HGCA

PROJECT REPORT No. 10

MILLING QUALITY INDEX FOR PREDICTING FLOUR YIELD

APRIL 1989

PRICE £3.00

HOME-GROWN CEREALS AUTHORITY

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Milling Quality Index for Predicting Flour Yield

by

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Final report of a twelve month project commencing August 1987 which was carried out at the Flour Milling and Baking Research Association. The project was funded with a grant of £19,200 from the Home-Grown Cereals Authority (project No 0042/1/87).

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FLOUR MILLING AND BAKING RESEARCH ASSOCIATION

Final Report

1 year project commencing 1st September 1987

ABSTRACT

The aim of the project was to devise a procedure, based on image analysis, for predicting the flour yield potential of a sample of wheat, which is superior to the existing unsatisfactory "specific weight" measurement.

Procedures were devised whereby grains could be cut in the plane of the crease so that a consistent face could be presented to the camera for T.V. imaging. By this means measurements related to endosperm content could be made. At the same time as these measurements other shape factors were also recorded and relationships among them were derived. Milling yield was assessed on laboratory Buhler mills operated in a standard fashion and grade colour figures for all machine flours were obtained. On a series of ten wheats, chosen to represent a wide range of milling types, milling extraction rate correlated with one shape factor with a coefficient of 0.78. Inclusion of a second factor in a stepwise regression increased the correlation coefficient to 0.925.

A high correlation was also found with specific weight but the relationship was negative whereas a positive relationship is expected and frequently relied upon as a predictor. The unexpected negative correlation between specific weight and flour yield illustrates the difficulty in predicting yield in a wide range of wheat types. With this in mind the performance of the image analysis system is particularly promising. The present system of grain preparation is unsuitable for routine application but if the use of the present image analysis regime with a larger number of wheat types is equally successful a simplified method of presentation can be devised.

OBJECTIVE

To devise a procedure, based on image analysis, for predicting the flour yield potential of a sample of wheat, which is superior to the existing unsatisfactory specific weight measurement.

INTRODUCTION

Extraction rate - the weight of flour produced per 100 parts of wheat milled - is an important factor in milling economics. The difference in the prices of flour and offals may be as much as £200 per tonne. Hence, millers would like to be able to assess the likely extraction rates of samples offered. Apart from knowledge of characteristics of individual cultivars, gained through experience or experimental evaluation, there is no reliable means of predicting milling yield. Specific weight measurement is performed routinely as a means of eliminating samples with much shrivelling - a factor which clearly reduces extraction rate - but if shrivelled samples are excluded correlations between specific weight and flour yield are generally acknowledged to be poor. A reliable means of predicting extraction rate would undoubtedly eliminate one of the major deficiencies in wheat trading requirements.

Prediction of milling extraction rate from a knowledge of grain morphological characteristics has been investigated in several studies (e.g. Hook, 1987). Characteristics such as grain length and breadth, crease depth and embryo size have been considered. In some studies endosperm content has been determined and related to milling extraction rate and grain size (Simmons and Meredith, 1979).

It is well known that the presence of shrivelled grains reduces milling yield. In addition to endorsing this, grain measurement and segregation showed that even, well-filled small grains contained less endosperm than large, well-filled grains, which gave better milling yields (Simmons and Meredith, 1979).

Marshall *et al* (1984) used simple geometric models to examine the effects of grain shape and size on milling yields. Their conclusions emphasised the importance of grain size rather than shape as being the most important. In spite of this the same authors (1986) later found that the significant linear relationship between milling yield and grain size found in samples of one cultivar grown at one site, broke down when different cultivars were included, even when they too were grown at the same site. These findings confirmed others which were cited, showing that they represent general experience. The universality of the simple notional relationship between grain size and endosperm content and hence extraction potential is thus not confirmed by experimentation.

Image analysis provides a means of rapidly asessing a range of morphological parameters that can be correlated individually or together, with quality factors measured by other methods.

The process of image analysis occurs in a series of stages as follows:

1. **Image capture** - in which a specimen is presented to a TV which acquires an image that is capable of conversion into electronic signals suitable for digital processing and storage.

2. **Segmentation** -- in which regions of interest within the image are separated one from the other, and from the background. The amount of processing at this stage may be considerable. Its extent depends upon the complexity of the task - that is the number of different regions requiring separation and the quality of the image obtained from the camera.

3. **Measuring** - the image, having been digitised consists of an array of picture points or pixels. Segmentation permits object pixels to be distinguished from non-object pixels. By counting pixels of different types area relationships can be quantified and by noting relationships of pixels (especially those at boundaries) one to another, linear measurements and angular relationships can be defined.

4. **Analysis** - Measurements taken on individual objects can be related one to another and to the total image. They are presented in a

form that can be logged and further analysed in data sets acquired from a group of similar images.

Different image analysis applications require emphasis to be placed at different stages in the process. Even when applied to the same problem different philosophies are adopted by users. Thus, in applying image analysis to cereal species and cultivar discrimination several approaches have been adopted. Symons and Fulcher (1988) examined grain sections so that only a small portion of a grain filled the field of view, Keefe and Draper (1984) relied upon information acquired from side elevations of single whole grains while Sapirstein *et al* (1987) imaged top elevations of several grains at one time. Increasing the number of grains in a visual field speeds up the analysis and facilitates consideration of a statistically acceptable number of grains within each sample. However, it reduces the number of pixels allocated to each grain and this reduces the resolution. The decision on approach is clearly subjective and largely arbitrary for little guidance is available on what constitutes a representative sample for cultivar identification and what degree of resolution is required to provide the necessary discrimination among types.

In the clearly similar context of the present study the choice of imaging procedure is equally subjective. In view of the marked lack of success achieved in previous attempts to relate grain morphology based on manual measurements to extraction rate, the approach we adopted was to acquire as much digitised information on a grain as possible from the camera by examining a maximally magnified image and to retain that information by limiting image processing to a minimum. The latter requirement can only be fulfilled if an image capable of segmentation without processing is obtained, that is to say the areas of interest must be clearly defined in the original image.

The lack of success of manual methods also influenced the decision to maximise the number of parameters recorded by attempting to present internal as well as external structural details for analysis. Some manual measurement studies had in fact measured the crease depth. However, this defined the distance at one point only and, as grain shape varies, the relationship between this single measurement and the depth of endosperm above the crease also can vary.

To increase grain shape definition further both the lateral view of the sagittally bisected grain and the top view were examined. Since each grain could be identified individually measurement from two directions not only doubled the information to be considered, it also provided a means of assessing the reproducibility of the measurements, such as length, common to both elevations.

MATERIALS AND METHODS

Image analysis system

The Seescan I3000 is a relatively low cost system providing facilities for digitising a T.V. image into 256 x 256 pixels. Colours and shades can be resolved into 128 grey shades in a "black and white" image. All programs are written in BASIC and are available for alteration or addition by a competent programmer. Images can be stored on 3.5 inch floppy discs (12 images per disc) or on an inbuilt Winchester disc (320 images).

The system is capable of being operated by users with no programming skills through a mouse-driven menu system. Menus are flexible so that options can be deleted or added by mouse-driven commands. For frequently repeated sequences task lists can be compiled. Once initiated these progress to completion without further operator intervention. Provision for interactive modification of images can be built in to the task list should this be necessary. A signal following the interaction is used to instruct the task list to proceed.

