.187
	Aldinga	1966	66.56	3.567	.705	.191
Prior's Chevalier	Waite	1964	68.48	1.962	.699	.090
	Waite	1966	70.17	2.280	.716	.143
	Bundaleer	1966	75.96	2.848	.834	.166
	Aldinga	1966	69.43	3.249	.733	.134
Resibee	Waite	1964	71.51	2.818	.696	.134
	Bundaleer	1966	77.20	2.261	.816	.129
	Aldinga	1966	70.62	3.044	.761	.170
CI. 3576	Waite	1964	63.83	3.680	.648	.134
	Waite	1966	61.73	3.629	.542	.145
	Bundaleer	1966	64.43	4.695	.534	.161
	Aldinga	1966	59.11	4.658	.454	.138
	LSD 5%		.42	.629	.017	.025

Variety Means

Long Outer Glume		70.01	2.679	.736	.168
Prior's Chevalier		71.01	2.585	.746	.133
Resibee (n = 3)		73.11	2.708	.758	.144
CI. 3576		62.28	4.166	.545	.145

Environment Means

	Waite	1964	68.41	2.617	.688	.122
	Waite (n=3)	1966	66.71	2.753	.657	.151
	Bundaleer	1966	73.26	3.151	.750	.161
	Aldinga	1966	66.43	3.630	.663	.158
LSD 5% (n = 4)			.21	.313	.006	.013
(n = 3 & 4)			.23	.339	.009	.013

slightly.

Secondly the regression coefficients of malt extract on log GA_3 concentration provided a measure of the varietal response of that character to GA_3. Figure 32 is an example of the results obtained. Referring again to Table 39, it can be seen that both varietal and environmental differences in response were evident; whilst the results are illustrated graphically in Figure 33. Both within environments and averaged over all environments CI. 3576 had a steeper regression slope than the other three varieties. This is in accord with the findings under section (a) where the varieties poorer in quality showed the greatest response to GA_3. On average the three remaining varieties could not be distinguished and neither, at any one environment, could Prior's Chevalier and Long Outer Glume. However, Resibee gave a significantly flatter response at Bundaleer 1966 and a steeper one at Waite 1964. The average varietal response at the Waite in two years was very similar whereas that for Bundaleer was significantly steeper and that for Aldinga significantly steeper again. Since the environmental responses did not follow the quality of the material as expressed by grain nitrogen content or malt extract it is likely that some other environmentally determined factor was operative.

For mean wort nitrogen content (Table 39) CI. 3576 was again distinct in having a lower level both within environments and on average. The results for the other three varieties and also the varietal means over environments closely paralleled the results for malt extract.

FIGURE 32

Regression lines showing the response of malt extract to increasing concentrations of GA_3 in 4 varieties.

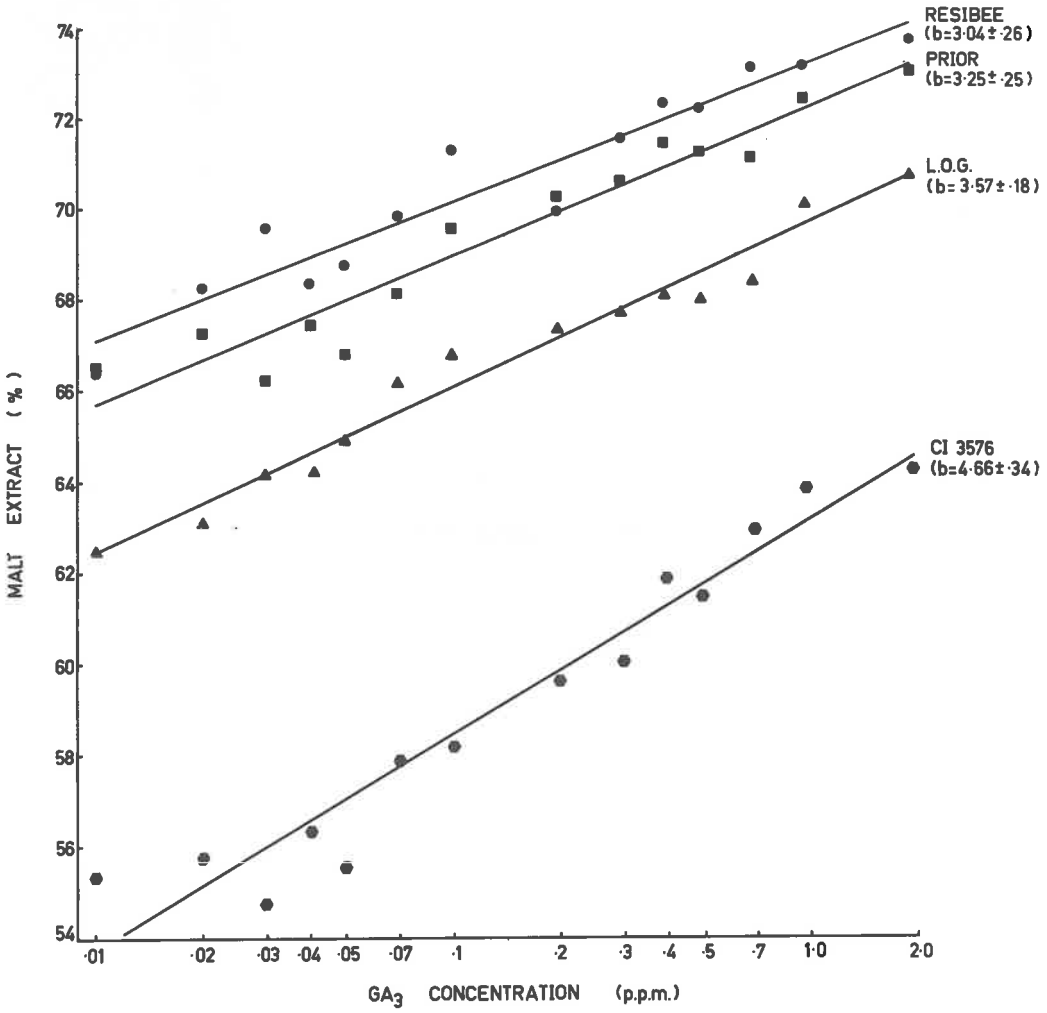
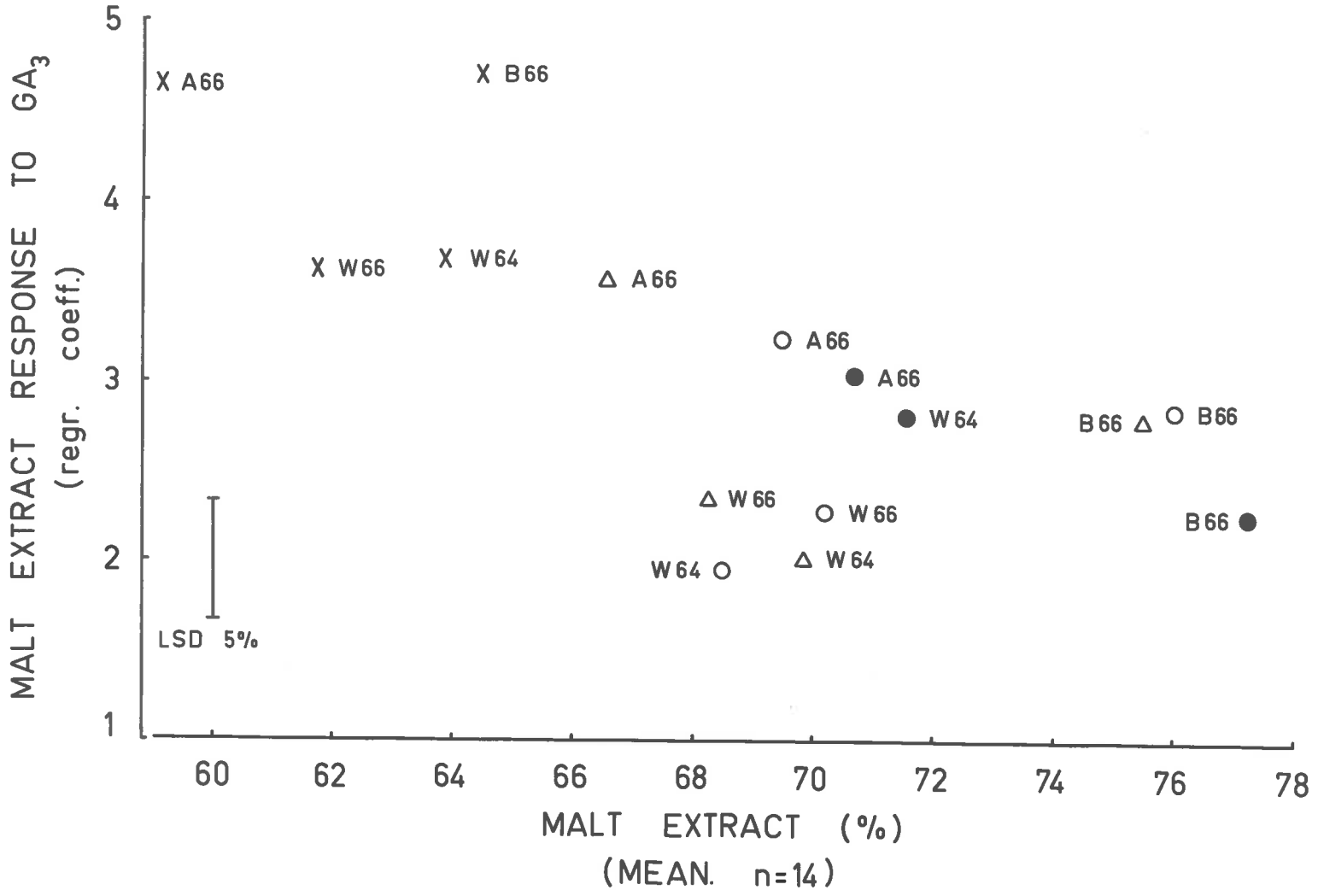

RESIBEE
(b=3·04±·26)
PRIOR
(b=3·25±·25)
L.O.G.
(b=3·57±·18)
CI 3576
(b=4·66±·34)
MALT EXTRACT (%)
74
72
70
68
66
64
62
60
58
56
54
·01
·02
·03
·04
·05
·07
·1
·2
·3
·4
·5
·7
1·0
2·0
GA3 CONCENTRATION (p.p.m.)

FIGURE 33

The relation between mean malt extract over 14 concentrations of GA_3 and the response (regression coefficient) of malt extract to increasing concentrations of GA_3 for 4 varieties at 4 sites in 4 years.

B = Bundaleer
C = Clinton
X = CI 3576
● = Resibee
M = Minlaton
W = Waite Institute
O = Prior
△ = Long Outer Glume.


MALT EXTRACT RESPONSE TO GA_3
(regr. coeff.)
5
4
3
2
1
X A66
X B66
X W66
X W64
△ A66
○ A66
● A66
● W64
B66 △ ○ B66
△ W66
○ W66
B66 ●
W64 ○
△ W64
LSD 5%
60
62
64
66
68
70
72
74
76
78
MALT EXTRACT (%)
(MEAN. n=14)

The response slopes for wort nitrogen were small but significant differences could be detected. Thus, on average, Long Outer Glume had a steeper response than the other three varieties which were closely comparable. This provides some further evidence (cf. Fig. 31) that varietal response to GA_3 in respect of increases in malt extract tends to be independent of the response in nitrogen solubilization. On the other hand the environment means of wort nitrogen response showed a slight positive association with those for malt extract although the two extreme slopes for each character were only just significantly different.

The quadratic term of the regressions were only significant in five cases, all with wort nitrogen. Three of these cases were for CI. 3576, (at W64, W66 and A66) whilst the other two cases were for Long Outer Glume (at W66 and A66). All the coefficients were positive and relatively small but do indicate a tendency to an exponential response curve in those two varieties. For Long Outer Glume the two environments are those at which the lowest extract values were obtained. In other words it was in the poorest quality material that a significant quadratic component for wort nitrogen was found.

(c) Forty varieties and two concentrations

To complete the study of varietal response to gibberellic acid the full set of 40 varieties was malted after treatment with either water or a solution of 1.0 ppm gibberellic acid. The treatments were chosen, as a result of the investigation under (a), as being the easiest to apply in a survey. Grain of the varieties was obtained from the trial grown at the Waite Institute in 1966. For each variety and treatment, duplicate samples of 25 grams were micro-malted with

a four day germination period (Table 11, page 81a). The kilned malts were analysed for malt loss, malt extract, wort nitrogen and diastatic activity; the full results are given in Appendix 15.

Analyses of variance of these characters are presented in Table 40. The duplicate malts were replicates, and the genotype-treatment interaction was used as a test of significance of varietal response to gibberellic acid treatment.

The difference between replicates in all characters except diastatic activity was significant although the values were relatively small; .36, 1.21 and .013 for malt loss, malt extract and wort nitrogen respectively. As was usual in this investigation replicates were confounded with malting batches, 20 samples being put through the micro-malting plant together. Replicate differences therefore reflect slight but inadvertent differences in the processing of individual batches. Malt loss and malt extract are apparently more sensitive to these differences than wort nitrogen and diastatic activity. This also indicates that at least some of the relatively large replicate effect found in the genotype-environment data could be due to batch differences in micro-malting.

For malting loss the difference between treatments was significant. The interaction term was not significant so that genotypes responded similarly to GA_3. This possibly represents a certain imprecision in the measurement of this character as the varieties did show some differences; Beka (14) had an increased loss of 1.13% due to GA_3 treatment in comparison with Compana (26) which had a decrease of 1.85%. On average the GA_3 treatment resulted in a decreased loss of .25% which is in accord with previous observations on the influence

TABLE 40

Mean squares from Analysis of Variance of four malt characters for 40 varieties malted with and without gibberellic acid

		MALT LOSS	MALT EXTRACT	WORT NITROGEN	DIASTATIC ACTIVITY
	D.F.	Mean Squares	Mean Squares	Mean Squares	Mean Squares
Replicates	1	5.055 ***	58.734 ***	.00736 *	.00178 N/S
Treatments	1	2.565 **	2605.319 ***	4.25267 ***	3.07970 ***
Genotypes	39	3.296 ***	56.472 ***	.01811 ***	.04770 ***
Genotype: treatment interaction	39	.324 N/S	5.743 ***	.00894 ***	.00790 ***
Residual	79	.273	1.946	.00163	.00225

For each component of variation variance ratios were calculated against the residual mean squares.

of this substance on malting (Briggs, 1963).

The difference between treatments was highly significant for malt extract with the use of GA_3 increasing the extract by an average of 8.1%. It should be noted that extract levels, averaging 61.7% and 69.8% for water and GA_3 respectively, are lower than normal malts because of the short, four day, germination period. The genotype component was, as might be expected, highly significant. Genotype-treatment interaction was also significant at the .1% level and varietal response to GA_3 ranged from 3.8 to 15.8% for White Smyrna (40) to CPI. 18197 (33) respectively.