For the two elevations examined different task lists were compiled. In the top-view task-list, only the silhouette of the whole grain was required to be measured and a single threshold was adequate. In the side-view task-list, grain silhouette and endosperm area had to be measured separately. Interaction was provided for, only on silhouette outline in both cases.

Parameters recorded

The diagrams of Figure 1 show the measurements that were made in both grain orientations.

In addition the following relationships were computed and recorded.

Side elevation				Top elevation	
Fullness	hl	:	As	Fullness	hl : A_T
Aspect ratio	h	:	l	Aspect ratio	w : l
Length ratio	l_1	:	l_2	Slope 1 - tan α 1	
Area ratio	A_1	:	A_S	Slope 2 - tan α 2	
Upper slope	h_2	:	$\frac{1}{2}l_2$		
Lower slope	h_3	:	$\frac{1}{2}l_2$		
Embryo slope	h_1	:	l_1		

Preparation of specimens for examination

Presentation of grains in a consistent orientation is vital for valid comparisons to be made. This in itself presents considerable problems as the smallness of grains makes them difficult to handle with fingers with precision and their smoothness and hardness make them difficult to handle with forceps. Further, once in a required position they are easily moved unless secured. Experiments were conducted with adhesive tapes but the points of contact on the ventral or lateral faces of grains are small and with standard adhesives such contacts are inadequate. Application of liquid adhesives gives rise to difficulties in defining outlines if the contact areas are increased by partial submersion. The wish to expose internal structural details imposed additional difficulties as the cutting of grains imposed considerable stress, making an even firmer hold necessary. Also half grains are even less stable when secured only by ventral contact. Although searches were made for suitable strong adhesive tapes, none was found which met the requirements and no other alternatives were found to embedding grains for machining and presentation. Embedding is inevitably time consuming and could not be considered as a method in routine analysis. However, at the stage when worthwhile parameters are being identified, the embedding method has considerable merit. When cast in plastic the grains are held in robust blocks that are easy to handle. The regular shape of blocks makes them easy to register for precision machining and for location on a "stage" for presentation to the camera. Blocks can be retained for further examination if necessary, and a clear embedding medium permits the detection of an uninterrupted outline, facilitating segmentation of the image captured against back-lighting.

The details of the system adopted for aligning grains and casting blocks is as follows:

Casting chambers as shown in Figure 2 are used. The grains are laid, with the embryo end consistently orientated, crease downward so that it registers with the rib on the base of the mould. The grains are retained in alignment and observation from the top reveals any misaligned grains. L.R. soft resin (London Resins Limited) is prepared, by mixing two solutions, and poured gently into the mould. The resin is of low viscosity and its hydrophilic properties permit rapid flow and close adhesion to the grains with a minimum of disturbance. Grains which become disturbed can be easily realigned with forceps. The resin becomes solid within a few minutes but is best left for several hours to harden completely. For removing the cast, lowering the temperature of the mould by placing it in melting ice causes the mould to contract and separate from the cast. The mould is dismantled and the block removed. The use of ice gives considerable advantages over alternative methods used earlier, these include use of grease as a barrier or clear adhesive tape on mating surfaces.

Some air bubbles trapped, particularly at the brush ends of grains corrupted the outline and required interactive definition of the silhouette during processing of the image.

Casts bear a groove on the underside corresponding to the rib on the base of the chamber. Correct alignment can be confirmed by reference to this. Material lying to the narrower side of the groove is removed by use of an engineer's milling machine, which gives a clean finish and can be controlled with precision. Alternative methods, requiring less skill were tried. Conventional band saws and cutting wheels (even diamond wheels) caused burning and smearing of the surface. A diamond-wire saw gave a satisfactory cut but had too small a working area to accommodate a full length cast. A larger model was not as precise and did not meet safety requirements.

Attempts to present transverse cut faces for examination of endosperm cavity details have not yet been successful.

Presentation of grains for imaging

T.V. cameras are best used in a horizontal position, hence the presentation set-up (Figure 3) is designed to permit this. The camera is mounted in a fixed position on a base. Also on the base is a mechanical microscope-stage permitting movement in the direction of the optical axis and from left to right at right angles to it. A perspex block fixed to the mechanical stage allows blocks to be mounted at a suitable height for the camera. The entire cast is first placed on the perspex block with the top of the grains towards the camera, and the grains are identified and measured in sequence. After machining to reveal the central plane-face the blocks are re-examined with the machined face towards the camera. Before each measuring session a standard length is measured to ensure that calibration remains valid.

Lighting

External measurements can be made from the image of a grain in silhouette. Hence, for this purpose, back-lighting is suitable. A 450 x 100mm light box fitted with flourescent tube, is mounted vertically behind the sample stand, on the same base as the camera and stand. For visualisation of the exposed endosperm it is necessary to provide incident lighting. In meeting this requirement several difficulties exist. Uniform lighting is difficult to provide under any circumstances but, in the present set-up, the working distance of the camera lens, adapted to achieve a large image of the grain, imposes additional problems. A solution to the problem has been found in the use of a parabolic reflector mounted in the cowl surrounding the camera lens. Light transmitted through and around the specimen block and the perspex holder, is reflected on to the specimen face. Adjustment of the focal length of the camera permits coincidence of the focal planes of lens and mirror, and the specimen can be examined in that position. Under these conditions the two areas required can be defined.

A Phillips Video 4 (Newvicon) camera is used with a 16mm F1.4 lens. The necessarily short working distance is achieved by use of a 10mm extension ring.

Because endosperm varies in its light transmittance/reflectance properties as a result of variation of mealiness/vitreousness, it has not been possible to achieve sufficiently consistent imaging conditions for providing contrast between endosperm and bran or embryo regions. To provide greater consistency in endosperm characteristics, iodine/potassium iodide solution is applied to the exposed face. All starch granules become stained dark purple, permitting starchy endosperm to be distinguished from surrounding tissues. Before applying the stain it has been found necessary to apply a thin coat of resin (methacrylate is water permeable) to the milled surface. This prevents migration of starch granules from the endosperm to other areas, where their presence would reduce demarcation among tissues.

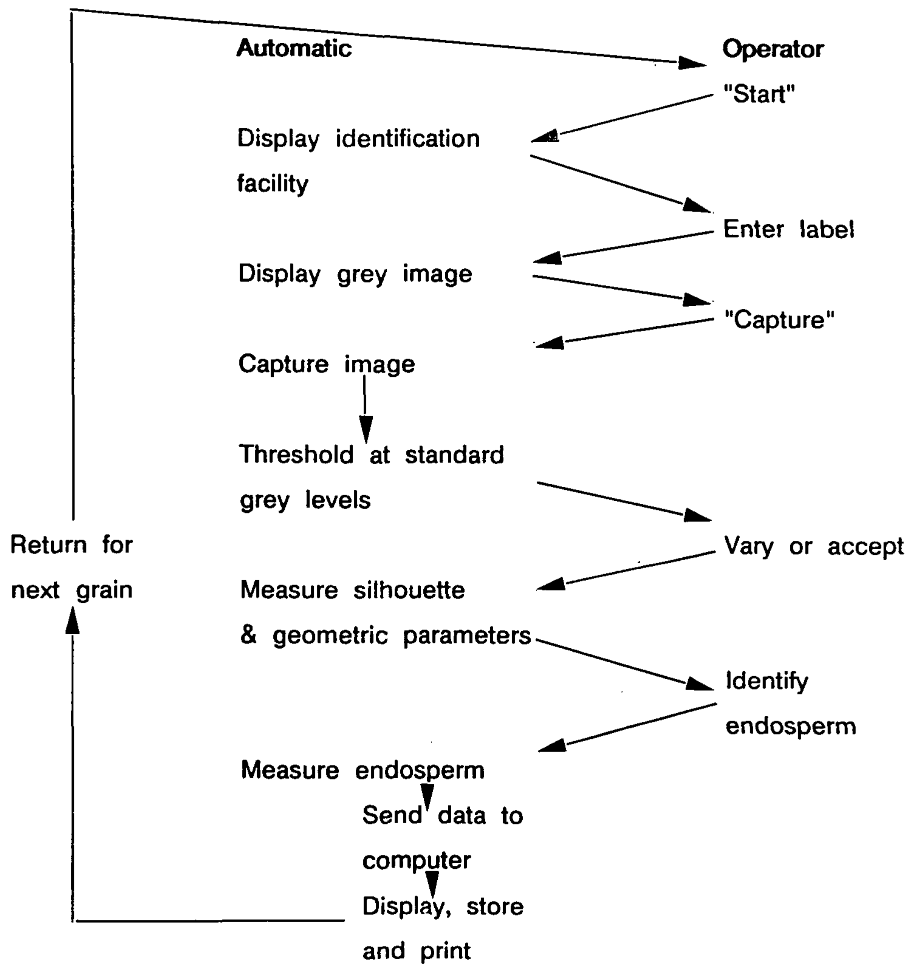
Different lighting conditions have been found to be optimal for the different views of grains. For top elevations a mask placed over the light box with a window 130mm x 50mm high centered on the optical axis, gave the best definition of the silhouette. For side elevations, in which two thresholds were needed an annulus of external diameter 40mm placed on the unmasked light box was favoured. A Wratten 12 optical filter was placed within the camera for both elevations.

The lighting conditions were adopted after much trial and error and the principles governing their effectiveness are not understood in all cases. They did however cope well with variations in bran colour among wheat types.

Image analysing

Task lists were constructed to provide a sequence of operations such as that below.

e.g. Sideview



The automatic aspects of entire sequence for each grain take approximately 15s. Operator activities take perhaps another 30s. It is rarely necessary to alter threshold levels and indeed much of the effort put into imaging was to avoid this. Occasionally grains can be seen to be incorrectly orientated and hence cut in the wrong place. An "abort" facility is written into the task lists to reject such grains.

Wheat samples

Details of the wheat types milled and examined are given in Table 1.

Milling

Millings were performed on a Buhler laboratory mill (MLU 202) fitted with flour covers (160μm aperture) throughout. Wheat samples (2kg) were milled after a lying time of 24h. A feed rate of 100g min^{-1} was employed and flour yields were expressed as a percentage of feed stock. The fine offal fraction was re-treated by one passage through a Buhler laboratory Impact Finisher (MLU 302) so as to bring flour yields more closely in to line with commercial practice. The millroom was maintained at a temperature of $18^{o} \pm 1^{o}C$ and $64 \pm 2\%$ relative humidity throughout.

Examination

Batches of 100 grains were randomly chosen by means of a "Numigral" seed counter (Falling Number Co Ltd). Damaged grains were discarded and replaced with sound grains. All accepted grains were embedded in blocks of 10 as described above.

Top elevations were examined and measured before removal of the unwanted plastic and half-grain by engineers' milling machine. Endosperms were stained with iodine/potassium iodide before presentation for lateral elevation analysis.

Processing of Grain Data

In order to facilitate the analysis of the grain data, the I3000 was connected to an Amstrad PPC640 portable computer, via the serial port. The Amstrad was used as a terminal to the I3000, (replacing its usual terminal), using a program written in C. This program also had the facility to save all incoming data to a disk file. The data thus saved could then be analysed on an IBM AT computer. Since no single software package was available which could perform all the necessary analysis, several packages were used, including Lotus 1-2-3, for basic analysis and data manipulation; GLIM, for more detailed analysis, and SAM (Statistical Analysis for Microcomputers), for stepwise regression. A certain amount of preprocessing of the data was necessary, using custom-written Basic programs.

Milling Results

Details of the millings of the ten wheat types are shown in Table 2.

Extraction rates varied between 69.9% and 78.01%. In all cases the first reduction provided the most flour and in all cases but one the first two reductions produced more than 60% of the total. The exception was Hornet 2. This wheat gave the lowest total flour yield and the first two reduction flours contributed less than 50% of the total. Examination of the milling details led to the conclusion that the sample had behaved exceptionally, possibly as a result of sieves having been blocked, and that this had led to an artificially low recorded flour yield. Insufficient stock remained for a repeat milling.

Grade colour figures (G.C.F.) were recorded for all individual flours and these are shown in Table 3. Values for total flours are weighted means of all the individual flours. The purpose of the measuring G.C.F. was to provide the basis of adjustment to extraction rates so that these might be expressed at constant G.C.F. Two methods of adjustment were envisaged, in the first, theoretical blends were to be made, starting with the whitest flour from each wheat and gradually adding progressively darker flours from the same milling until the target G.C.F. was achieved. In the event individual machine flours from each wheat tended to be relatively similar and quite large differences existed among flours from the different wheat types. As a result it was not possible, with available stocks, to achieve the required G.C.F. harmonisation.

The second method of achieving G.C.F.-adjusted extraction rates was to use an accepted factor for relating extraction rate and G.C.F. An additional 2.5% extraction rate is indicated by a reduction of 1 G.C.F. unit. (Dexter and Martin 1986). Based on this form of adjustment the total extraction rates, expressed at an arbitrary G.C.F. of 5% are mostly increased. Their values appear in Table 3.

Image analysis results

At least 100 grains of each wheat type were embedded in London resin (soft) as described above. All grains were identified and examined by image analysis in both top and side elevation. Where necessary intervention by the operator took place to define part of the outline where the boundary of the silhouette was not clear. A number of grains had to be eliminated owing to poor image resolution, and only those grains for which both views provided adequate images were considered for statistical analysis.

The final numbers accepted for all types are shown in Table 4. Measurements of CWRS appeared to be prone to considerable error and cv Appollo and cv Mercia also fell undesirably below 100 grains each.

Correlations between measured characteristics or derived relationships. and flour yield are given in Table 5.

The anomalous milling results for Hornet 2 were excluded and the relationships shown in Table 6 then applied.

The nature of selected relationships is depicted in a series of figures 4 - 9.

The three best relationships were length ratio (side), length ratio (top), Angle 1 (top) and embryo slope (side).

The length ratio defines the relative distance of the grain's widest point from the embryo tip. The high correlations with extraction rate achieved by this ratio measured both in top and side elevations suggests that it is an important characteristic of grain shape in the present context. Only the better relationship is shown in graphic form (Figure 4). Most points lie close to a notional line, with CWRS as an outlier. The two next-best relationships found were with slope length 1 measured in the top elevations and embryo slope, measured in the side elevation. In the former, (Figure 5) the correlation is very dependent upon the lowest point, while in the latter, most points lie close to a line, with one outlier (Figure 6).

Because the three measurements depicted in Figures 5 and 6 are apparently closely related to the length ratios they do not contribute greatly to the establishment of a step-wise correlation. The greatest contribution here comes from the length itself, which, on its own, is correlated poorly with extraction rate (Figure 7). The best further introduction into the stepwise correlation is the side upper slope (Figure 8). The entire stepwise correlation is shown in Table 7.