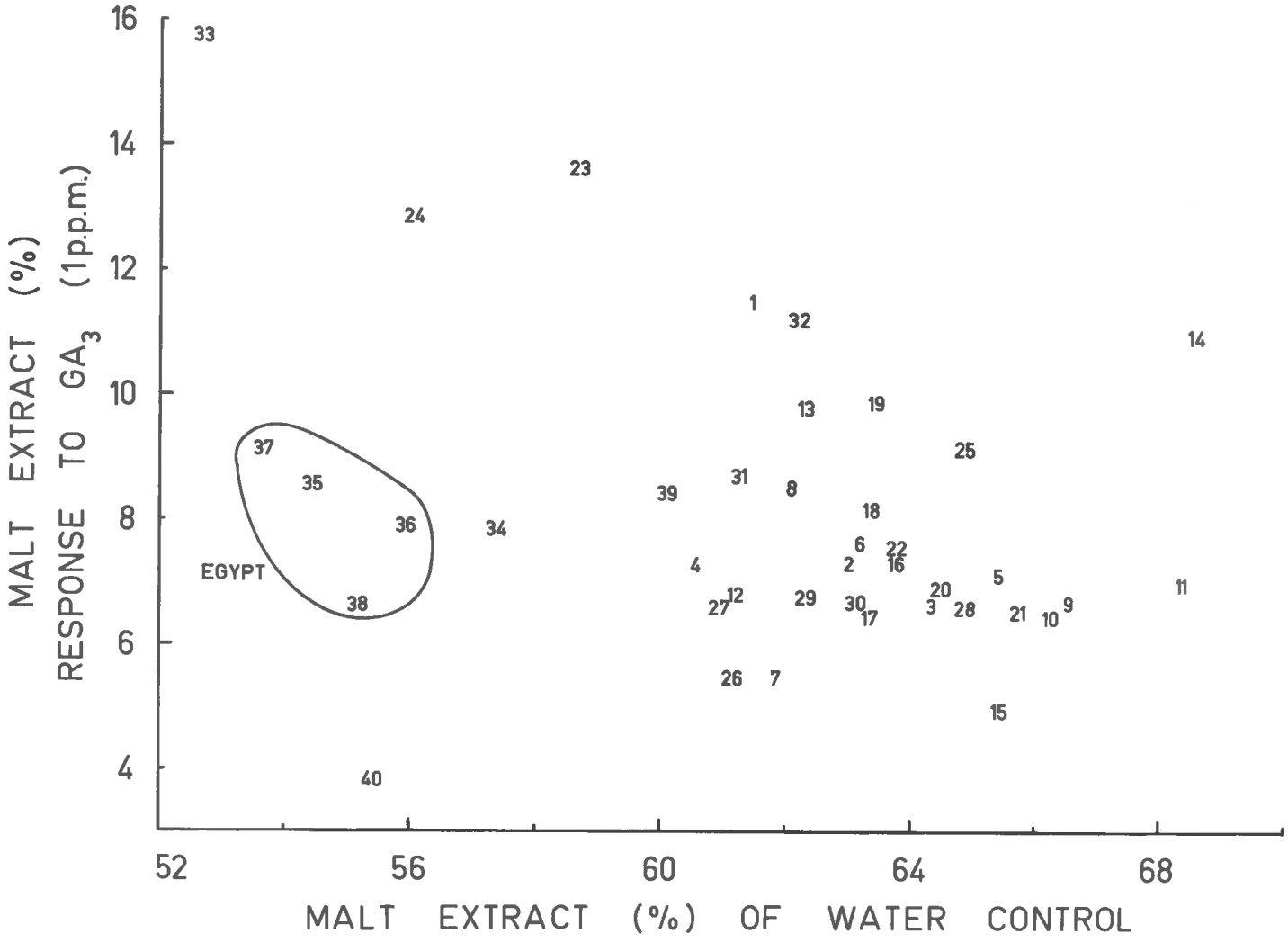
The association between extract response and the extract of the water control (Fig. 34) was slightly inverse ($r = -.32^*$) whilst the relative position of the eight varieties previously investigated (1, 11, 14, 27, 28, 32, 33, 36) is barely comparable with that in Figure 30. Although CPI. 18197 (33) had the largest response allied with the lowest control extract the Egyptian varieties, also low in extract, were much less responsive to GA_3. At the other end of the scale, Beka (14) had the highest extract combined with a relatively large response in contrast to Proctor (11) with a similar extract but considerably lower response.

In section (a) it was suggested that the better the variety the less opportunity for response to GA_3, because extracts would be approaching a ceiling value. Extract levels in this experiment with material from Waite 1966 were lower than those of the previous investigation from Bundaleer 1963. The previous inverse trend was mainly due to the large response of the non-malting varieties. Here both malting and non-malting varieties showed a significant range of

FIGURE 34

The relation between malt extract and the response of malt extract to GA_3 in 40 varieties.

(For key to varietal numbering see Table 8, page 77a).


MALT EXTRACT (%) RESPONSE TO GA_3 (1p.p.m.)
16
14
12
10
8
6
4
52
56
60
64
68
MALT EXTRACT (%) OF WATER CONTROL
EGYPT
33
23
24
1
32
14
13
19
37
25
35
31
39
8
18
36
34
6
22
4
2
16
5
11
20
12
29
27
30
3
28
21
10
9
17
38
26
7
15
40

responses to GA_3. If, as seems possible, from this experiment, varietal response to GA_3 is independent of extract level then it should be possible to select accordingly, but within the limitations of the ceiling effect.

All the mean squares for wort nitrogen were significant. The values for the varieties ranged from Retu (37) at .43% to Noyep (30) at .66% when untreated, whilst the response varied from .12% to .68% for White Smyrna (40) and Kankyo (23) respectively. The response of the majority of varieties fell between .2 and .4% (Fig. 35) and the association between response and the untreated level was not significant ($r = -.14$). There was thus no evidence of the slight positive association found in the results in section (a) and the majority of varieties, including those from Egypt, had a more or less similar increase in nitrogen solubilization due to GA_3 treatment. Four varieties, Domen (8), Kankyo (23), Hanna (24) and CPI. 18197 (33), gave a greater response than the others and apart from the small response of White Smyrna (40) are the only anomalous varieties within this set.

For the final character, diastatic activity, treatment, genotype and interaction differences were all significant at the .1% level. The average difference between treatments was .277 maltose equivalents. Beka (14) at .931 maltose equivalents was the highest variety without GA_3, whilst CPI. 18197 (33) at .509 was the lowest. The range of responses to treatment was from .123 to .543 maltose equivalents for White Smyrna (40) and Domen (1) respectively, and the association between response and the value for the untreated sample (Fig. 36) was not significant ($r = -.13$).

FIGURE 35

The relation between wort nitrogen and the response of wort nitrogen to GA_3 in 40 varieties.

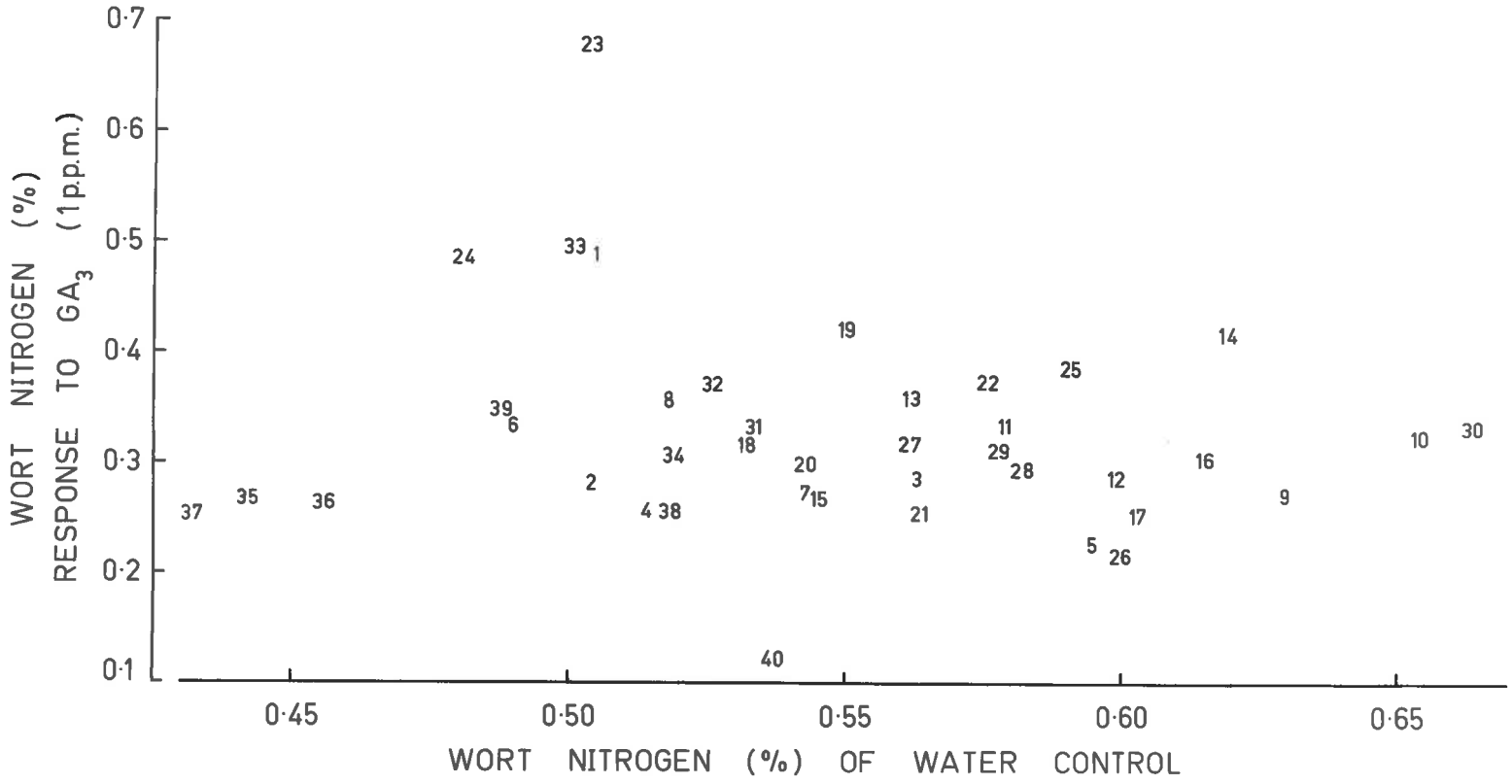
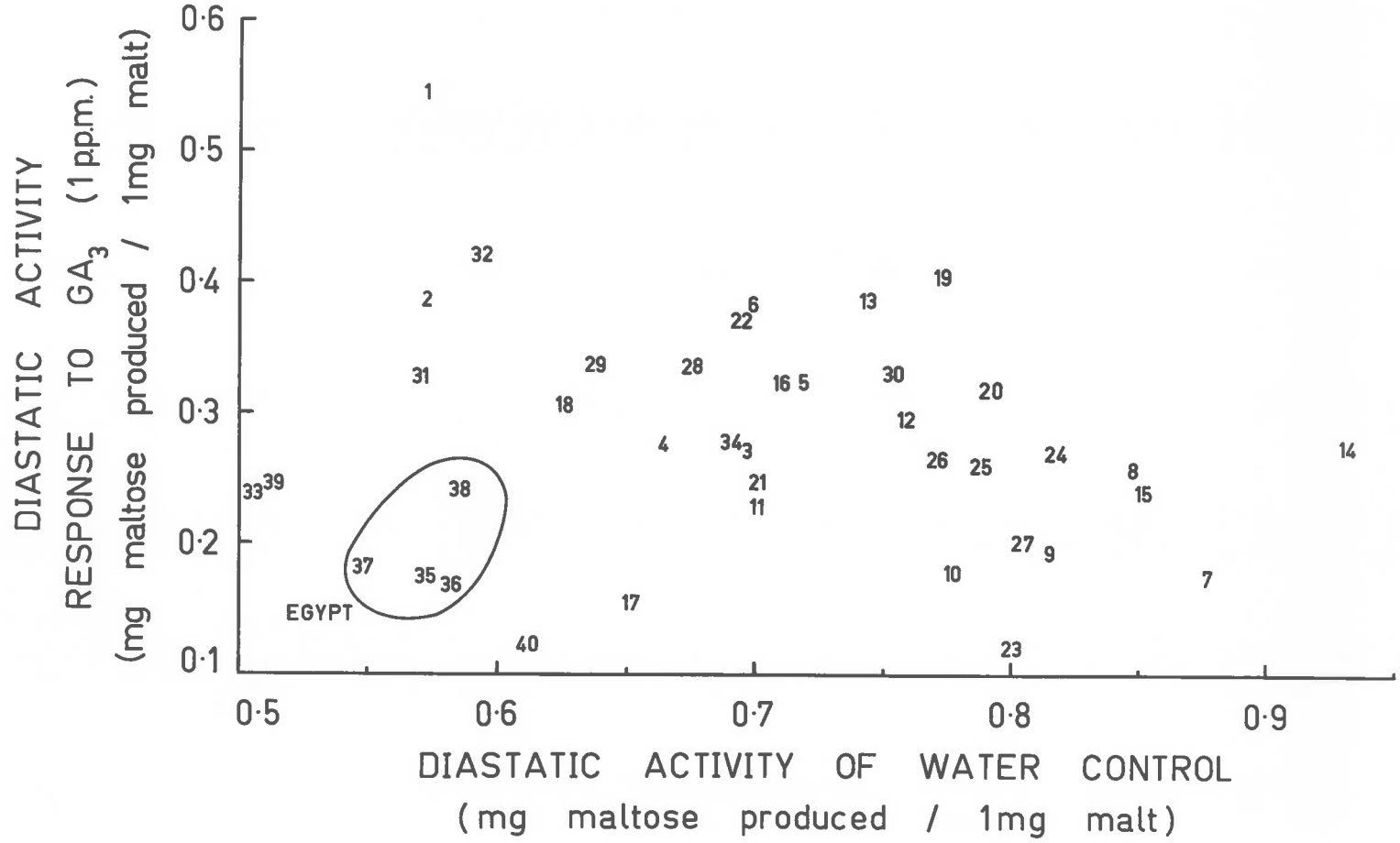

WORT NITROGEN (%) RESPONSE TO GA_3 (1 p.p.m.)
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0·45
0·50
0·55
0·60
0·65
WORT NITROGEN (%) OF WATER CONTROL
23
24
33
1
19
14
25
32
22
8
13
39
6
31
11
10
30
18
27
34
29
16
20
28
2
3
12
9
7
15
37
35
36
4
38
21
17
5
26
40

FIGURE 36

The relation between diastatic activity and the response of diastatic activity to GA_3 in 40 varieties.