For comparison with the relationships established through image analysis measurements, particularly that with length ratios, that between extraction rate and specific weight is also shown (Figure 9). While the correlation coefficient for the latter is relatively high, it is a negative one; the reverse of that normally relied upon on in predicting milling extraction rate. The high coefficient appears to depend mainly on the influence of three points representing two wheat types (Avalon, characterised by a low specific weight, and Yecora with a high specific weight).

Discussion

The unusual relationship between specific weight and flour yield demonstrates the inadequacy of this measurement as a predictive factor when several wheat types are under consideration. It also demonstrates the hazards involved in considering a small number of grain types in a comparison of this nature. Clearly a larger number would be more reliable for giving an indication of the consistency of the relationships involved. The removal of Hornet 2 due to its anomalous milling made a substantial difference to all the correlation coefficients, which demonstrates the distorting influence of a single result when so few results are available.

In spite of all the experimental deficiencies that came to light in the analysis the correlation between length ratios and flour yield are encouraging. A regression based on the 9 samples falls close to all the European wheats in the set, leaving only CWRS as an outlier. While a universal relationship would be highly desirable, one describing European wheats only will be extremely useful and worthwhile. The present results give rise to far more optimism than have previous morphology-based systems of prediction (see introduction for references).

As well as being time consuming the embedding method of grain preparation and presentation proved unsatisfactory in that interactive definition of length was too frequently required because of air bells, particularly in the brush area. This led to an unexpectedly high difference between the lengths measured in the two grain orientations and the consequent rejection of many grains from the analysis. The number rejected was particularly high in the case of CWRS wheat, and this factor may have contributed to its outlying position in Figure 4. The smallness of the grains and their narrow crease gave rise to problems in orientation since the rib on the mould base did not fit the crease in some cases. Since the experiment's completion efforts to locate adhesive tapes that form strong enough bonds have been redoubled and some promising products have been identified. An improved colour filter combination has also been discovered and the adoption of these two improvements should permit elimination of operator interaction altogether, making the system automatic except for specimen presentation and identification.

Consideration of more than one factor to give a step wise regression was expected to be necessary to achieve a satisfactory correlation. In the event only two descriptors were needed for a coefficient above 0.9. Steps beyond two have little meaning when such small numbers of samples are involved but the possibilities for considering several steps in dealing with larger numbers in the future remains.

The small set of samples that we were able to analyse produced results which suggest that the method should be pursued. Greater numbers of samples should be examined taking the same measurements but using improved methods for preparation and presentation. Although it is difficult to justify continued examination of endosperm area/total area relationships on the basis of the correlation attained, it would be premature to exclude this as a possible factor at this stage, even though the preparation of the surface is complicated by this requirement.

The morphological factors which appear to be important in determining extraction rate were unexpected and no explanation can be offered for their manner of influence. Should they prove to be as well related to milling quality as this preliminary survey suggests, not only will they offer a basis of mill intake assessment and early selection screening for breeders but may ultimately lead to a better understanding of the fundamental influences on milling quality.

Acknowledgements

The authors wish to acknowledge the technical assistance they received from Miss Jackie Croft. The milling was performed under the direction of Dr. S.C.W. Hook. Mr. Alan Leer and his workshop staff greatly assisted through construction of preparation and presentataion devices. Mr. Chris Moffett produced the diagrams.

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Figure Captions

Figure 1. Automatically recorded parameters of grains on segmented images. a) Side elevation, b) Top elevation.

Figure 2. Exploded view of mould and cast.

Figure 3. System of presentation of embedded grains to T.V. camera.

Figure 4. Relationship between flour yield (% of weight of feedstock 14% moisture basis) and length ratio measured on the side elevation of grains. The points are identified with the name of the wheat type to which they relate. On other graphs identification is possible by reference to respective positions on the "yield" axis.

Figure 5. Relationship between flour yield and slope length 1 as measured on the top elevation.

Figure 6. Relationship between flour yield and embryo slope as measured on the side elevation.

Figure 7. Relationship between flour yield and grain length.

Figure 8. Relationship between flour yield and upper slope measured on the side elevation.

Figure 9. Relationship between flour yield and specific weight of grain.

Table 1

Wheat types milled and examined by Image Analysis

	Where grown	Texture	Colour	Milling quality
cv Appollo	UK	Soft	Red	Poor
cv Avalon 1	UK	Hard	Red	Good
cv Avalon 2	UK	Hard	Red	Good
*CWRS No.1	Canada	Very hard	Red	Excellent
cv Fortress	UK	Hard	Red	Good
German	Germany	Soft	Red	Poor
cv Hornet 1	UK	Very soft	Red	Poor
cv Hornet 2	UK	Very soft	Red	Poor
cv Mercia	UK	Hard	Red	Good
cv Yecora	Spain	Very Hard	White	Very good

* Canada Western Red Spring Grade No. 1

Table 2

Flour yields in individual Buhler laboratory-mill fractions

	Break			Reduction			Finisher		Total
Wheat type	I	II	III	1	2	3	ex offals	ex bran	
	%	%	%	%	%	%	%	%	%
1. *cv* APPOLLO	3.75	7.64	1.60	32.64	16.09	5.42	4.48	2.14	73.75
2. *cv* AVALON 1	6.16	8.95	1.87	48.53	7.71	1.41	1.41	1.97	78.01
3. *cv* AVALON 2	5.53	9.22	1.81	47.73	8.22	1.66	1.45	1.61	77.23
4. CWRS No.1	5.33	9.38	1.88	43.07	11.80	1.84	1.48	1.36	76.14
5. *cv* FORTRESS	4.50	8.31	1.58	38.83	15.67	3.32	2.76	1.34	76.31
6. GERMAN	4.94	7.54	1.50	41.10	13.55	3.24	3.39	1.79	77.05
7. *cv* HORNET 1	4.39	8.47	1.70	31.73	16.43	5.39	3.99	2.22	74.32
8. *cv* HORNET 2	4.92	8.24	2.13	19.19	15.73	10.11	6.99	2.65	69.96
9. *cv* MERCIA	4.30	7.95	1.46	39.51	13.98	2.82	2.13	1.70	73.85
10. *cv* YECORA	3.54	8.16	1.78	24.80	20.24	9.72	2.96	1.30	72.50

Table 3

Grade colour figures of individual Buhler laboratory-mill and finisher flours

	Break			Reduction			Finisher		Total
Wheat type	I	II	III	1	2	3	ex offals	ex bran	(weighted mean)
	%	%	%	%	%	%	%	%	%
1. *cv* APPOLLO	3.75	2.75	6.4	2.6	2.85	4.85	7.2	14.4	3.6
2. *cv* AVALON 1	3.25	3.05	6.7	1.5	6.0	11.7	18+	18+	3.28
3. *cv* AVALON 2	5.3	4.9	7.75	3.3	7.1	12.95	21	22.1	5.07
4. CWRS No.1	2.25	0.65	4.0	-0.35	1.05	6.5	12.4	16.2	1.0
5. *cv* FORTRESS	5.3	4.0	6.95	2.65	3.3	7.0	14.3	17.35	4.04
6. GERMAN	3.3	2.8	6.8	2.1	3.4	7.1	11.8	14.7	3.5
7. *cv* HORNET 1	4.55	3.2	7.4	2.85	3.3	5.0	9.25	14.7	4.05
8. *cv* HORNET 2	4.85	3.3	7.25	3.55	3.75	3.8	6.25	14.6	4.5
9. *cv* MERCIA	3.7	2.8	5.5	1.65	2.65	6.3	13	14.15	2.95
10. *cv* YECORA	3.6	1.2	3.5	-0.3	-0.1	1.3	8.2	13.3	1.1

Table 4

Nos. of grains accepted for analysis

Wheat type	No. of accepted grains
cv Appollo	45
cv Avalon 1	94
cv Avalon 2	167
CWRS No. 1	22
cv Fortress	87
German	102
cv Hornet 1	95
cv Hornet 2	113
cv Mercia	60
cv Yecora	156

Table 5

Correlations with milling extraction rate and measured or derived characteristics for all 10 samples.

Top elevation		Side elevation	
Length ratio	0.610	Length ratio	0.515
Angle 1	0.568	Area ratio	0.116
Angle 2	0.196	Upper slope	- 0.268
Area	- 0.217	Lower slope	- 0.339
Length	- 0.364	Embro slope	- 0.587
Width	0.034	Area	- 0.484
Fullness	- 0.154	Length	- 0.419
Aspect ratio	- 0.463	Height	- 0.552
		Fullness	0.479
		Aspect ratio	0.051

Table 6

Correlations with milling extraction rate and measured or derived characteristics - 9 samples (Hornet 2 removed).

Top elevation		Side elevation		Other	
Length ratio	0.685*	Length ratio	0.779 *	Specific	
Angle 1	0.551	Area ratio	0.217	weight	-0.737*
Angle 2	0.122	Upper slope	- 0.185	1000	
Area	0.209	Lower slope	0.328	grain wt	-0.089
Length	- 0.026	Embryo slope	- 0.550		
Width	0.387	Area	0.114		
Fullness	- 0.018	Length	- 0.082		
Aspect		Height	- 0.282		
ratio	0.439	Fullness	0.486		
		Aspect ratio	0.142		

* = significant at 5% level

Table 7

Stepwise correlation between extraction rate and morphological descriptions. (Hornet 2 excluded).

Step	Variable	Correlation
1	Length ratio (side)	0.779
2	Length	0.925
3	Upper slope (side)	0.951
4	Fullness (top)	0.994

Fig. 1a: Side elevation

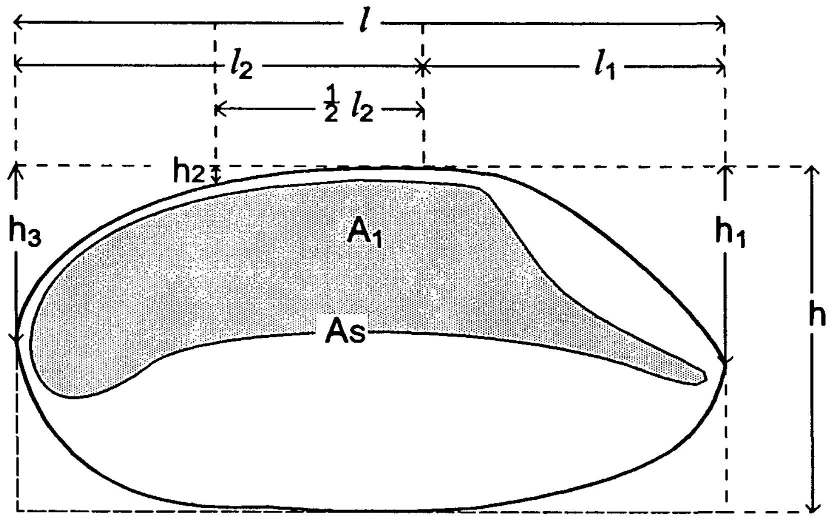
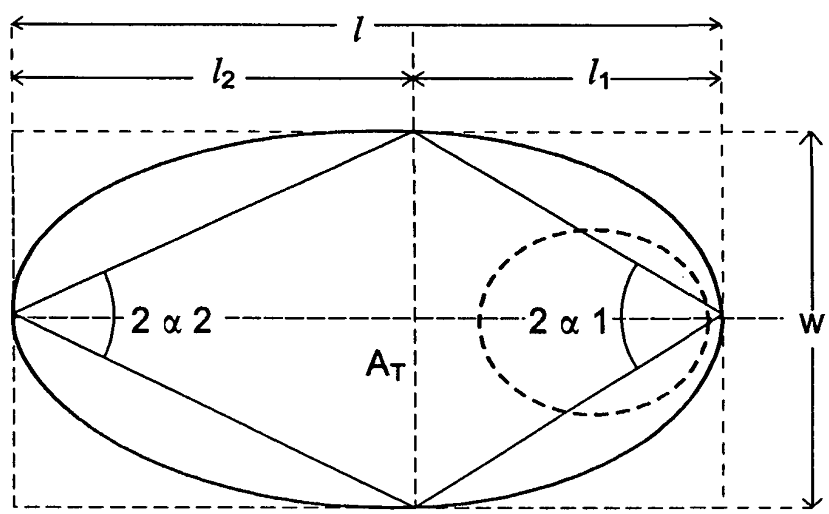