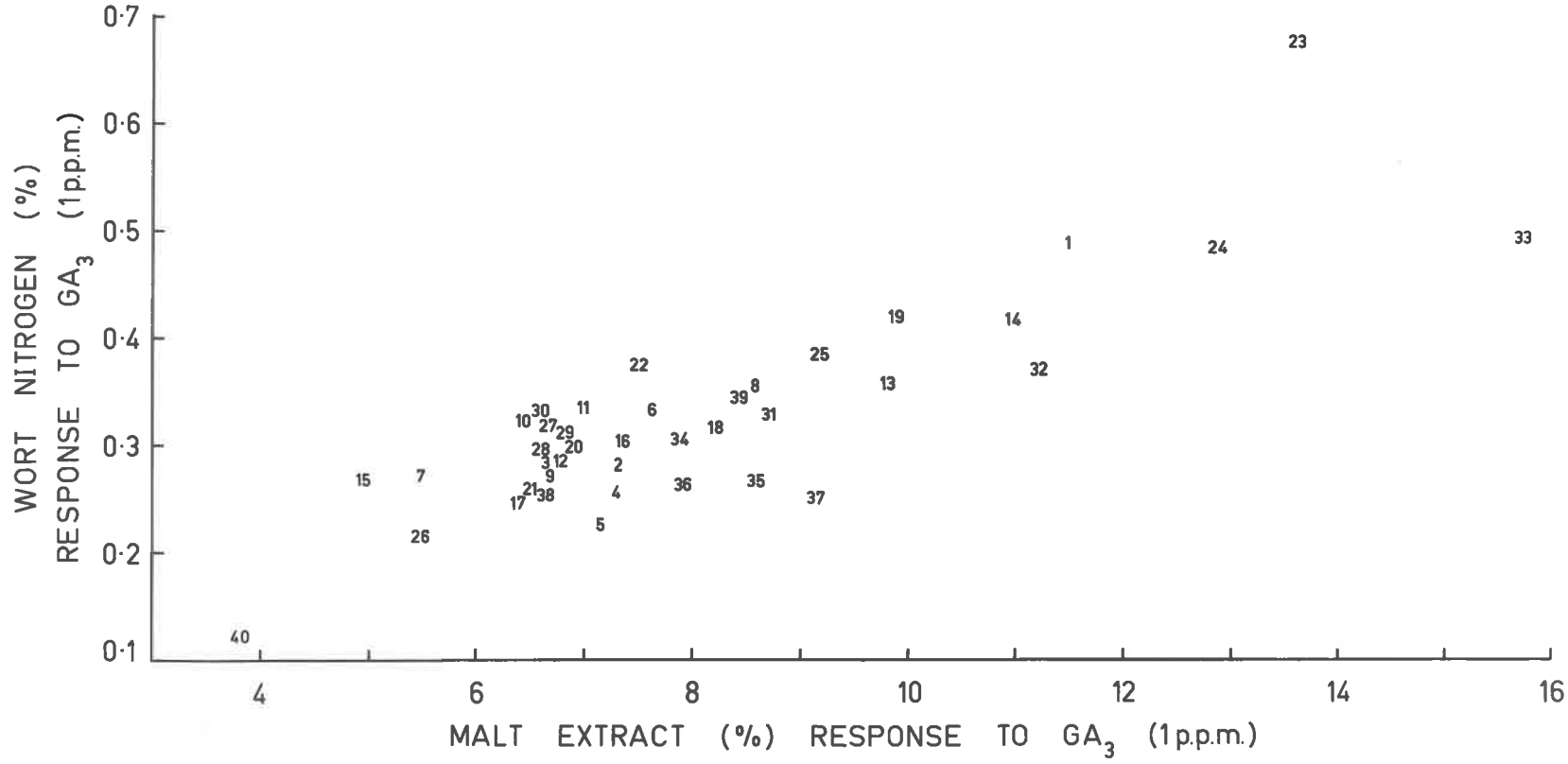

DIASTATIC ACTIVITY
RESPONSE TO GA3 (1 p.p.m.)
(mg maltose produced / 1mg malt)
0·6
0·5
0·4
0·3
0·2
0·1
0·5
0·6
0·7
0·8
0·9
DIASTATIC ACTIVITY OF WATER CONTROL
(mg maltose produced / 1mg malt)
EGYPT
1
32
2
31
29
28
6
22
13
19
16 5
30
20
18
12
4
34
3
26
25
24
14
33
39
38
21
11
8
15
37
35
36
27
9
10
7
17
40
23

In the experiment in section (a) there was a definite, positive, relationship between diastatic activity response and the level of the untreated control. Even if the eight varieties used in that experiment are inspected in Figure 36 no such a relationship is apparent. Thus except for a slight inverse association for malt extract there was, for this material (Waite 1966), no relationship between response to GA_3 and the level of the untreated control. This is almost certainly due to the wide range of varietal material included. But in section (b) there was some indication that responsiveness to GA_3 was influenced by the environment as well as being a varietal character. The interaction of genotype and environment components of responsiveness would be sufficient explanation of the discrepancies encountered in the present results.

Further, when extract response was plotted against wort nitrogen response there was in section (a) (Fig. 31, page 151) a slight inverse association, whereas when the results of 40 varieties from Waite 1966 were so plotted (Fig. 37) there was a significant positive association ($r = .85^{**}$). In this case then, and in contrast to section (a) increases in extract due to GA_3 treatment were associated with increased proteolysis.

FIGURE 37

The relation between the response of malt extract and the response of wort nitrogen to GA_3 in 40 varieties.


WORT NITROGEN (%) RESPONSE TO GA3 (1p.p.m.)
0·7
0·6
0·5
0·4
0·3
0·2
0·1
4
6
8
10
12
14
16
MALT EXTRACT (%) RESPONSE TO GA3 (1p.p.m.)
40
15
7
26
17
21
38
9
3
12
28
30
10
27
29
20
11
5
4
2
16
22
6
34
36
18
39
8
31
35
37
25
13
19
14
32
1
24
23
33

DISCUSSION

The yield and quality of any crop plant is dependent on the influences and interactions of environment and genotype, but although barley has been grown in the Mediterranean climates of southern Australia, California, Chile and North Africa for a considerable period there is a paucity of information on the factors influencing its yield and malting quality under such conditions. In this study, some of the main factors have been elucidated.

The chief environmental influence on yield was found to be seasonal rainfall, whilst rainfall during three spring months had a considerable effect on grain nitrogen content. Since the latter was all important in determining many aspects of malting quality the environment had its main influence on grain quality through grain nitrogen content. On the other hand the chief determinant of varietal differences in malting quality was insoluble carbohydrate content, a measure of the material that remains unextractable after malting. The property of high extractability appeared to be confined to a small specialised group of varieties. Much of the interaction of environment and genotype was caused by differences in varietal maturity. Thus varietal performance depended on the frequency with which the life cycle could be completed before the onset of the moisture stresses of late spring, which are experienced with greater or lesser severity each year. Patterns of interaction between environment and genotype were evident in all the quality characters measured including response to gibberellic acid. The various factors found to be influencing grain yield and malting quality will be considered in more detail below.

1. Seasonal rainfall as a determinant of grain yield

Conditions for crop growth in southern Australia with its predominantly winter rainfall are completely different from those experienced in N.W. Europe or the main cereal areas of North America. Cereal crops sown in mid-winter when the soil is sufficiently moist come to ear in early spring and ripen for harvest in late spring to early summer. Vegetative growth is prolonged over three or four months of cool relatively moist winter weather whilst ear and grain development is accomplished quite rapidly in the remaining two months under conditions of rising temperatures, increasing evapotranspiration and declining rainfall.

Moisture stress at some stage in crop growth, although more particularly at the ripening stage, is a recurrent hazard in the South Australian cereal belt. This area, which lies roughly within the ten to twenty inch isohyets, is subject to considerable seasonal variations and also to irregularities in week by week precipitation. Only in the highest rainfall areas are above optimum amounts of rain received in some seasons (e.g. Waite 1964) and the generally light, free draining barley soils are rarely waterlogged. Thus, as has been pointed out elsewhere, (Cornish, 1950; Finlay and Wilkinson, 1963) grain yields in cereal crops are most importantly influenced by seasonal variability in rainfall. If barley yields are so influenced then inevitably grain quality will also be.

Soil moisture status during crop growth depends on the interaction of several factors including; soil type and its inherent moisture holding capacity, moisture reserves from the previous year, precipitation and evaporation during the current year and losses due to

crop transpiration. It is unlikely, therefore, that rainfall alone would provide a very precise measure of the environment. However the importance of precipitation during the growing season (April-November) was evident in this investigation when, after two invalid results were excluded, the correlation between grain yield and rainfall for 13 sites was so high ($r = .75^*$). This gave a value for r^2 of .56 which is close to Cornish's (1950) finding from more extensive data that '50% or more of the observed variation in (wheat) yield is expressible in terms of rainfall'.

As a component of yield, grain size is undoubtedly influenced by the same environmental factors. But since grain filling, the laying down of carbohydrate, occurs during the spring months moisture stresses at that time might be more important. In the present study the evidence for this was not clear cut and the correlation with the spring rainfall was in fact lower than the correlation with the April-November rainfall. Two conflicting factors may have been operative. These are, an inherent limit to grain size and competition for carbohydrate. The latter could occur when many grains have been initiated but where carbohydrate availability is limited. At anthesis a well developed crop is more liable to moisture stress by reason of its high transpiration load, and as Aspinall (1965) has pointed out moisture stress limits grain filling either by reducing photo-synthesis or the translocation of carbohydrate within the plant. Under equivalent spring soil moisture a gradation between two extreme situations might occur. In the first a crop with a high yield potential bearing many heads, may produce only thin grains due to evapotranspiration stresses, whereas in the second a crop of limited

yield potential experiences less stress and produces well filled grains. Thus seasonal conditions affect yield potential, grain size and the final grain yield, whilst grain size, in terms of carbohydrate deposition, has a considerable influence on malting quality.

2. Spring rainfall as a determinant of grain nitrogen content

In considering grain quality in cereals it has been reiterated in the literature that protein (nitrogen) levels are chiefly dependent on environmental factors. The present study was no exception; the environmental variance for grain nitrogen was markedly larger than the genotype variance (Table 15, page 100a) whilst its heritability was lower than all other characters except yield (Table 20, page 119a). The majority of authors also agree that it is climatic conditions rather than soil type or nutrient status which have the greatest influence. Although grain nitrogen and yield were negatively associated the correlation was not significant, neither was the association with seasonal rainfall or grain size. The chief determinant of grain nitrogen was spring rainfall, with soil type possibly playing a lesser role (Fig. 3, page 95).

Under winter conditions in southern Australia, the temperatures, although not low enough to prevent crop growth, are sufficiently low to reduce the activity of soil micro-organisms to a minimum. Precipitation is in excess of evaporation and soil nitrates are lost by leaching. In some instances crops show visible signs of nitrogen deficiency. In spring with the onset of warmer weather, the micro-organisms become active depending on soil moisture status. Spring rainfall is balanced by evaporation and transpiration so that leaching is unlikely, but warm moist conditions will encourage nitrogen

mineralization and also nitrogen losses due to denitrification (Bremmer and Shaw, 1958-59; Stefanson and Greenland, 1970). Thus the level of spring rainfall influences the amount of soil nitrogen available to the plant and to the grain. Whilst the nitrogen percentage in the grain will be influenced by the extent to which seasonal conditions allow the grain to fill. As a consequence of these factors the best grain quality, which for barley is a low grain nitrogen, is obtained in seasons of average to above average rainfall when the grain filling period is prolonged by good spring rains.

In addition to spring rainfall grain quality is dependent on soil type and nutrient status. The nutrient status of the soil is generally the result of the amount of nitrogen fixed in previous medic or clover crops, therefore pasture growth in one season can affect crop growth in subsequent seasons.

3. The influence of grain nitrogen on malting quality

A second theme that recurs in the literature on barley quality is the paramount influence of grain nitrogen content on malting and the characteristics of the subsequent malt. This is widely accepted and the commercial assessment and grading of grain for malting is largely based on nitrogen content.

Only two investigations, the Canadian and the present one, make a clear distinction between the environmental and genotypic relations of the various quality characters. Despite wide differences in environments and material used there was an excellent agreement in the results of the environmental influences on grain nitrogen. The correlation coefficients involving grain nitrogen, malt extract, wort

nitrogen and diastatic activity in both studies were similar in sign and quite close in magnitude and ranking (Table 1, page 17a and Table 22, page 121a). These findings, together with those of other authors, support the principle that malt extract is strongly, but inversely correlated with grain nitrogen content whilst wort nitrogen and diastatic activity are somewhat less strongly, but positively dependent upon the same character. Further, the negative associations between extract and wort nitrogen, and extract and diastatic activity were found to be due to their mutual dependence on grain nitrogen.

In other comparisons of the Canadian results with those obtained in this study the environmental correlations between grain nitrogen, and insoluble carbohydrate, steep time and malt loss were less well matched. Although all had the same sign their magnitude was different. The Canadian correlations between grain nitrogen and steep time and malt loss were significant, (Anderson, et al. 1941) whilst those of the present study were quite small, and the relative magnitude was reversed for the association between grain nitrogen and insoluble carbohydrate. Since insoluble carbohydrate also showed a reasonably high correlation with yield and grain size it is likely to be linked to these and grain nitrogen through their being mutually influenced by moisture stress during the grain filling process. It might be suggested that if grain nitrogen in Canada were more dependent on soil fertility then insoluble carbohydrate would be less likely to be affected similarly. Reasons for the other contrasts in results are less clear, although they could also be due to environmental influences on grain ripening.

The influence of the environment on grain nitrogen content and

hence on the quality characters was further emphasized by the principal component analysis. Although the first component was largely attributable to another character, insoluble carbohydrate, the second component was designated 'grain nitrogen' because of it's high positive loadings on grain nitrogen, wort nitrogen and diastatic activity, and somewhat lower negative loadings on yield and malt extract (Table 31, page 137a). When the component scores of each of the original 480 entries were subjected to analyses of variance 75% of the total sums of squares of the second component were attributable to environments and 82% of those of the first 'extractability', component to genotypes. These results provide a clear distinction of the two most important quality components into an environmental one and a genotypic one, with grain nitrogen content most strongly tied to the environmental.

4. The importance of insoluble carbohydrate as criterion of varietal quality

The grain character with the largest loading on the first component was insoluble carbohydrate with thousand grain weight having a lesser role (Table 31, page 137a). The distinction between the environmental importance of grain nitrogen and the genotypic role of insoluble carbohydrate was also strongly evident from the stepwise regression analysis (Table 28, page 134a) where of all the malt characters only cold water extract was not dependent upon these two grain characters. Further, insoluble carbohydrate itself had a high heritability (97%, Table 20, page 119a).

The genotypic importance of insoluble carbohydrate was first recognised by Bishop and Marx (1934) when they expounded the carbo-

hydrate regularity principle, suggesting that every variety had a different carbohydrate pattern. It was for this reason that they employed insoluble carbohydrate as a basis for extract prediction. The Canadians preferred barley extract for prediction as it showed a greater array of significant correlations, both between and within varieties than did the insoluble residue they measured in lieu of insoluble carbohydrate (Table 3, page 19a). In fact their variable was only significantly correlated with between-variety differences in thousand grain weight ($r = -.61^{*}$) and malt extract ($r = -.91^{**}$) and within-variety differences in steep time ($r = -.67^{*}$). In contrast, in the present study insoluble carbohydrate was significantly correlated, between varieties, with all characters except yield and the coefficients were negative for all except thousand grain weight ($r = .81^{***}$) and grain nitrogen ($r = .48^{*}$) (Table 23, page 125a). Within varieties the only significant association was with malt extract ($r = -.71^{*}$) and although the coefficient with steep time ($r = -.67$) was the same as above it was not significant (Table 22, page 121a).

The reason for the different results would seem to lie in the varieties used in the investigations. The range of variety means for insoluble carbohydrate in this study was large from 6.5 to 10.3% (Appendix 4) in comparison with that of the Canadian material of 8.9 to 11.3% (Ayre, et al., 1940). It is interesting that although Bishop and Marx (1934) gave results for only six varieties, three of which were closely similar in type, their range of insoluble carbohydrates was as great as that herein because of the inclusion of some non-European varieties. When in the present study the 25 variety

European subset was considered the range was small, the highest variety averaging only 8.5%, and it can be seen from the stepwise regression analysis (Tables 28 and 30, pages 134a and 135c) that its importance in varietal malting quality was considerably reduced. Some aspects of varietal differences in this character have already been touched upon in section 3 (d) (page 108) when the analysis of variance was discussed. It may be concluded from these results that insoluble carbohydrate could be a useful criterion when selecting among progenies of poor quality parents but that it would be far less discriminating when the parents had an acceptable level of quality.

Although insoluble carbohydrate was largely genotypically determined, it was influenced to some extent by the environment. Over six sites the range of mean values was small, 7.8-8.3% (Appendix 8) and from the analysis of variance (Table 16, page 108a) the proportion of the total variation attributable to environments was quite small (2%). However, within varieties there was some indication of an association, although not significant, with grain nitrogen content ($r = .54$) and thousand grain weight ($r = -.60$) (Table 22, page 121a). Thus there was a tendency for insoluble carbohydrate to increase with the grain nitrogen content and to decrease when grain size increased. Evidently, the environmental factors that permit the grain to fill properly not only 'dilute' the nitrogen in the grain but also the insoluble carbohydrate. Since the latter is largely cell wall material and grain filling is dependent upon starch deposition the relationship is clear. Cell walls are composed mainly of hemicelluloses or beta-glucans. In excessive amounts these

viscous materials can cause filtering difficulties after the malt has been mashed (Drayton 1968). In Australia such difficulties are associated with grain from seasons in which ripening has taken place under conditions of moisture stress. Although Sparrow and Meredith (1969) came to the conclusion that beta-glucanase activity was a more important determinant of varietal 'maltability' than beta-glucan content, there does seem to be a case for selecting varieties low in insoluble carbohydrate, and hence beta-glucan, in order to minimise the chance of encountering the above difficulty.

The relation between insoluble carbohydrate and thousand grain weight was indicated in section 5(b) (page 125). There it was pointed out that although the malt quality characters were fairly strongly associated with grain size this was due to their dependence on insoluble carbohydrate and its correlation with grain size ($r = .81^{***}$). This is in contrast to the Canadian findings where the correlation between insoluble carbohydrate and grain size was negative ($r = -.61^{*}$), grain size was not significantly associated with the malt characters and insoluble carbohydrate only with malt extract ($r = -.91^{**}$). In other words they found a tendency for the varieties with the largest grains to have the least insoluble material. Of the 12 varieties used in the Canadian studies, nine were six row but this is insufficient to say whether the association in this direction is a feature of six row varieties.

In the present study it was the inclusion of the varieties, from North Africa that accounted for the positive correlation between insoluble carbohydrate and grain size (Fig. 18, page 126). Within the European subset the association was not significant ($r = .21$)

and grain size was not associated with the malt characters and insoluble carbohydrate only slightly with malt loss ($r = -.49^*$) and malt extract ($r = -.44^*$).

It is interesting therefore that Whitehouse (1968b) argues, from results obtained with a set of 16 European varieties including five from above, that inherently small seeded varieties have the best potential for malting quality (extract). Also within the European context Whitmore (personal communication) has stressed the importance of reducing insoluble carbohydrate but warned that if it was appreciably less than 7 per cent of the dry weight pre-germination was liable to occur under damp harvest conditions.

The inference made under 5(b) (page 125) was that it should be possible to select the type of material, preferred by the Australian maltster, with larger grains than the average European varieties, but with equivalent malting quality, provided concurrent selection was made for a low level of insoluble carbohydrate. Although the value of insoluble carbohydrate as a selection criterion was reduced in better quality material it still retained some genetic importance because of its relative insensitivity to environmental change; in the discriminant analysis of the European subset it was still the most effective character in discrimination (Table 36, page 145a). Also, under the dry harvest conditions of southern Australia the chances of pre-germination are negligible. The combination of larger grain and good quality has been achieved to some extent in Clipper (Proctor x Prior A) which has a thousand grain weight similar to that of Prior's Chevalier (42 grams) but an insoluble carbohydrate level and quality approaching that of Proctor. The next step would be to

achieve the low insoluble carbohydrate level of Beka and a further advance in quality whilst maintaining grain size.

5. Discrimination of European and non-malting varieties

From the discriminant analysis in 7 (page 141) it was concluded that the European malting varieties represented a small specialized group within the variation available in the species. For breeding purposes the non-malting varieties could be important sources of yield and adaptation especially under the very different, winter rainfall climate of southern Australia. However their deficiencies in grain and malt characters would need attention in a breeding programme for malting barley. The discriminant analysis procedure would help in this selection and a major conclusion of such an analysis in this investigation was that the non-malting varieties were deficient in extractability and probably slow to produce endosperm modifying enzymes. In selecting for malting types when North African varieties have been used as parents attention at least in the first instance should be given to low insoluble carbohydrate and high levels of cold water extract.

In the graph of the first two canonical axes (Fig. 25, page 142) the two Victorian varieties Research M.R. (31) and Resibee (32) tended to be intermediate between the European and South Australian groups. This is understandable as these varieties are selections from a cross between the old English variety, Plumage Archer and Prior from South Australia. This result also lends support to Whitehouse's (1969) suggestion that, in the absence of dominance and epistasis, the mean of a hybrid population will, lie midway between its two parents on a canonical graph.

The separation of the Egyptian from other varieties would explain why it has been virtually impossible to obtain good malting lines from single crosses in which they are parents. A point on the graph, midway between the Egyptian CI. 3576 (36) and Proctor (11) lies close to White Smyrna (40) and well outside the European group. On Whitehouse's theory it could have been predicted that crosses involving at least 75% European germ plasm would have been necessary to obtain a proportion of segregants of acceptable malting quality. This has been found in subsequent selection studies.

6. Maturity as a prime factor in genotype-environment interaction

The interaction of genotype and environment has an important bearing on the quality of material produced at different places and seasons in South Australia. It has been pointed out that yield and quality of the grain are influenced by the amount of spring rainfall and the time available for grain filling before moisture stress causes plant senescence. This being so the relative maturity of a variety will have an important effect on its malting quality. In general, the probability of moisture stress increases as the spring advances; temperatures and evapotranspiration rise whilst rainfall decreases. Thus the earlier maturing varieties are less likely to be affected by moisture stress and are able to complete their ripening more frequently. It is possible that some varieties are better able to withstand moisture stress but there is no evidence that this is a major factor in varietal differences.

With regard to yield excessive earliness may be a disadvantage in that early varieties, with a short life cycle, would be restricted in vegetative growth, tillering and hence yield potential. Of the 40

varieties studied only Noyep (30) could be considered excessively early, whilst it is apparent from Figure 4 (page 96) that there was a tendency within the Australia:North African group and within the European group, for the earlier varieties to be the higher yielding. A point of interest is that the South Australian varieties (28, 29) were nearly a week later and were lower yielding than the Egyptian varieties (35, 36, 37). There is, therefore, scope for producing locally adapted varieties with earlier maturity and higher yields.

The response-to-environment coefficients calculated in this thesis provide a measure of the relative stability of the varieties to environmental change. In view of the foregoing arguments it would be expected that these coefficients would tend to be positively correlated with maturity; the early varieties should be more stable and the later varieties less stable. As a group, the European varieties should be more sensitive to environmental change because they will complete their life cycle and give high yields of good quality grain under favourable conditions, but under moisture stress both yield and quality will suffer more than in the earlier maturing varieties from North Africa and Australia.

The association between maturity and yield stability was very highly significant although it did not account for a high proportion of the variation ($r = .51^{***}$) (Table 25, page 129a), probably due to the limitations to yield, outlined above, in the earliest varieties. On the other hand, as already referred to in 3(c) and 5(c) (pages 106 and 129), the correlations between maturity and grain nitrogen stability was larger ($r = .60^{***}$) and was paralleled by that with the responses of malt extract and wort nitrogen and the smaller but

significant associations with the responses of cold water extract and diastatic activity. This provides a further reflection of the environmental importance of grain nitrogen in determining malting quality.

The lack of association between maturity and grain size stability (Table 25, page 129a) indicates that although maturity and thousand grain weight were correlated (r = .69***, Fig. 6, page 99) the actual response of grain size to environmental change was not dependent upon the inherent size of the grain (Fig. 9, page 105). Thus the small seeded European varieties and the large seeded Egyptian varieties were relatively stable, whilst the Australian and some others with intermediate seed size were relatively unstable. Although it might be expected that small grains would be filled even under unfavourable seasonal conditions and would be more stable across environments, it was found that the large grained Egyptian varieties were equally stable. The Egyptian varieties are well adapted to the climate of southern Australia by reason of their evolution under similar conditions, whereas the South Australian varieties are believed to have become adapted by mutation from a European type to an earlier maturing form. The developmental physiology of the South Australian varieties should be similar to the European varieties but that of the Egyptian varieties could be different. Aspinall (1963) has shown that CI. 3576 (36) does have a different growth pattern; it only produces a limited number of tillers, compared to Piroline (20) which will tiller indefinitely with adequate nutrient supply. This limited tillering and head production may mean that the Egyptian varieties are more certain to fill the grains that are produced.

In view of the pattern of association between maturity and character stability it is not surprising that the European varieties are relatively unstable in all the malt characters, the Australian and Continental varieties are more stable and the Egyptian the most stable. This also tends to be the ranking of the inherent level of each malt quality character with the strongest association occurring with diastatic activity ($r = .66^{***}$; Fig. 15, page 114). If the highest levels of malting quality are associated with a relative instability of expression there could be a problem in selecting good quality varieties adapted to southern Australia. The question as to whether average or above average stability is desirable in malting quality characters will be considered later. However, it should be noted that for grain nitrogen (Fig. 10, page 106) there is no relationship between response to environment and the inherent nitrogen level ($r = .27$) and it should be possible to combine any level of grain nitrogen with any type of stability.

7. Varietal response to gibberellic acid

In this investigation it was found that both the environment and the genotype influenced the response of the three malt characters to GA_3. An example of the environmental effect is evident in sections 8(a) and (c) (pages 148 and 154), where the varieties that were common to Bundaleer 1963 and the Waite 1966, showed different relationships between 1. the inherent level of diastatic activity and its response to GA_3 and between 2. the responses of malt extract and wort nitrogen. This environmental effect is even more clearly evident in section 8(b) (Table 39, page 152a), but the results, although limited, do not support a relation between responsiveness

and grain nitrogen content.

In commercial malting the view held is that the poorer the material, as indicated by its higher nitrogen content, the more responsive it is to GA_3. In practice this has led to the use of lower, cheaper, grades of barley which, with the addition of GA_3, produce malts up to brewery specification.

Considerable differences in genotypic response to GA_3 were evident in section 8 (pages 147-158). Most striking was the large response in malt extract of the North African varieties. It has been noted already that these varieties, particularly the ones from Egypt, were deficient in several aspects of malting quality, including extractability and enzyme potential. Poor extractability has been already attributed to high levels of insoluble carbohydrate. If responsiveness to GA_3 indicates a low level of inherent gibberellin the deficiency in enzyme potential might be due to a less well developed hormone system than is present in malting barleys. In the Egyptian varieties the added GA_3 may have only speeded up enzyme release and the process of modification, without increasing the amount of extract that would have been obtained over a longer germination period. In other words, the four day period employed did not realise the maximum extract. This could apply to all varieties, but if the malting varieties modify more rapidly than the non malting types they would be nearer their upper limit of extract after four days and thus appear less responsive to the speeding up of modification by GA_3. This distinguishes the inherent rate of modification and the inherent level of potential extract, two processes which might be related, although, only the former is influenced by added GA_3.

Although extract has an upper limit this does not appear to be the cause for diastatic activity although it seems likely there would be if germination were prolonged. Where the response of diastatic activity to GA_3 was dependent upon the inherent level of the enzyme (Bundaleer 1963) it appeared that there was no upper limit to its activity. This is consistent with the known mechanism of gibberellin in triggering the synthesis and release of hydrolytic enzymes from the aleurone and suggests that varieties might differ, either in rate of synthesis or in number of sites at which synthesis takes place. Added GA_3 could trigger synthesis at more sites than the natural gibberellin diffusing from the embryo and thus the varieties with inherently greater enzyme activity (rate or sites) would exhibit greater responsiveness in a specified time.

One difference between the results in 8(a) and 8(c) (pages 148 and 154) was the relation between the responses of malt extract and wort nitrogen; inverse in the former and strongly positive in the latter (Figs. 31 and 37) (pages 151 and 158). Results from elsewhere (SECOBRAH, 1961) suggest a positive relationship and indicate that increases in extract due to GA_3 treatment are due, at least in part, to increased quantities of soluble nitrogen compounds in the wort. Since this must depend upon the amount of protein available for proteolysis it would be expected that the higher the grain nitrogen content the more likely a positive association between the two responses. In the better quality material from Bundaleer 1963 the increase in malt extract is not due solely to increased wort nitrogen and therefore provides a real gain in fermentable material. Although this represents an environmental difference there are indications

from 8(b) (Table 39, page 152a) that there are varietal differences in the relation between the two responses. Thus, although on average, CI. 3576 had the steepest response for malt extract, Long Outer Glume was the steepest for wort nitrogen. The separation of these two responses at the varietal level could have important implications in the selection of varieties suitable for malting with GA_3.

The main difficulty in elucidating from malt quality results, the nature of the response to GA_3 is that both of these characters are secondary and removed from the primary sites of action of the enzyme mobilizing system. What needs to be studied is the effect of environment and genotype on the rate of formation of gibberellin in the embryo, its translocation and action in the aleurone, and the subsequent rate of enzyme synthesis and release. Application of gibberellic acid to complement, or anti-gibberellin substances to block, this system could also be used to elucidate the inherent level of natural gibberellin. This appears to be an important aspect of malting quality that has received little attention. It would require more sophisticated techniques than employed in this investigation and although technically feasible might pose problems when applied to the numbers of samples required in a breeding programme.

8. Breeding for improved barley malting quality

As a result of the preceding investigations an approach to the breeding and quality testing of malting barley may be suggested. An important conclusion of this study was that the majority of quality characters although apparently quantitatively inherited, are nonetheless highly heritable. This was apparent for malt extract, wort

nitrogen and diastatic activity (Table 20, page 119a), and also has support from the work of other authors (Table 7, page 52a).