Fig. 1b: Top elevation



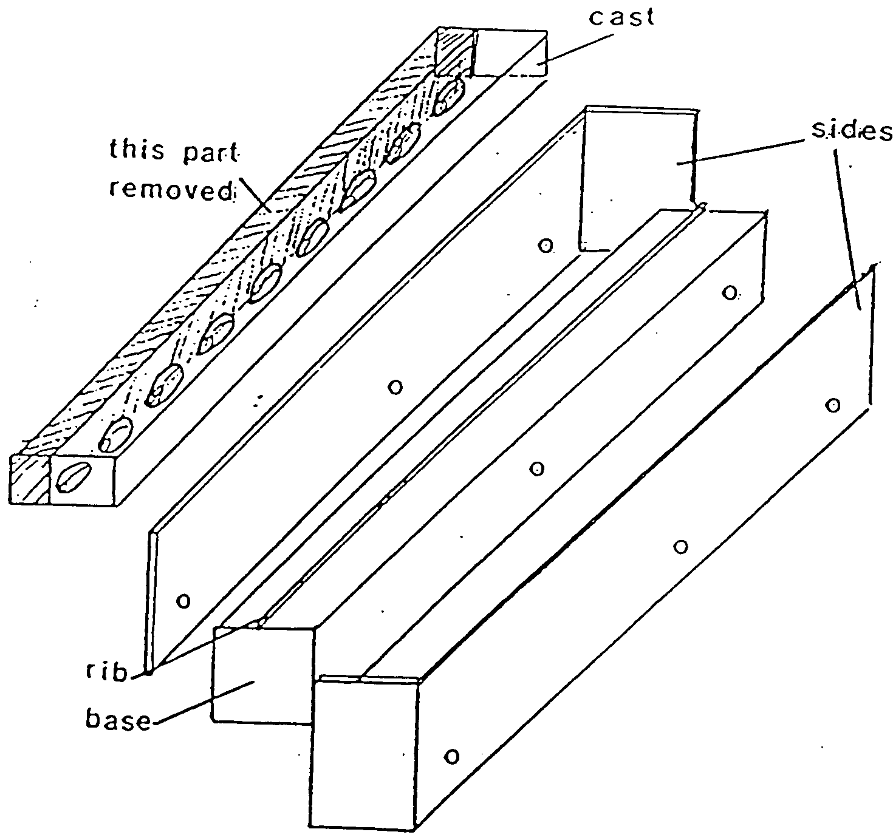

cast
sides
this part
removed
rib
base

Fig 2

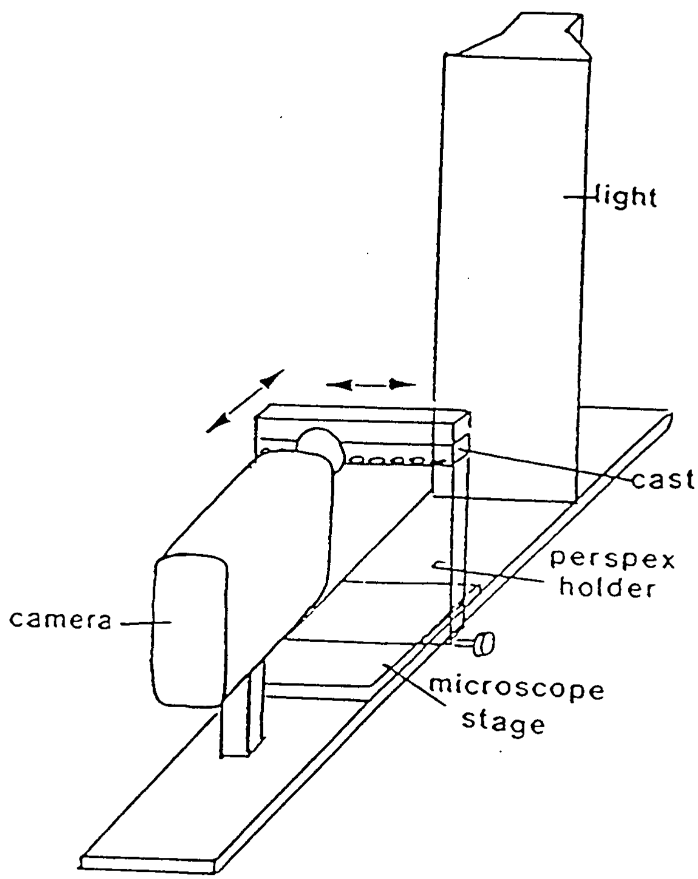

light
cast
perspex
holder
camera
microscope
stage

Fig 3

Fig 4

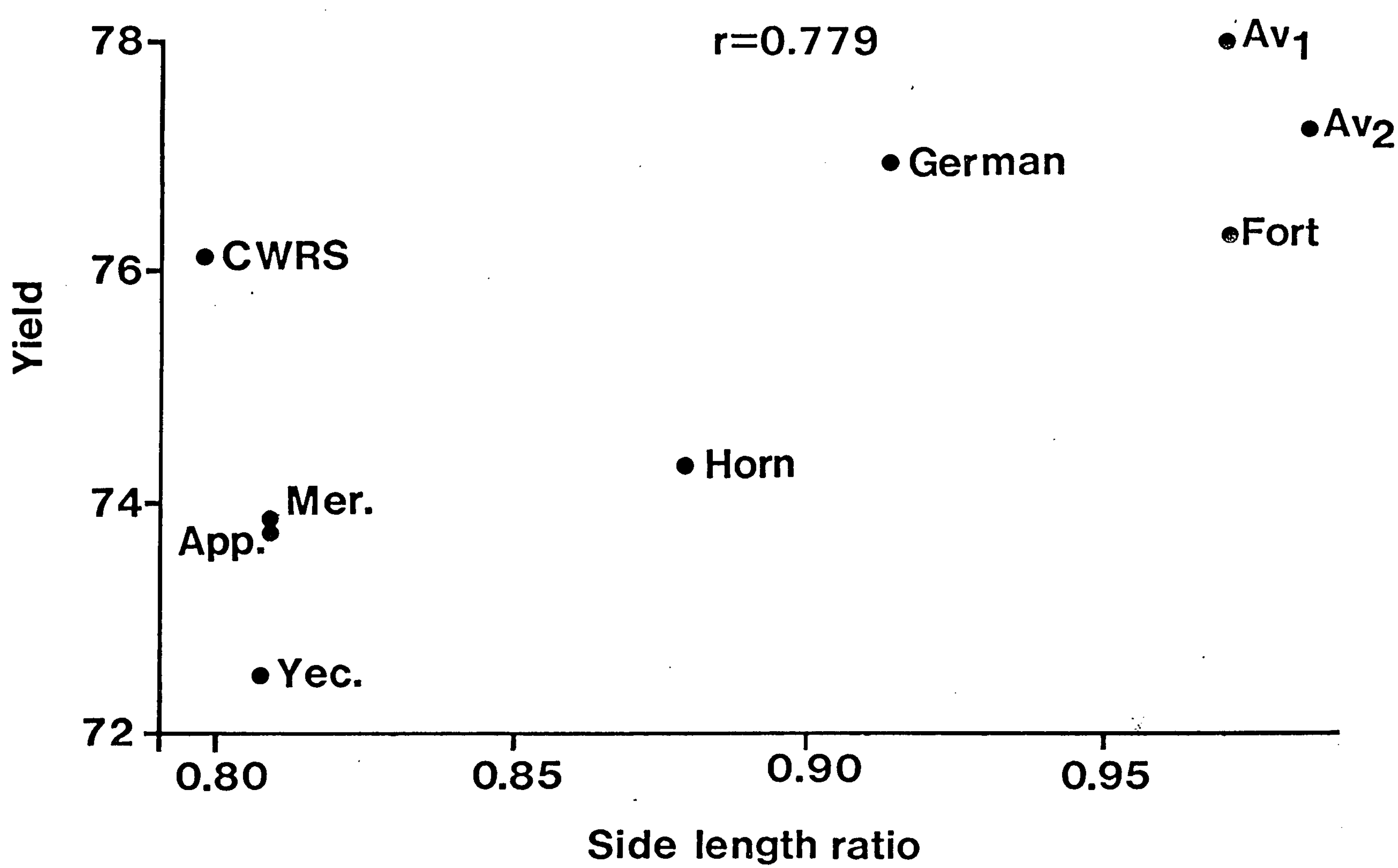

r=0.779
Yield
78
76
74
72
0.80
0.85
0.90
0.95
Side length ratio
CWRS
Mer.
App.
Yec.
Horn
German
Av1
Av2
Fort