High heritability for a character implies that varieties and selections will tend to be ranked in a similar order across environments or generations and that prediction of performance from one environment or generation will be relatively accurate. This being the case repetitive testing for quality will not be necessary. Thus selections from segregating populations which give high or low extract in one generation will tend to be similarly ranked in subsequent generations. This means that quality tests such as micro-malting which are usually time consuming, can be limited to certain stages of a breeding programme thus enabling large numbers, rather than many replicates of selections to be analysed.

Apart from characters which are quantitatively inherited some quality characters are under simple genetic control. In barley high amylose and high lysine are due to single recessive genes and the proportion of total beta-amylase which is free is controlled by a single gene with incomplete dominance. In crop plants single gene control of important quality characters is not uncommon and other examples outside barley include the absence of erucic acid in oil seed rape and the alkaloid content of lupins. Whilst milling quality in wheat, appears to be controlled by a few genes. Such characters are all amenable to backcrossing techniques enabling their rapid introduction into bred material.

As mentioned in the introduction the commercial processor is concerned mainly with environmental variations in quality. This variation is largely evident in grain nitrogen content, and to a

lesser extent carbohydrate. Perhaps it would be more correct to say that the environment influences the grain protein-carbohydrate ratio and the consequent differences in quality. For the breeder this does have a bearing on the choice of material to be tested. Although, the commercial processor utilizes only a proportion of the range of material produced, the breeder, due to seasonal influences at his trial sites, may have to extend his testing outside this range. Care needs to be exercised since it cannot necessarily be assumed that the ranking of varieties is constant to the extremes of the environmental range. In any event the final stages of testing at the semi-commercial level must be performed on acceptable material.

With regard to grain quality an understanding of the factors underlying genotype-environment interaction is now emerging. Aspects have been pointed out in the foregoing discussion following the finding that varieties with an optimal maturity are able more consistently to produce a fully developed grain under the conditions of southern Australia. Other factors are operative and the following train of interactions may well be implicated. Varietal differences in the ability of the plant to take up soil nitrogen interacts with soil fertility at all stages during the growing season and determine the actual amount of nitrogen in the plants. The amount of nitrogen in the grain is dependent upon the inherent ability to translocate plant nitrogen and the seasonally determined period over which translocation of both nitrogen and carbohydrate occurs. Varietal differences in the final pattern of yield components together with the relative duration of various parts of the life cycle and the

ability to translocate carbohydrate to the grain, all interact with soil fertility, seasonal rainfall and the moisture stresses imposed by seasonal and diurnal variations in temperature. These factors determine whether a variety can complete its life cycle, finish ripening and achieve its inherent grain quality. As so many factors are involved and operate at different times it is understandable that genotype-environment interactions are an important problem to plant breeders. Studies of these factors need to continue, both singly and in combination but for the moment the breeder may have to consider the factors as a whole and analyse his results by procedures such as the adaptation analysis.

The statistics of the adaptation analysis have been used extensively in this thesis and it was proposed that for grain yield the most useful genotypes would be those combining average high yield with wide adaptability (i.e. average stability, b = 1.0 or in the context of this thesis, b = 0.0) and that the deviations from their regressions should be minimal (Sd^2 = 0.0). There is little doubt that a predictable response is desirable for all crop performance characters. But, it is suggested the most appropriate slope of the response curve for grain quality could be different to that for grain yield.

Maximum expression is required for some quality characters, such as malt extract, but there are other characters such as wort nitrogen where excessive levels are undesirable and optimum values are sought. For example, although the highest levels of grain nitrogen content are obviously unacceptable to the maltster and brewer, the very lowest levels (below 1.4%) can also be undesirable in providing insufficient

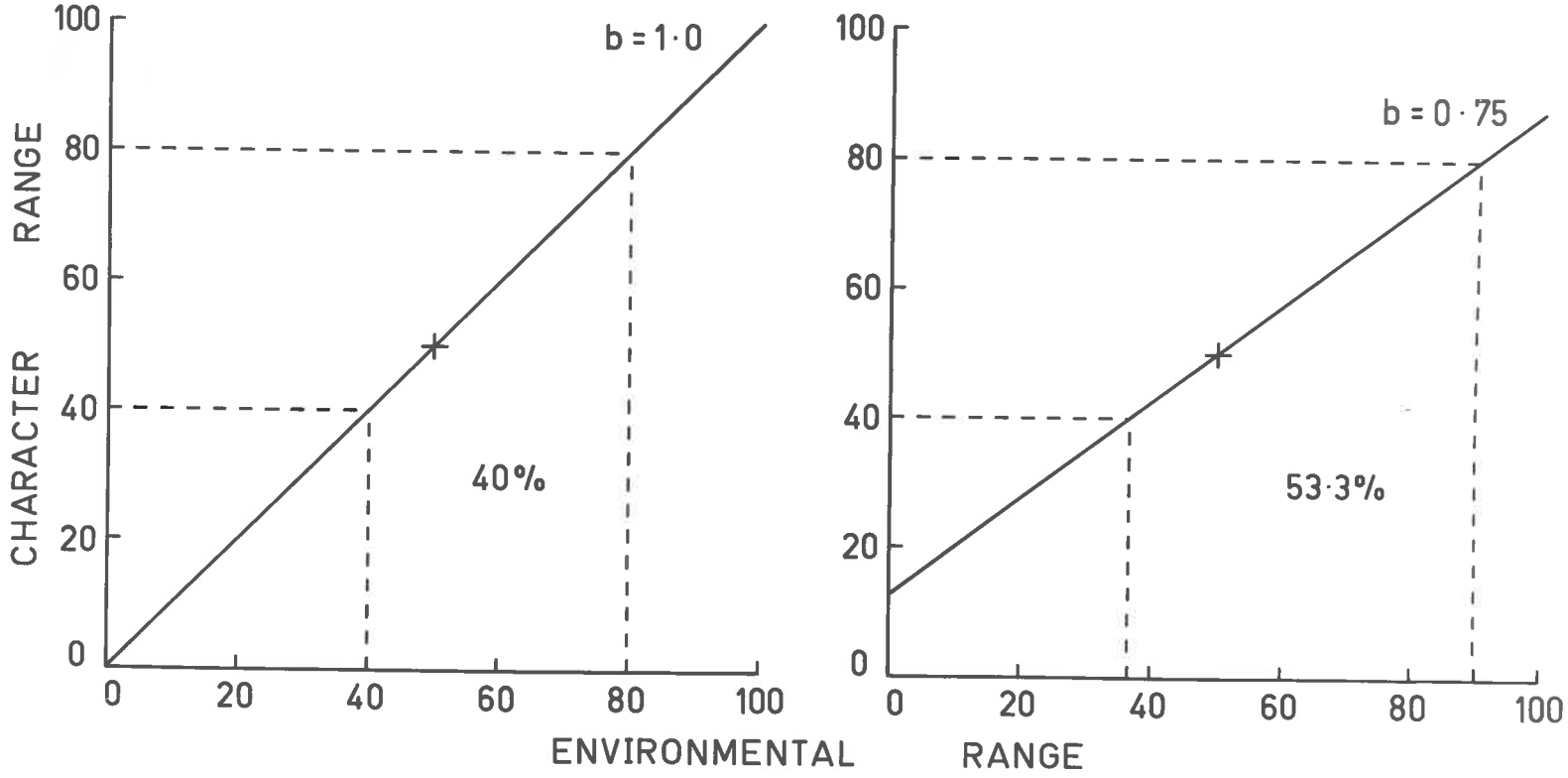
yeast metabolites, especially where protein reduced flour or low protein grists are added to the mash. Thus the commercial processor rarely accepts, as suitable for his purposes, all the produce of a crop grown over an area. Further, the commercially acceptable material does not necessarily occur at either extreme of the character range but often falls between certain intermediate values.

Figure 38, illustrates a hypothetical case of the effect of two varieties with different responses to environmental change on the above considerations. In the left hand graph, for a variety with average stability (b = 1.0), if 40% of the character range is commercially acceptable this proportion will be obtained from 40% of the environments under which the crop is grown. Whereas, in the right hand graph, for a variety with above average stability (b = 0.75), the same 40% of the character range is obtained from 53.3% of the environments. Thus the second variety would be more likely to provide sufficient acceptable material in any one year. It is suggested, therefore, that varieties which are relatively stable in performance would provide for the commercial producer a greater constancy of product over site and season.

For some malting characters it may not be easy to breed varieties that combine stability and high levels of the character. Diastatic activity is an example (Fig. 15, page 114) the varieties with high mean values of diastatic activity were unstable for this character. In other grain or malt quality characters it would be easier and it is noteworthy that for grain nitrogen content the association was negligible (Fig. 10, page 106) and it should be possible to breed stable varieties with a low content.

FIGURE 38

A comparison of two hypothetical varieties with different responses to environmental change and the effect this would have on the proportion of the crop achieving commercial acceptance.


b = 1·0
b = 0·75
CHARACTER RANGE
ENVIRONMENTAL RANGE
40%
53·3%
0
20
40
60
80
100

The association between the mean of a character and its response to environmental change in a set of varieties also provides a guide to the breeder of the number of environments over which a character needs to be tested for selection purposes. Thus if the correlation between the statistics is high, as with diastatic activity, then varietal ranking will tend to be consistent across the environments (Fig. 16, page 114) and testing can be confirmed to a few sites. As already mentioned this is one aspect of high heritability but high values for heritability can also result where the genotypic variance is large compared to the environmental. Under such circumstances varieties might differ considerably in their relative stability but continue to rank in a similar order across environments because of a wide separation in their mean values. Here the plot of stability on mean would show a negligible correlation although the calculated heritability would be high. The adaptation analysis can thus be used to elaborate on the heritability estimate. In the latter case it would be necessary to decide whether the environments used in calculation were a representative sample before deciding how many should be used in testing.

As a result of the findings in this study and the conclusions drawn it is suggested that in South Australia a breeding programme for improved malting barleys must utilize varietal material from North Africa. This material, particularly that from Egypt, is outstanding for its adaptability and performance under a winter rainfall climate; it has also been found that several varieties from the area exhibit high levels of resistance to certain fungal and nematode diseases. The chief disadvantage of the North African varieties from the point

of malting is their low extractability and enzyme potential. As has been shown they are so divergent from malting varieties that single crosses between the two types are unlikely to give progeny acceptable for malting. More complex crosses or selection and recrossing would be necessary to obtain the desirable combination of agronomic performance and acceptable quality. Such a programme has been initiated and although considerable progress has been made the ultimate aim is still to be achieved.

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APPENDIX 1

Calculation of steeping time.

(The mathematics in this appendix are due to G.N. Wilkinson).

In order to devise a method for calculating the time required to bring samples to 44% moisture a detailed study was undertaken of water uptake under the steep schedule employed in this investigation (Table 11, page 81a). Three varieties, Prior, Proctor and Waite 775 were steeped and weighed at intervals from 0-90 hours.

Graphs of the data plotting weight against time indicated an initial exceedingly rapid uptake of water (i.e. increase in weight). After about eight hours the characteristics of the rate of uptake appeared to change to the form of a negative exponential, with the water content or weight reaching a ceiling level. Subsequent mathematical treatment of the data supported this hypothesis and results obtained less than ten hours after the start of immersion were excluded from the calculations.

The form of the curve that could be fitted to the data was as follows:-

$$y = a\,(1 - e^{-k(t - t_o)}) \qquad (1)$$

where y = weight (gms) of the sample at time t (hrs)

a = ceiling weight

k = relative rate of change of uptake

t = time from immersion of sample

t_o = the time at which the weight would be zero assuming that this relationship holds over the whole range of t.

The above function may be written:

$$\log_e (y - a) = -\log_e a - k (t - t_o) \qquad (2)$$

which is a linear function in $(t - t_o)$.

It was then assumed that, given a standard curve of this form, based on a function fitted to actual test data, any other samples would have a fitted function parallel to the standard but differ only in displacement, or ceiling value a.

In the test data used, this was found to be approximately true, for the three rather diverse varieties. Average values of a = 50 grams, k = .017 and t_o = -68.0 hours were used for subsequent calculations.

For each test sample weights (Y_{xt}) were measured at three times, usually 24, 48 and 72 hours after immersion. The expected weights (Y_t) at these times were also obtained from the standard curve. Both sets of weights were then used in the second form of the curve (2) to determine corresponding displacements of the sample linear function from the standard, for each value of Y_{xt}.

The function may also be written:-

$$\log_e y = \log_e a + \log_e (1 - e^{-k(t - t_o)})$$

if y_t = standard y at time t

y_{xt} = sample y at time t

and a, ax corresponding values of the ceiling

then: $\log_e y_{xt} - \log_e y_t = \log_e a_x - \log_e a$

i.e. $$a_x = \frac{a \cdot y_{xt}}{y_t}$$

in $$y_{xt} = a_x (1 - e^{-k(t - t_o)})$$

From this equation for the sample, the time t_z may be found at which the sample reaches any given value of weight (y_z)

$$t_z = t_o + \frac{1}{k} \log_e \left(1 - \frac{y_z}{a_x}\right)$$

The procedure was performed on each of the three sample times and weights in turn, individual and average estimates were made for the ceiling value and the time required to reach the required weight (44.6 g). The calculation of three separate values of a_x served to detect errors in sample weights since the three values normally showed a close approximation to each other.

APPENDIX 2

YIELD PERFORMANCE OF 40 VARIETIES OVER 15 SITES

GRAIN YIELD

	VARIETY	MEAN	B	SE(B)
1	DOMEN	232	.030	.136
2	FREJA	298	.351	.086
3	RIKA	263	.250	.075
4	BONUS	281	.320	.106
5	RIGEL	285	.297	.095
6	DELTA	308	.307	.093
7	CAMBRINUS	296	.248	.114
8	EMIR	311	.345	.115
9	IMPALA	312	.199	.128
10	G/SPRATT	199	.098	.120
11	PROCTOR	245	.464	.144
12	MAYTHORPE	275	.237	.082
13	BALDRIC	307	.223	.180
14	BEKA	295	-.122	.126
15	CERES	294	.188	.099
16	PORT 2 ROW	230	-.019	.100
17	BOA FE	231	.018	.106
18	MORGENROT	253	.165	.058
19	HAISA II	236	-.251	.101
20	PIROLINE	262	-.033	.163
21	UNION	271	.026	.147
22	JULIANE	255	-.142	.165
23	KANKYO	248	-.231	.158
24	HANNA	264	-.371	.095
25	GOLDFOIL	211	-.201	.122
26	COMPANA	253	-.167	.144
27	L O GLUME	242	-.217	.119
28	PRIORS	265	-.159	.151
29	PRIOR A	262	-.169	.136
30	NOYEP	240	-.352	.172
31	RESEARCH M R	262	-.064	.115
32	RESIBEE	261	-.102	.142
33	CPI 18197	298	-.193	.137
34	CPI 18198	279	-.257	.162
35	WAITE 775	328	-.039	.234
36	CI 3576	341	-.083	.250
37	RETU	317	-.025	.252
38	G H SINAI	291	-.016	.153
39	CI 5611	245	-.181	.228
40	WHITE SMYRNA	192	-.373	.163
	LSD 1%	29	.086	

APPENDIX 3

GRAIN SIZE AND NITROGEN CONTENT PERFORMANCE OF 40 VARIETIES OVER 11 SITES

		THOUSAND GRAIN WEIGHT			GRAIN NITROGEN		
	VARIETY	MEAN	B	SE(B)	MEAN	B	SE(B)
1	DOMEN	36.3	-.227	.192	2.17	.162	.067
2	FREJA	33.8	-.376	.150	2.10	.153	.113
3	RIKA	32.5	-.479	.277	2.11	.057	.097
4	BONUS	33.4	-.324	.200	2.14	.159	.114
5	RIGEL	34.1	-.171	.146	2.08	.032	.091
6	DELTA	34.7	-.330	.191	2.12	.132	.150
7	CAMBRINUS	34.9	.372	.248	2.08	.118	.102
8	EMIR	31.6	-.177	.114	2.11	-.000	.062
9	IMPALA	31.4	-.235	.191	2.10	-.012	.065
10	G/SPRATT	32.8	.056	.214	2.19	.272	.206
11	PROCTOR	30.9	.517	.395	2.01	.200	.128
12	MAYTHORPE	34.1	-.337	.200	2.10	.219	.097
13	BALDRIC	34.4	.000	.173	2.15	.194	.103
14	BEKA	33.0	-.085	.096	1.97	-.008	.061
15	CERES	35.2	.284	.191	2.12	.018	.048
16	PORT 2 ROW	36.7	.167	.130	2.08	-.027	.090
17	BOA FE	32.0	-.448	.161	2.30	.209	.075
18	MORGENROT	33.8	-.349	.242	2.10	.162	.063
19	HAISA II	33.6	-.254	.149	2.16	.169	.064
20	PIROLINE	32.9	-.143	.084	2.11	-.055	.070
21	UNION	34.9	.056	.167	2.04	.042	.089
22	JULIANE	34.1	.060	.128	2.07	-.029	.055
23	KANKYO	39.8	.425	.255	2.03	-.173	.066
24	HANNA	37.9	-.296	.220	2.05	-.216	.105
25	GOLDFOIL	32.0	-.382	.235	2.21	.175	.090
26	COMPANA	39.0	.506	.245	2.13	-.036	.098
27	L O GLUME	40.3	.462	.181	2.15	-.113	.047
28	PRIORS	38.1	.509	.245	2.05	-.158	.044
29	PRIOR A	38.1	.528	.181	2.11	-.171	.035
30	NOYEP	39.9	.010	.244	2.18	-.427	.085
31	RESEARCH M R	36.1	.266	.131	1.94	.088	.086
32	RESIBEE	38.7	.438	.245	1.99	.001	.080
33	CPI 18197	43.0	.259	.317	2.21	-.158	.116
34	CPI 18198	50.8	.393	.370	2.12	-.228	.077
35	WAITE 775	44.9	-.295	.224	2.00	-.247	.130
36	CI 3576	43.6	-.133	.274	2.07	-.269	.131
37	RETU	43.9	-.246	.310	2.00	-.319	.131
38	G H SINAI	44.2	.063	.132	2.18	-.079	.086
39	CI 5611	42.1	.350	.361	2.22	.127	.112
40	WHITE SMYRNA	39.0	-.433	.176	2.18	.039	.071
	LSD 1%	1.4	.149		.09	.058	

APPENDIX 4

MEANS OF THREE CHARACTERS FROM 40 VARIETIES OVER 6 SITES

	VARIETY	INSOL CHS MEAN	STEEP TIME MEAN	MALTING LOSS MEAN
1	DOMEN	7.19	48.7	8.71
2	FREJA	7.64	48.7	7.97
3	RIKA	7.42	53.3	9.23
4	BONUS	7.32	45.3	8.38
5	RIGEL	7.59	50.0	8.69
6	DELTA	7.33	46.0	8.94
7	CAMBRINUS	7.82	49.3	8.57
8	EMIR	7.42	53.3	9.39
9	IMPALA	7.65	43.3	9.74
10	G/SPRATT	7.75	47.5	9.59
11	PROCTOR	7.42	50.8	8.48
12	MAYTHORPE	7.63	43.9	8.08
13	BALDRIC	7.39	49.3	8.52
14	BEKA	6.59	48.1	10.48
15	CERES	7.62	54.4	8.67
16	PORT 2 ROW	7.60	54.4	9.30
17	BOA FE	7.91	44.4	10.08
18	MORGENROT	7.65	43.7	8.43
19	HAISA II	6.90	50.3	9.36
20	PIROLINE	7.69	44.3	8.98
21	UNION	7.02	56.5	9.43
22	JULIANE	6.52	56.9	10.12
23	KANKYO	8.52	39.6	8.62
24	HANNA	8.29	47.5	7.04
25	GOLDFOIL	7.06	45.5	9.15
26	COMPANA	7.96	58.0	8.41
27	L O GLUME	8.14	52.8	8.38
28	PRIORS	7.89	60.7	8.74
29	PRIOR A	7.85	59.8	8.63
30	NOYEP	7.86	59.4	8.57
31	RESEARCH M R	8.49	52.9	8.27
32	RESIBEE	8.05	55.6	8.75
33	CPI 18197	9.44	34.3	8.81
34	CPI 18198	10.28	43.5	8.75
35	WAITE 775	10.14	38.1	6.60
36	CI 3576	10.22	38.8	6.58
37	RETU	10.25	37.1	6.27
38	G H SINAI	9.38	50.5	7.47
39	CI 5611	8.07	54.0	6.50
40	WHITE SMYRNA	9.25	46.1	6.92
	LSD 1%	.40	5.6	.83

APPENDIX 5

MALT EXTRACT AND COLD WATER EXTRACT PERFORMANCE OF 40 VARIETIES OVER 6 SITES

		MALT EXTRACT			COLD WATER EXTRACT		
	VARIETY	MEAN	B	SE(B)	MEAN	B	SE(B)
1	DOMEN	71.5	.465	.269	19.9	.784	.406
2	FREJA	70.4	.235	.165	18.1	.343	.278
3	RIKA	70.9	.003	.139	18.0	.419	.168
4	BONUS	70.0	.032	.135	17.5	.828	.161
5	RIGEL	70.5	.167	.093	17.6	-.005	.126
6	DELTA	71.5	-.190	.053	17.5	-.174	.226
7	CAMBRINUS	72.2	.054	.156	18.7	-.267	.218
8	EMIR	71.5	-.136	.129	18.4	-.398	.237
9	IMPALA	73.2	-.156	.103	19.3	.170	.337
10	G/SPRATT	70.2	.119	.122	19.2	-.297	.231
11	PROCTOR	72.8	.327	.087	19.2	-.168	.395
12	MAYTHORPE	71.3	.266	.119	19.7	.193	.367
13	BALDRIC	70.7	.567	.183	19.6	.098	.181
14	BEKA	75.2	.020	.211	19.9	.120	.484
15	CERES	70.6	.139	.155	17.5	-.516	.249
16	PORT 2 ROW	71.1	.134	.136	17.8	.068	.149
17	BOA FE	69.3	.439	.203	20.0	.700	.438
18	MORGENROT	72.1	.115	.089	19.9	.490	.214
19	HAISA II	70.5	.037	.176	18.3	-.303	.299
20	PIROLINE	70.8	-.035	.181	18.4	.358	.185
21	UNION	73.6	.078	.102	18.3	-.059	.203
22	JULIANE	73.1	-.090	.122	18.7	-.394	.208
23	KANKYO	68.5	-.319	.188	19.5	.041	.359
24	HANNA	65.7	.100	.244	16.5	-.203	.127
25	GOLDFOIL	71.4	.194	.131	19.9	.368	.255
26	COMPANA	70.6	-.288	.208	16.9	-.373	.194
27	L O GLUME	69.1	.168	.080	17.0	.069	.228
28	PRIORS	71.0	-.297	.143	16.5	-.349	.356
29	PRIOR A	70.3	-.162	.115	16.5	-.242	.223
30	NOYEP	68.5	-.622	.144	16.5	-.193	.272
31	RESEARCH M R	71.8	.045	.096	19.3	.094	.256
32	RESIBEE	71.4	.239	.196	19.0	.342	.241
33	CPI 18197	64.4	.062	.119	18.2	.033	.354
34	CPI 18198	65.4	-.151	.223	15.9	.162	.278
35	WAITE 775	57.0	-.553	.363	13.8	-.309	.606
36	CI 3576	56.8	-.637	.249	13.6	-.511	.708
37	RETU	56.9	-.557	.265	13.9	-.479	.491
38	G H SINAI	64.5	.036	.199	15.8	-.460	.269
39	CI 5611	66.1	.128	.408	14.3	-.267	.351
40	WHITE SMYRNA	64.1	.027	.307	16.9	.289	.218
	LSD 1%	1.5	.110		.8	.186	

APPENDIX 6

WORT NITROGEN AND DIASTATIC ACTIVITY PERFORMANCE OF 40 VARIETIES OVER 6 SITES

		WORT NITROGEN			DIASTATIC ACTIVITY		
	VARIETY	MEAN	B	SE(B)	MEAN	B	SE(B)
1	DOMEN	.620	.171	.194	1.047	.353	.341
2	FREJA	.491	-.109	.161	.713	-.252	.315
3	RIKA	.534	.163	.054	.729	.360	.214
4	BONUS	.462	-.193	.179	.605	.384	.082
5	RIGEL	.476	-.097	.141	.710	.419	.193
6	DELTA	.498	.311	.171	.758	-.245	.077
7	CAMBRINUS	.545	.159	.144	.832	.262	.100
8	EMIR	.530	.342	.196	.820	.005	.106
9	IMPALA	.591	.195	.145	.870	-.224	.139
10	G/SPRATT	.585	.354	.336	.753	.176	.519
11	PROCTOR	.559	.240	.360	.768	.212	.492
12	MAYTHORPE	.562	.223	.436	.811	.391	.328
13	BALDRIC	.566	.388	.185	.830	.295	.394
14	BEKA	.600	.249	.253	.884	.227	.271
15	CERES	.503	.283	.307	.854	.460	.258
16	PORT 2 ROW	.561	-.077	.105	.669	.273	.145
17	BOA FE	.554	-.211	.294	.723	-.009	.178
18	MORGENROT	.576	.452	.366	.836	.727	.263
19	HAISA II	.542	-.017	.160	.856	.421	.107
20	PIROLINE	.540	-.161	.229	.790	.411	.144
21	UNION	.544	.120	.222	.823	-.142	.237
22	JULIANE	.564	.127	.154	.882	.314	.215
23	KANKYO	.541	-.216	.277	.627	-.296	.169
24	HANNA	.493	.029	.085	.653	-.215	.145
25	GOLDFOIL	.572	.667	.116	.909	.054	.293
26	COMPANA	.556	-.238	.203	.645	.200	.143
27	L O GLUME	.540	-.277	.290	.778	.245	.425
28	PRIORS	.554	.196	.272	.682	.084	.172
29	PRIOR A	.569	.065	.278	.649	.245	.107
30	NOYEP	.603	-.456	.570	.682	-.282	.110
31	RESEARCH M R	.548	-.036	.161	.771	-.178	.102
32	RESIBEE	.600	.188	.324	.825	-.050	.219
33	CPI 18197	.536	-.440	.137	.586	-.442	.198
34	CPI 18198	.516	-.711	.162	.583	-.676	.155
35	WAITE 775	.352	-.333	.124	.375	-.598	.101
36	CI 3576	.350	-.232	.109	.377	-.647	.154
37	RETU	.357	-.380	.047	.409	-.577	.226
38	G H SINAI	.491	-.254	.311	.445	-.046	.132
39	CI 5611	.430	-.381	.192	.436	-.902	.246
40	WHITE SMYRNA	.479	-.103	.201	.650	-.736	.277
	LSD 1%	.033	.141		.073	.141	

APPENDIX 7

PREDICTED EXTRACT PERFORMANCE AND RELATIVE EXTRACT MEANS OF 40 VARIETIES OVER 6 SITES

		PREDICTED EXTRACT			RELATIVE EXTRACT
	VARIETY	MEAN	B	SE(B)	MEAN
1	DOMEN	72.6	.377	.174	-1.07
2	FREJA	72.9	.066	.189	-2.52
3	RIKA	73.1	.077	.065	-2.19
4	BONUS	73.2	-.260	.107	-3.22
5	RIGEL	72.5	-.006	.156	-2.04
6	DELTA	73.5	-.100	.104	-1.98
7	CAMBRINUS	72.2	.096	.109	0.61
8	EMIR	72.7	-.142	.179	-1.20
9	IMPALA	72.1	-.298	.196	1.02
10	G/SPRATT	71.0	.174	.144	-0.78
11	PROCTOR	73.5	.130	.160	-0.75
12	MAYTHORPE	72.6	-.037	.162	-1.33
13	BALDRIC	73.1	.240	.116	-2.39
14	BEKA	75.7	-.151	.123	-0.46
15	CERES	71.9	.041	.200	-1.30
16	PORT 2 ROW	72.5	-.177	.167	-1.40
17	BOA FE	70.8	.368	.251	-1.53
18	MORGENROT	72.7	.008	.170	-0.57
19	HAISA II	73.8	-.247	.153	-3.28
20	PIROLINE	72.1	-.372	.285	-1.36
21	UNION	74.5	-.081	.222	-0.91
22	JULIANE	74.9	-.207	.085	-1.75
23	KANKYO	70.4	-.607	.182	-1.88
24	HANNA	70.4	-.316	.213	-4.75
25	GOLDFOIL	73.0	.118	.160	-1.52
26	COMPANA	71.2	.057	.113	-0.63
27	L O GLUME	70.7	.134	.115	-1.56
28	PRIORS	71.9	-.102	.137	-0.86
29	PRIOR A	71.2	.027	.125	-0.92
30	NOYEP	70.1	-.426	.140	-1.55
31	RESEARCH M R	71.4	.153	.099	0.43
32	RESIBEE	71.5	.048	.156	-0.07
33	CPI 18197	66.8	.068	.159	-2.38
34	CPI 18198	65.4	.360	.389	-0.03
35	WAITE 775	66.4	.438	.274	-9.46
36	CI 3576	66.1	-.038	.081	-9.25
37	RETU	65.8	-.090	.166	-8.89
38	G H SINAI	67.5	.283	.118	-2.99
39	CI 5611	70.4	.169	.330	-4.38
40	WHITE SMYRNA	68.1	.227	.206	-4.02
	LSD 1%	1.3	.107		1.36

APPENDIX 8

Site means (2 replicates) of two grain, five malt and two derived characters. (See Table 10, page 81 for grain nitrogen figures)

Sites		Insoluble Carbohydrate (%)	Steep time (hrs)	Malt loss (%)	Malt extract (%)	Cold water extract (%)	Wort nitrogen (%)	Diastatic activity (maltose equivalents)	Predicted extract (%)	Relative extract (%)
Clinton	1964	7.89	50.2	7.78	71.7	17.1	.466	.579	74.5	-2.9
Bundaleer	1964	7.91	49.1	9.13	73.4	18.9	.488	.565	73.6	-0.2
Waite	1964	8.06	53.1	7.89	69.5	18.8	.602	.819	71.7	-2.3
Bundaleer	1963	8.09	43.5	8.65	68.8	17.7	.489	.656	71.3	-2.5
Minlaton	1963	7.82	54.9	9.77	68.6	17.9	.563	.788	70.1	-1.5
Waite	1965	8.25	42.7	8.02	63.1	16.4	.576	.889	66.6	-3.5
LSD 1%		.15	2.2	.32	.6	.3	.013	.031	.5	.5

APPENDIX 9

Latent roots of a matrix of 11 principal components

Components	Latent Roots	Cumulative Proportion of Total Variance
1	4.437	.40
2	2.281	.61
3	1.184	.72
4	.967	.81
5	.728	.87
6	.501	.92
7	.357	.95
8	.230	.97
9	.192	.99
10	.123	1.00
11	.00001	1.00

APPENDIX 10

Mean Squares from Analysis of Variance of the principal components scores for 40 varieties grown at six sites

	D.F.	Component 1 Mean Squares	Component 2 Mean Squares	Component 3 Mean Squares	Component 4 Mean Squares	Component 5 Mean Squares
Environments	5	40.674***	163.354***	29.378***	34.366***	13.153***
Replicates within environments	6	4.383***	.662**	1.904***	1.210***	.932***
Genotypes	39	44.481***	2.345***	6.510***	3.830***	3.426***
Genotype; environment interaction	195	.516***	.674***	.553***	.474***	.501***
Residual	234	.257	.209	.202	.182	.197

Variance ratios were calculated against the residual mean squares.