Fig 5

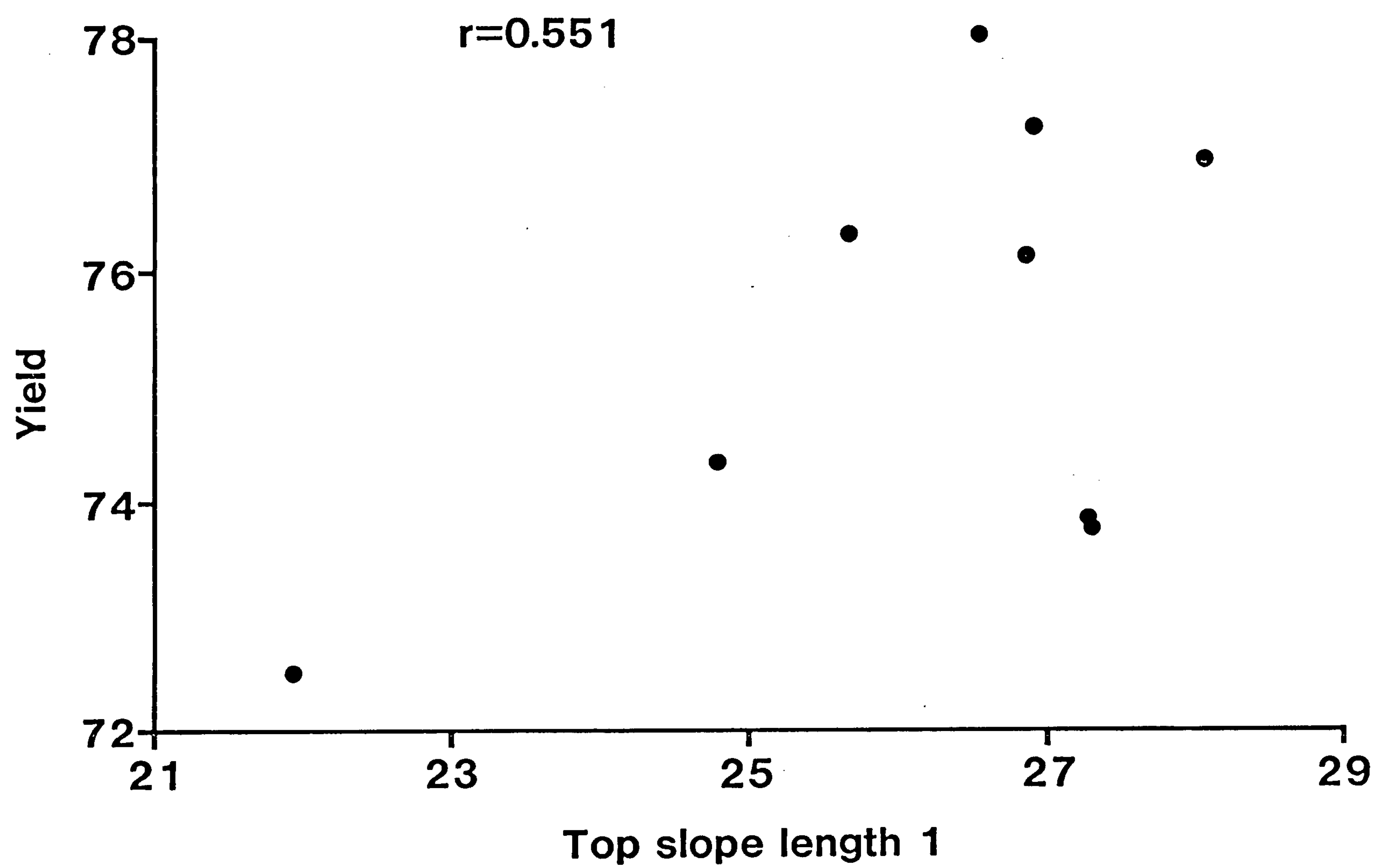


Fig 6

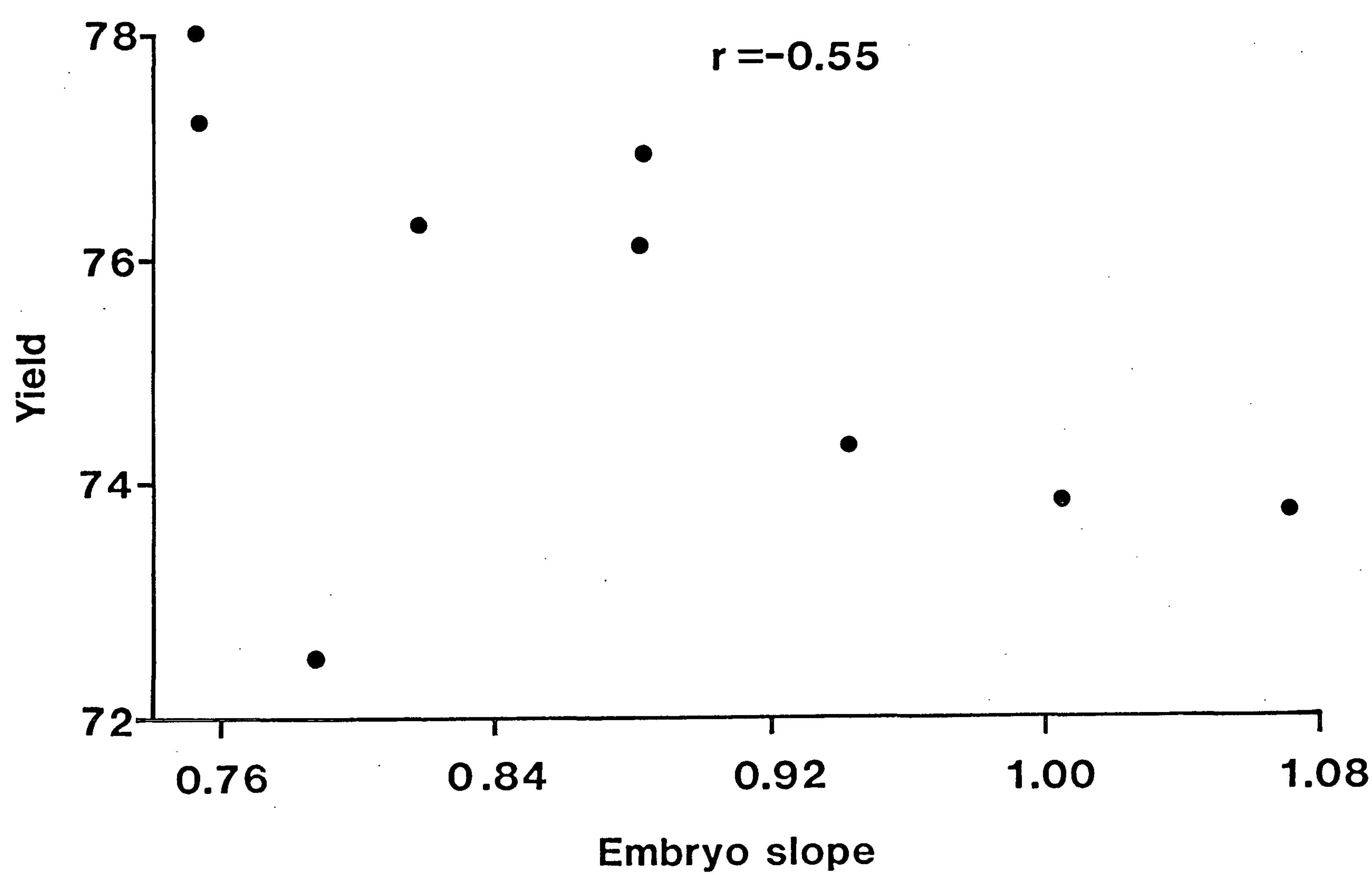