APPENDIX 11

Latent roots of eight canonical axes (40 varieties)

Axis	Latent roots	Cumulative proportion of total variance
1	45.496	.71
2	8.056	.84
3	4.873	.92
4	2.031	.95
5	1.382	.97
6	.866	.98
7	.741	.99
8	.310	1.00

APPENDIX 12

Latent roots of eight canonical axes (25 varieties)

Axis	Latent roots	Cumulative proportion of total variance
1	5.264	.32
2	3.684	.55
3	3.245	.75
4	1.819	.86
5	1.016	.93
6	.511	.96
7	.434	.99
8	.238	1.00

APPENDIX 13

Malt analyses of eight varieties treated with five concentrations of GA_3

	GA_3 (ppm) Concentration	Domen	Proctor	Beka	Long Outer Glume	Prior's	Resibee	CPI 18197	CI 3576
Malt extract (%)	0	71.3	71.2	74.6	70.9	70.1	69.8	59.0	56.1
	.001	71.2	71.7	74.4	70.2	70.3	70.6	59.0	55.9
	.01	71.3	73.5	76.8	71.3	70.9	70.4	61.2	56.1
	.1	73.8	75.3	79.0	72.1	72.5	73.6	64.3	57.4
	1.0	77.2	78.2	81.5	76.3	76.5	76.4	68.4	63.3
Diastatic activity (maltose equivalents)	0	.655	.422	.701	.802	.361	.598	.434	.222
	.001	.655	.439	.712	.821	.361	.595	.433	.222
	.01	.665	.496	.731	.834	.371	.603	.478	.222
	.1	.807	.575	.809	.914	.377	.656	.586	.227
	1.0	.974	.641	.974	1.130	.535	.827	.632	.357
Wort nitrogen (%)	0	.483	.485	.550	.536	.442	.487	.435	.327
	.001	.507	.497	.562	.508	.444	.496	.430	.329
	.01	.494	.504	.566	.530	.437	.489	.470	.315
	.1	.604	.536	.650	.616	.508	.578	.514	.325
	1.0	.694	.628	.779	.786	.616	.712	.649	.439

APPENDIX 14

Malt extract (%) of four varieties from four sites treated with water or 14 gibberellic acid concentrations

GA_3 Concentration	Long Outer Glume				Prior's Chevalier				Resibee			CI. 3576			
	W64	W66	B66	A66	W64	W66	B66	A66	W64	B66	A66	W64	W66	B66	A66
0	65.4	65.0	70.6	61.3	66.0	67.2	71.2	65.4	67.1	73.7	65.9	59.9	57.3	59.6	55.6
.01 ppm	67.2	66.3	71.2	62.4	66.4	67.6	72.7	66.5	68.4	74.5	66.4	60.1	58.4	59.7	55.3
.02 "	67.9	66.8	73.6	63.1	67.5	68.3	74.3	67.3	68.1	74.5	68.3	60.5	58.4	60.6	55.7
.03 "	69.3	66.1	74.0	64.2	67.1	68.8	73.4	66.2	70.0	76.0	69.6	62.0	59.5	60.7	54.7
.04 "	69.2	67.3	74.5	64.2	66.5	68.9	74.7	67.4	70.2	76.4	68.4	62.2	59.6	61.7	56.3
.05 "	68.7	66.4	73.9	64.9	68.0	69.3	73.9	66.8	70.1	76.1	68.8	61.5	60.0	62.5	55.5
.07 "	68.4	68.5	74.0	66.2	68.0	69.4	75.0	68.1	70.6	76.2	69.8	62.8	60.0	62.8	57.9
.1 "	69.2	67.3	75.8	66.8	67.4	70.0	75.5	69.6	72.0	76.9	71.3	62.8	60.4	62.6	58.2
.2 "	70.7	68.1	75.3	67.3	68.1	70.3	76.2	70.3	71.9	78.0	70.0	63.8	61.6	65.0	59.6
.3 "	71.2	67.4	76.0	67.7	69.7	70.6	77.4	70.6	71.5	78.4	71.6	64.8	63.7	66.1	60.0
.4 "	70.4	69.4	75.9	68.0	69.7	71.0	76.8	71.5	73.0	78.0	72.3	65.2	63.4	67.4	61.9
.5 "	70.8	68.2	77.9	68.0	69.2	71.1	78.0	71.2	73.0	78.7	72.2	66.3	64.0	67.4	61.5
.7 "	71.3	70.7	77.6	68.3	70.0	72.4	78.1	71.1	73.9	78.8	73.1	66.6	64.6	67.9	62.9
1.0 "	71.2	70.8	78.2	70.1	70.3	71.8	78.7	72.5	74.1	79.3	73.2	66.0	64.7	68.3	63.8
2.0 "	72.2	72.0	78.1	70.7	70.9	73.1	78.7	73.0	74.3	79.0	73.7	69.2	65.9	69.5	64.2

W64 = Waite 1964
W66 = Waite 1966
B66 = Bundaleer 1966
A66 = Aldinga 1966

The results for the water controls were not used in the calculation of the means and regression coefficients in Table 39 (page 152a).

APPENDIX 14 (Cont.)

Wort nitrogen (%) for four varieties from four sites treated with water or 14 gibberellic acid concentrations

GA_3 Concentration	Long Outer Glume				Prior's Chevalier				Resibee			CI. 3576			
	W64	W66	B66	A66	W64	W66	B66	A66	W64	B66	A66	W64	W66	B66	A66
0	.56	.55	.59	.50	.61	.58	.61	.56	.54	.63	.57	.53	.44	.39	.36
.01 ppm	.59	.61	.63	.52	.62	.55	.64	.58	.57	.67	.56	.55	.43	.39	.35
.02 "	.60	.60	.67	.55	.63	.63	.72	.60	.53	.70	.63	.55	.42	.41	.37
.03 "	.64	.57	.68	.57	.63	.62	.67	.61	.62	.73	.66	.56	.45	.42	.37
.04 "	.63	.61	.73	.60	.62	.61	.77	.66	.63	.75	.64	.57	.45	.44	.37
.05 "	.64	.61	.68	.59	.66	.63	.73	.68	.65	.75	.67	.57	.46	.44	.35
.07 "	.63	.65	.73	.65	.69	.62	.80	.76	.65	.78	.72	.57	.47	.48	.39
.1 "	.67	.65	.79	.64	.68	.68	.80	.71	.68	.77	.76	.60	.49	.46	.41
.2 "	.75	.74	.82	.74	.68	.73	.86	.73	.69	.86	.77	.64	.52	.51	.44
.3 "	.80	.70	.86	.75	.73	.75	.92	.80	.71	.86	.83	.65	.60	.58	.47
.4 "	.74	.79	.87	.79	.75	.79	.88	.78	.77	.88	.82	.71	.65	.62	.53
.5 "	.76	.75	.98	.83	.74	.78	.93	.79	.76	.86	.82	.73	.61	.64	.49
.7 "	.81	.88	.94	.81	.76	.80	.96	.84	.83	.92	.92	.77	.64	.70	.55
1.0 "	.80	.86	.99	.87	.77	.81	.98	.85	.81	.95	.86	.76	.67	.65	.61
2.0 "	.88	.98	1.02	.96	.82	.90	1.01	.87	.84	.94	.99	.84	.73	.73	.66

W64 = Waite 1964
W66 = Waite 1966
B66 = Bundaleer 1966
A66 = Aldinga 1966

The results for the water controls were not used in the calculation of the means and regression coefficients in Table 39, (page 152a).

APPENDIX 15A

MALTING LOSS AND MALT EXTRACT (MEANS OF 2 REPLICATES) FOR 40 VARIETIES TREATED WITH WATER OR GA3 (1PPM)

	VARIETY	MALTING LOSS		MALT EXTRACT	
		-GA3	+GA3	-GA3	+GA3
1	DOMEN	4.62	4.52	61.5	73.0
2	FREJA	5.12	5.20	63.0	70.3
3	RIKA	6.22	5.98	64.3	71.0
4	BONUS	5.91	5.33	60.6	67.8
5	RIGEL	7.36	5.69	65.4	72.5
6	DELTA	5.43	5.63	63.2	70.8
7	CAMBRINUS	5.66	4.80	61.8	67.3
8	EMIR	5.58	5.72	62.1	70.7
9	IMPALA	5.83	5.82	66.5	73.2
10	G/SPRATT	6.46	6.08	66.2	72.6
11	PROCTOR	5.75	5.38	68.4	75.4
12	MAYTHORPE	5.87	5.92	61.1	67.8
13	BALDRIC	7.58	7.43	62.3	72.1
14	BEKA	8.29	9.42	68.5	79.5
15	CERES	6.55	5.63	65.4	70.4
16	PORT 2 ROW	6.60	5.84	63.7	71.0
17	BOA FE	6.94	6.60	63.3	69.8
18	MORGENROT	5.64	5.68	63.3	71.5
19	HAISA II	6.15	6.57	63.4	73.3
20	PIROLINE	5.68	5.48	64.5	71.4
21	UNION	6.79	5.89	65.8	72.3
22	JULIANE	6.44	6.24	63.7	71.2
23	KANKYO	4.47	4.37	58.7	72.3
24	HANNA	4.47	4.25	56.1	69.0
25	GOLDFOIL	6.71	6.46	64.9	74.0
26	COMPANA	7.57	5.72	61.1	66.6
27	L O GLUME	5.49	5.82	61.1	67.7
28	PRIORS	6.16	6.39	64.9	71.5
29	PRIOR A	5.95	5.94	62.3	69.1
30	NOYEP	6.27	5.89	63.1	69.7
31	RESEARCH M R	5.71	4.84	61.3	70.0
32	RESIBEE	4.55	4.29	62.2	73.4
33	CPI 18197	4.76	5.04	52.7	68.5
34	CPI 18198	8.10	7.95	57.4	65.3
35	WAITE 775	7.21	6.23	54.5	63.0
36	CI 3576	6.01	5.77	55.9	63.8
37	RETU	5.23	6.02	53.7	62.8
38	G H SINAI	6.08	6.31	55.2	61.8
39	CI 5611	5.78	5.36	60.1	68.5
40	WHITE SMYRNA	6.60	5.84	55.4	59.2
	LSD 1 %	1.38	1.38	3.7	3.7

APPENDIX 158

WORT NITROGEN AND DIASTATIC ACTIVITY (MEANS OF 2 REPLICATES) FOR 40 VARIETIES TREATED WITH WATER OR GA3 (1PPM)

		WORT NITROGEN		DIASTSTIC ACTIVITY	
		-GA3	+GA3	-GA3	+GA3
1	DOMEN	.505	.995	.573	1.116
2	FREJA	.504	.785	.573	.960
3	RIKA	.563	.850	.695	.969
4	BONUS	.515	.771	.665	.942
5	RIGEL	.595	.822	.718	1.043
6	DELTA	.490	.823	.699	1.075
7	CAMBRINUS	.543	.815	.877	1.051
8	EMIR	.518	.877	.848	1.106
9	IMPALA	.630	.902	.815	1.010
10	G/SPRATT	.654	.978	.777	.957
11	PROCTOR	.579	.914	.701	.931
12	MAYTHORPE	.599	.886	.757	1.055
13	BALDRIC	.562	.921	.743	1.132
14	BEKA	.619	1.038	.931	1.213
15	CERES	.545	.813	.852	1.095
16	PORT 2 ROW	.615	.920	.709	1.034
17	BOA FE	.603	.856	.652	.807
18	MORGENROT	.532	.849	.625	.931
19	HAISA II	.550	.971	.772	1.178
20	PIROLINE	.543	.842	.791	1.111
21	UNION	.564	.818	.702	.951
22	JULIANE	.576	.951	.696	1.070
23	KANKYO	.504	1.184	.801	.921
24	HANNA	.481	.967	.818	1.089
25	GOLDFOIL	.591	.978	.783	1.043
26	COMPANA	.600	.816	.772	1.038
27	L O GLUME	.562	.880	.804	1.006
28	PRIORS	.582	.876	.676	1.013
29	PRIOR A	.578	.890	.638	.976
30	NOYEP	.664	1.008	.753	1.084
31	RESEARCH M R	.534	.864	.572	.901
32	RESIBEE	.526	.898	.594	1.018
33	CPI 18197	.501	.997	.509	.753
34	CPI 18198	.519	.826	.693	.971
35	WAITE 775	.442	.710	.573	.748
36	CI 3576	.456	.720	.582	.751
37	RETU	.430	.682	.549	.733
38	G H SINAI	.517	.773	.586	.827
39	CI 5611	.488	.833	.513	.758
40	WHITE SMYRNA	.537	.659	.613	.736
	LSD 1%	.106	.106	.125	.125

APPENDIA 16

DISTANCES BETWEEN 40 VARIETIES IN 8 DIMENSIONAL SPACE

VALUES FOR SQ.ROOT OF D SQUARED

VARIETIES	DOMEN	FREJA	RIKA	BONUS	RIGEL
FREJA	3.30				
RIKA	4.15	1.93			
BONUS	4.11	1.38	1.68		
RIGEL	3.62	1.02	1.69	1.41	
DELTA	3.17	1.57	1.96	1.56	1.10
CAMBRINUS	2.50	1.75	2.53	2.65	1.81
EMIR	3.50	2.08	1.38	2.31	1.86
IMPALA	3.31	3.23	2.83	3.40	3.23
G/SPRATT	3.78	2.39	1.88	2.48	2.50
PROCTOR	3.26	2.15	1.90	2.40	2.49
MAYTHORPE	2.18	1.97	3.07	2.75	2.67
BALDRIC	2.31	1.67	2.56	2.44	2.32
BEKA	3.06	3.75	3.26	3.64	3.74
CERES	3.12	1.94	2.68	2.76	1.47
PORT 2 ROW	4.69	2.80	2.36	2.69	2.50
BOA FE	4.50	3.09	2.84	3.18	3.30
MORGENROT	2.11	2.27	3.10	2.97	2.84
HAISA II	2.62	2.00	2.29	2.17	1.95
PIROLINE	2.89	1.43	1.91	1.85	1.52
UNION	2.98	2.27	2.00	2.48	1.87
JULIANE	3.20	3.12	2.51	3.06	2.85
KANKYO	6.10	5.21	6.16	5.63	5.44
HANNA	5.69	3.55	4.51	3.92	3.65
GOLDFOIL	2.05	2.84	3.19	3.23	3.19
COMPANA	5.65	3.95	3.95	4.09	3.65
L O GLUME	4.97	3.82	4.57	4.36	3.57
PRIORS	5.80	4.06	3.85	4.16	3.61
PRIOR A	6.05	4.32	4.03	4.31	3.95
NOYEP	6.23	4.60	4.30	4.59	4.32
RES M R	3.82	2.51	3.42	3.58	2.75
RESIBEE	3.67	2.95	3.56	3.75	2.99
CPI 18197	8.94	7.87	8.63	8.19	7.93
CPI 18198	12.18	11.21	11.88	11.58	11.03
WAITE 775	13.62	11.84	12.62	12.04	11.80
CI 3576	13.37	11.47	12.22	11.67	11.43
RETU	12.99	11.17	12.00	11.42	11.16
G H SINAI	9.64	7.79	8.30	8.00	7.70
CI 5611	7.91	5.73	6.20	5.67	5.50
W SMYRNA	7.07	5.17	6.16	5.75	5.30

APPENDIX 16 (CONT)

VARIETIES	DELTA	CAMB.	EMIR	IMPALA	G/SPRATT
CAMBRINUS	1.74				
EMIR	1.95	2.16			
IMPALA	2.77	2.33	2.29		
G/SPRATT	2.55	2.33	2.39	2.24	
PROCTOR	2.37	2.08	1.61	1.90	2.11
MAYTHORPE	2.52	1.81	2.85	2.66	2.35
BALDRIC	2.36	2.04	2.42	2.95	2.21
BEKA	3.03	3.30	2.72	2.17	3.16
CERES	1.71	1.69	2.29	3.54	3.37
PORT 2 ROW	2.71	2.95	3.38	3.92	2.33
BOA FE	3.57	3.48	3.09	3.23	1.79
MORGENROT	2.60	1.75	2.76	2.20	2.24
HAISA II	1.57	2.42	2.12	3.19	2.78
PIROLINE	1.33	1.30	1.92	2.13	1.51
UNION	1.48	1.92	1.69	2.75	2.80
JULIANE	2.34	3.02	1.99	3.01	3.35
KANKYO	5.72	5.38	6.70	6.66	5.05
HANNA	4.23	4.34	5.27	6.12	4.50
GOLDFOIL	2.75	2.62	2.43	2.33	3.00
COMPANA	3.92	3.85	4.79	5.27	3.99
L O GLUME	3.86	3.67	5.05	5.58	4.40
PRIORS	3.91	3.98	4.67	5.35	4.16
PRIOR A	4.19	4.27	4.95	5.48	4.23
NOYEP	4.53	4.59	5.29	5.74	4.36
RES M R	3.31	2.11	3.50	3.82	2.77
RESIBEE	3.25	2.38	3.88	4.08	2.89
CPI 18197	8.29	8.03	9.29	9.27	7.63
CPI 18198	11.39	11.09	12.50	12.61	11.20
WAITE 775	12.41	12.55	13.38	14.16	12.37
CI 3576	12.07	12.20	12.99	13.80	12.01
RETU	11.78	11.87	12.73	13.50	11.75
G H SINAI	8.24	8.14	9.20	9.69	7.92
CI 5611	5.92	6.31	7.12	8.01	6.61
W SMYRNA	6.01	5.74	6.75	7.46	5.82

APPENDIX 16 (CONT)

VARIETIES	PROCTOR	M/THORPE	BALDRIC	BEKA	CERES
MAYTHORPE	2.13				
BALDRIC	2.10	1.11			
BEKA	2.54	3.18	3.04		
CERES	3.03	3.03	2.76	3.98	
PORT 2 ROW	3.43	3.65	3.40	4.45	3.22
BOA FE	3.15	3.00	2.68	3.92	4.26
MORGENROT	1.99	.56	1.39	2.87	3.14
HAISA II	2.60	2.47	1.77	2.61	2.26
PIROLINE	1.93	1.64	1.64	2.93	2.23
UNION	2.19	2.92	2.57	2.59	1.77
JULIANE	2.57	3.47	2.93	1.90	2.87
KANKYO	6.54	5.03	5.14	7.31	5.89
HANNA	5.37	4.57	4.39	6.77	4.15
GOLDFOIL	2.13	1.94	1.84	1.86	3.37
COMPANA	4.78	4.83	4.77	6.00	3.90
L O GLUME	5.28	4.52	4.46	6.21	3.42
PRIORS	4.87	5.11	4.95	6.02	3.77
PRIOR A	4.99	5.27	5.15	6.14	4.24
NOYEP	5.25	5.43	5.29	6.36	4.65
RES M R	3.43	2.69	2.81	4.99	2.84
RESIBEE	3.79	3.03	3.03	4.85	2.93
CPI 18197	9.29	7.95	8.03	10.10	8.34
CPI 18198	12.68	11.58	11.68	13.52	11.05
WAITE 775	13.72	12.65	12.46	14.85	12.18
CI 3576	13.34	12.35	12.15	14.54	11.83
RETU	13.05	11.99	11.83	14.26	11.53
G H SINAI	9.29	8.56	8.51	10.58	8.08
CI 5611	7.22	6.99	6.87	8.56	5.85
W SMYRNA	6.92	5.91	5.82	8.41	5.65

APPENDIX 16 (CONT)

VARIETIES	PORT 2R	BOA FE	M/ROT	HAISA II	PIROLINE
BOA FE	3.68				
MORGENROT	3.75	2.96			
HAISA II	3.28	3.43	2.60		
PIROLINE	2.60	2.53	1.65	1.90	
UNION	2.88	4.01	2.89	1.71	2.08
JULIANE	3.86	4.22	3.38	1.76	2.84
KANKYO	4.77	5.10	5.29	5.86	5.07
HANNA	3.35	5.01	4.97	4.64	4.13
GOLDFOIL	4.56	3.39	1.74	2.15	2.34
COMPANA	1.92	5.35	4.97	4.72	4.00
L O GLUME	2.95	5.37	4.75	4.41	3.90
PRIORS	2.03	5.50	5.24	4.69	4.13
PRIOR A	2.06	5.62	5.39	4.96	4.34
NOYEP	2.23	5.72	5.56	5.18	4.59
RES M R	3.06	3.43	2.81	3.76	2.54
RESIBEE	2.33	3.99	3.16	3.57	2.73
CPI 18197	7.00	7.58	8.18	8.58	7.73
CPI 18198	9.92	11.55	11.79	11.92	11.15
WAITE 775	11.25	12.17	13.03	12.68	12.25
CI 3576	10.90	11.80	12.72	12.37	11.91
RETU	10.69	11.56	12.36	12.09	11.61
G H SINAI	6.42	8.34	8.85	8.80	8.03
CI 5611	4.60	7.54	7.32	6.67	6.30
W SMYRNA	5.09	5.87	6.27	6.39	5.62

APPENDIX 16 (CONT)

VARIETIES	UNION	JULIANE	KANKYO	HANNA	GOLDFOIL
JULIANE	1.42				
KANKYO	6.45	7.30			
HANNA	5.00	6.02	3.52		
GOLDFOIL	2.72	2.45	6.60	6.02	
COMPANA	4.04	5.27	4.97	3.20	6.01
L O GLUME	4.27	5.46	3.82	2.38	5.79
PRIORS	3.92	5.11	5.48	3.49	6.11
PRIOR A	4.21	5.35	5.54	3.67	6.31
NOYEP	4.57	5.64	5.38	3.65	6.53
RES M R	3.58	4.68	4.14	3.47	4.12
RESIBEE	3.32	4.45	3.84	3.24	4.37
CPI 18197	9.08	9.99	3.08	5.28	9.49
CPI 18198	11.97	13.09	7.25	8.25	13.10
WAITE 775	13.25	14.15	8.49	8.56	14.08
CI 3576	12.91	13.82	8.31	8.22	13.77
RETU	12.65	13.58	7.93	7.91	13.44
G H SINAI	8.85	9.97	4.90	4.57	10.14
CI 5611	6.45	7.57	5.82	3.25	8.29
W SMYRNA	6.77	7.81	3.33	2.35	7.47

VARIETIES	COMPANA	L.O.G.	PRIORS	PRIOR A	NOYEP
L O GLUME	2.30				
PRIORS	.76	2.50			
PRIOR A	.73	2.87	.66		
NOYEP	1.09	3.00	1.20	.69	
RES M R	3.54	3.10	3.81	4.11	4.32
RESIBEE	2.62	2.15	2.94	3.18	3.28
CPI 18197	6.72	5.62	7.15	7.17	6.93
CPI 18198	8.83	7.85	9.09	9.15	8.96
WAITE 775	10.64	9.60	10.82	10.92	10.72
CI 3576	10.29	9.32	10.46	10.56	10.37
RETU	10.07	9.01	10.27	10.38	10.20
G H SINAI	5.39	5.06	5.68	5.64	5.41
CI 5611	3.36	3.69	3.47	3.46	3.51
W SMYRNA	4.78	3.65	5.06	5.28	5.22

APPENDIX 16 (CONT)

VARIETIES	RES M R	RESIBEE	CPI 18197	CPI 18198	WAITE 775
RESIBEE	1.65				
CPI 18197	6.60	6.30			
CPI 18198	9.71	9.19	4.84		
WAITE 775	11.12	11.00	6.30	6.00	
CI 3576	10.77	10.70	6.20	6.07	.72
RETU	10.43	10.38	5.84	5.84	.91
G H SINAI	6.73	6.30	3.78	4.65	5.81
CI 5611	5.81	5.22	6.67	7.99	8.66
W SMYRNA	4.18	4.40	4.06	7.01	7.06

VARIETIES	CI 3576	RETU	G.H.S.	CI 5611
RETU	.69			
G H SINAI	5.51	5.33		
CI 5611	8.32	8.14	4.21	
W SMYRNA	6.69	6.33	3.74	4.55

APPENDIX 17

DISTANCES BETWEEN 25 VARIETIES IN 8 DIMENSIONAL SPACE

VALUES FOR SQ.ROOT OF D SQUARED

VARIETIES	DOMEN	FREJA	RIKA	BONUS	RIGEL
FREJA	3.33				
RIKA	4.38	2.14			
BONUS	4.20	1.52	1.75		
RIGEL	3.69	1.13	1.82	1.57	
DELTA	3.23	1.68	2.07	1.65	1.15
CAMBRINUS	2.60	2.06	2.96	3.04	2.11
EMIR	3.64	2.15	1.45	2.33	1.94
IMPALA	3.55	3.63	3.40	3.87	3.70
G/SPRATT	3.91	2.65	2.26	2.81	2.76
PROCTOR	3.39	2.33	2.13	2.53	2.70
MAYTHORPE	2.23	2.22	3.51	3.08	2.99
BALDRIC	2.37	1.69	2.78	2.50	2.43
BEKA	3.36	4.02	3.46	3.76	3.99
CERES	3.31	2.12	2.91	2.98	1.53
PORT 2 ROW	5.03	3.28	2.68	3.15	2.78
BOA FE	4.52	3.18	3.13	3.41	3.52
MORGENROT	2.22	2.59	3.61	3.38	3.23
HAISA II	2.96	2.20	2.44	2.18	2.09
PIROLINE	2.90	1.59	2.26	2.14	1.75
UNION	3.33	2.59	2.13	2.63	2.01
JULIANE	3.76	3.51	2.71	3.20	3.13
GOLDFOIL	2.18	2.97	3.48	3.33	3.43
RES M R	4.09	3.07	4.09	4.25	3.27
RESIBEE	4.04	3.45	4.07	4.31	3.34

APPENDIX 17 (CONT)

VARIETIES	DELTA	CAMB.	EMIR	IMPALA	G/SPRATT
CAMBRINUS	2.03				
EMIR	2.01	2.49			
IMPALA	3.22	2.53	2.81		
G/SPRATT	2.75	2.44	2.64	2.40	
PROCTOR	2.50	2.38	1.70	2.12	2.26
MAYTHORPE	2.82	2.02	3.15	2.83	2.55
BALDRIC	2.45	2.35	2.54	3.34	2.48
BEKA	3.20	3.72	2.95	2.71	3.45
CERES	1.85	2.03	2.50	4.08	3.65
PORT 2 ROW	2.95	3.34	3.68	4.43	2.68
BOA FE	3.76	3.55	3.29	3.38	1.86
MORGENROT	2.96	1.96	3.14	2.33	2.45
HAISA II	1.75	3.03	2.31	3.97	3.29
PIROLINE	1.56	1.37	2.13	2.36	1.59
UNION	1.58	2.50	1.91	3.43	3.17
JULIANE	2.62	3.77	2.35	3.97	3.94
GOLDFOIL	2.96	2.98	2.64	2.74	3.29
RES M R	3.79	2.29	4.04	4.13	3.08
RESIBEE	3.61	2.61	4.33	4.47	3.17

VARIETIES	PROCTOR	M/THORPE	BALDRIC	BEKA	CERES
MAYTHORPE	2.34				
BALDRIC	2.26	1.38			
BEKA	2.69	3.58	3.33		
CERES	3.38	3.44	3.00	4.37	
PORT 2 ROW	3.90	4.26	3.88	4.79	3.45
BOA FE	3.17	2.99	2.72	4.22	4.52
MORGENROT	2.24	.63	1.77	3.34	3.61
HAISA II	2.93	3.07	2.05	2.92	2.54
PIROLINE	2.02	1.73	1.76	3.24	2.50
UNION	2.61	3.53	2.94	2.84	2.02
JULIANE	3.08	4.22	3.41	2.26	3.30
GOLDFOIL	2.21	2.10	1.94	2.19	3.77
RES M R	3.97	3.09	3.36	5.64	3.28
RESIBEE	4.34	3.58	3.61	5.40	3.22

APPENDIX 17 (CONT)

VARIETIES	PORT 2R	BOA FE	M/ROT	HAISA II	PIROLINE
BOA FE	4.07				
MORGENROT	4.37	2.98			
HAISA II	3.67	3.83	3.31		
PIROLINE	3.00	2.56	1.78	2.42	
UNION	3.06	4.36	3.56	1.90	2.49
JULIANE	4.22	4.77	4.23	1.94	3.45
GOLDFOIL	5.08	3.52	2.01	2.55	2.55
RES M R	3.64	3.67	3.17	4.54	2.82
RESIBEE	2.64	4.26	3.67	4.23	3.03

VARIETIES	UNION	JULIANE	GOLDFOIL	RES M R
JULIANE	1.62			
GOLDFOIL	3.19	3.07		
RES M R	4.28	5.59	4.68	
RESIBEE	3.81	5.17	4.98	1.87