Fig 7

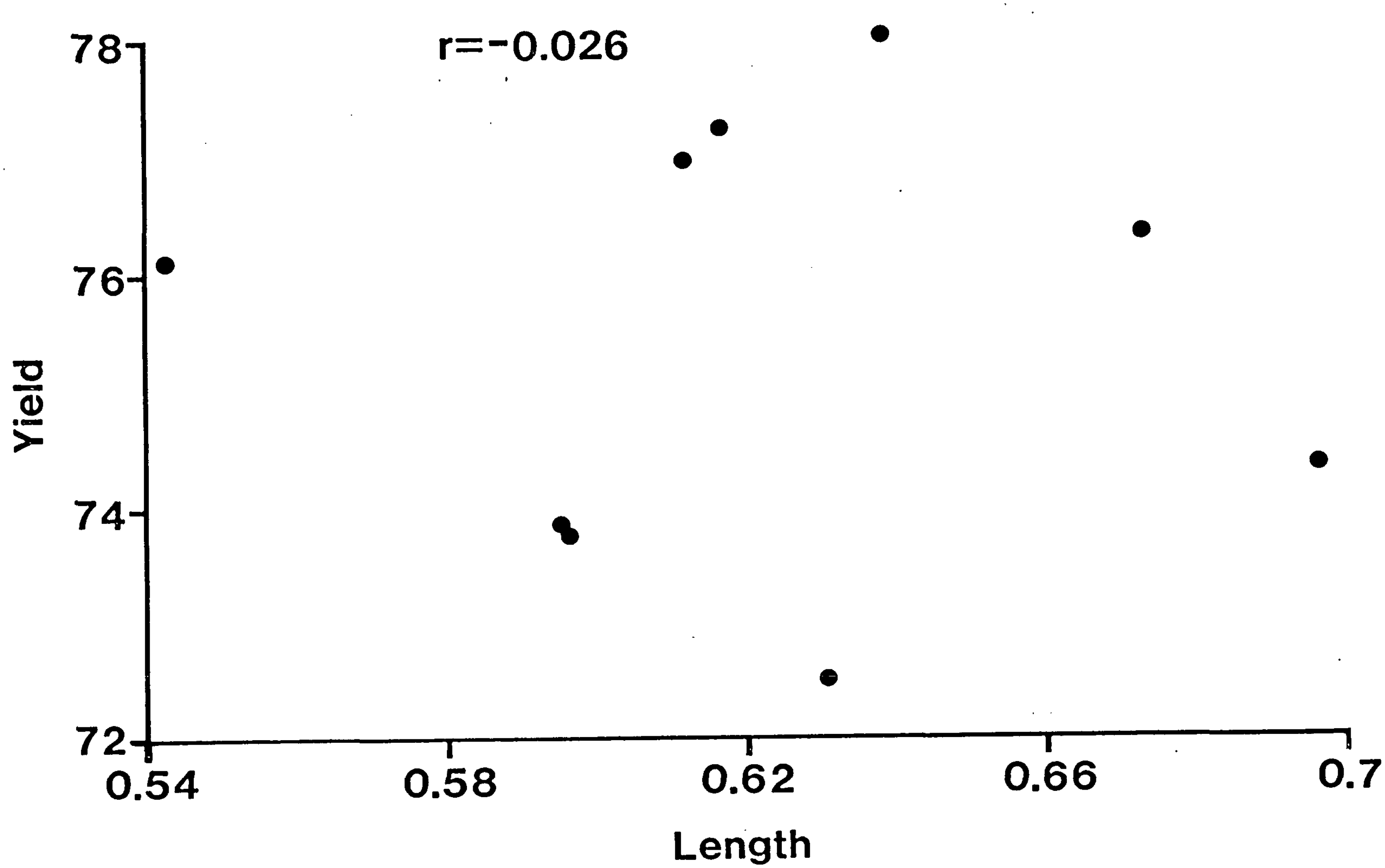


Fig 8

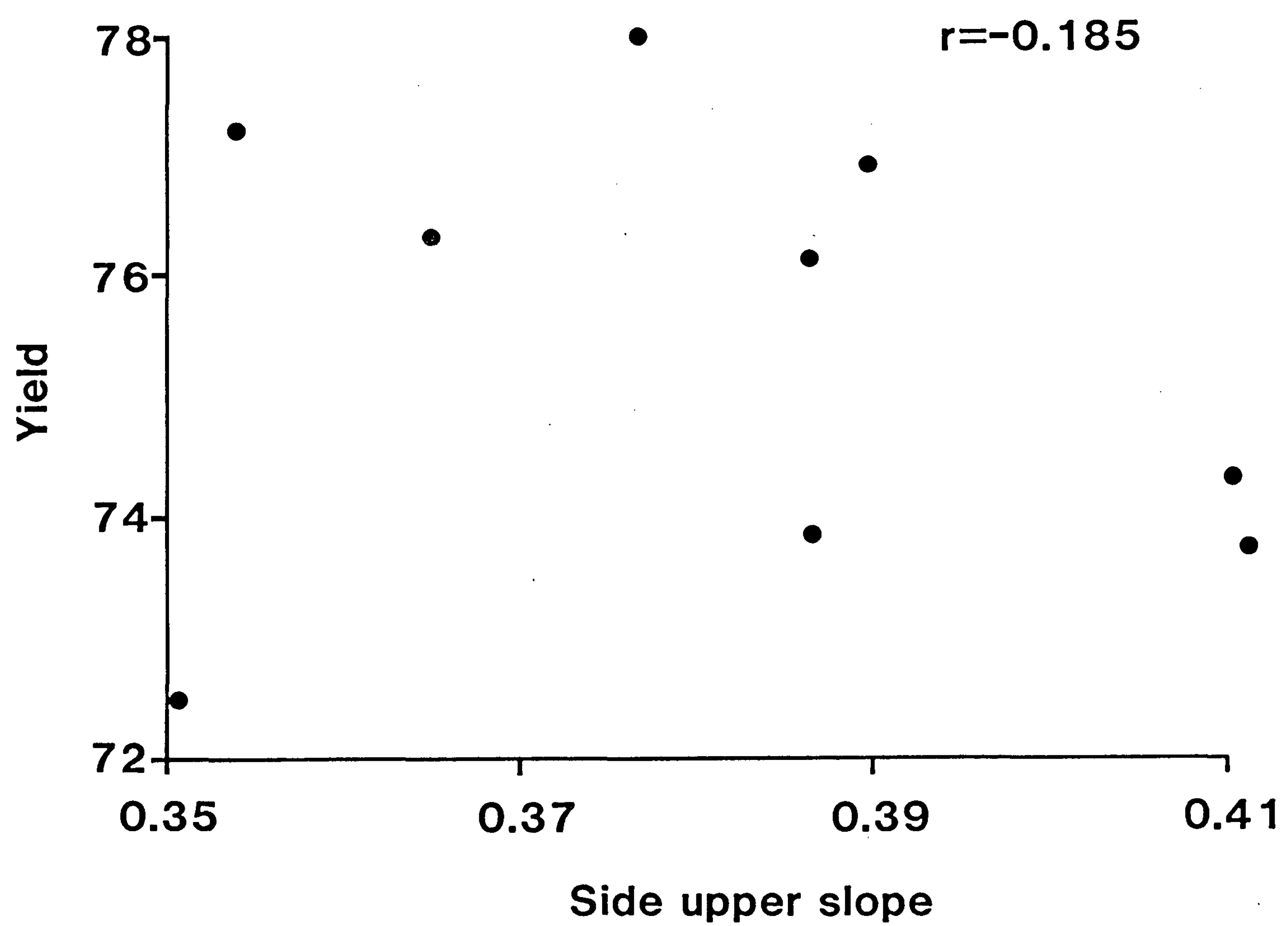


Fig 9