HGCA

PROJECT REPORT No. 32

EXPLOITATION OF THE GENETIC POTENTIAL OF OATS FOR USE IN FEED AND HUMAN NUTRITION

APRIL 1991

PRICE £5.00

HGCA PROJECT REPORT No. 32

Exploitation of the genetic potential of oats for use in feed and human nutrition

by

Dr T. R. BUTLER-STONEY
Dr J. VALENTINE

Final report of a three year project which commenced in May 1987. The work, which is ongoing, was carried out by the Crop Improvement Department of the Welsh Plant Breeding Station under the Direction of Professor D. Wilson. The work was supported by a grant of £76,966 from the Home-Grown Cereals Authority (Project No: 0008/1/86).

CONTENTS

I. ABSTRACT

Raising the levels of protein and oil would increase the value and marketability of oat grain. Genetic sources of high grain protein and oil content have been incorporated into modern cultivated oats. For oil content, winter oat lines were identified with levels of up to 2% dry matter (DM) more oil, equivalent to 0.5 MJ/kg DM higher metabolisable energy (ME), than the NIAB Recommended variety Image, currently the most widely grown winter oat variety. For protein content, spring sown winter and spring oats were identified with levels of up to 3% DM above Rollo and 4% above Dula, currently the most widely grown spring oat variety.

Near infra-red reflectance spectroscopy was used to obtain quick and reliable estimates of protein and oil content. This method could potentially be used to assess other grain composition components from samples used for oil and protein estimation.

Continued work on selection for high oil content should take into account the need to break the observed correlation between plant height and oil content. The high protein content of *Avena maroccana* is now expressed in both spring and winter oats. Recovering winter hardiness will be essential to the successful exploitation of this material in winter oats.

II. INTRODUCTION

Annual production of oats in the UK between 1987/88 and 1990/91 ranged from 510,000 to 600,000 tonnes, of which 165,000 to 235,000 tonnes is accounted for by human and industrial consumption (H-GCA Weekly Digest, 29 October 1990). The latter, together with a proportion of the remainder used by animal feed compounders, is subject to H-GCA levy. As well as fulfilling demand in these markets, oats have potential for a

greater role than at present, as an alternative cereal acting as a break crop to confer yield increases in subsequent crops of wheat (Prew *et al.*, 1986) and barley (Jenkyn *et al.*, 1988). Oats have considerable resource potential as a livestock feed and for industrial fractionation (Webster, 1986; Bennett, 1989; Hutchinson & Cook, 1988, 1989), against a background of agricultural and socio-economic change (Valentine, 1990a). The successful development of naked oats, effectively a new crop, resulted in over 10,000 tonnes of oats being used in specialised markets (including racehorse feed, malting, oat bran extraction) in 1990 (Valentine, 1990b) with a further increase projected for 1991. In the longer-term, scope exists for expansion into new markets and general animal feeds in place of imported raw materials (Doyle & Valentine, 1988).

Valuable characteristics of oats for feeding to livestock include high oil content with a composition high in unsaturated fatty acids, high quality protein and, of less importance, their fibre content and composition. If growers could produce grain of consistently higher nutritive value by the use of different varieties or management, then more oats would be fed to livestock. For instance, husked or naked oats could be used in cattle rations where the cereal inclusion rate is at present only 20%. For pigs, naked oats could replace soya bean protein (Doyle & Valentine, 1988). Increasing oil and protein content is also likely to raise the potential for the use of oats in industrial fractionation. For instance, a valuable emulsifier has been discovered in oats (patent number PCT/GB88/00321). The economics of industrial scale extraction of emulsifier or any other high value fractions would be influenced by the value of the various by-products such as oil, protein or starch fractions. An expansion of the oat area for any new outlet could also benefit millers and other users with specific quality requirements by giving them a wider choice of the crop. There may also be export opportunities, the

present main exporters of oats being Sweden, France and Australia with the USA, Germany and the USSR being net importers of oats.

Unlike wheat and barley, oats contain relatively high levels of oil. The range in the UK is about 3-7% (Hutchinson & Martin, 1955, a and b). Oil contains 2.55 times as much energy as carbohydrate such as starch on a weight for weight basis. Winter oats usually have higher oil content and lower husk content and therefore higher ME than spring oats. It has been calculated that 1% DM rise in oil content would increase the ME value of grain by 0.25 MJ/kg DM in ruminants (ADAS, 1986).

Oat protein has a better balance of essential amino acids then either wheat or barley, and in oats the proportion of lysine in the protein remains more or less constant with increasing protein content, unlike other cereals. Good possibilities exist for improving protein content (Valentine, 1987; Doyle & Valentine, 1988).

MAFF funded work at WPBS on improving the genetic potential of oats has resulted in the introduction of new winter oat varieties with a distinct yield advantage over older varieties and also winter and spring naked oats, with good progress being made in selection for high winter hardiness, dwarfness, resistance to diseases such as BYDV and other environmental stresses. By using cytological techniques, genes for high protein from *Avena maroccana*, a wild tetraploid species with up to 30% protein found in Morocco (a newly discovered species first reported by Murphy *et al.*, 1968) were transferred to *A. sativa*, the cultivated oat (Thomas, Haka & Arangzeb, 1980). Selection for fertility, *A. sativa*, spikelet morphology and good general agronomic performance was then undertaken and a preliminary screen of field performance made in 1986 (Rogers & Thomas, 1987). The latter work was supported by the H-GCA under old funding arrangements.

Despite the success of the *A. maroccana* transfer, budgetary restrictions at WPBS caused funds to be withdrawn in 1986 from work on nutritional quality in oats in the Forage Chemistry Group. This work had been funded by DES rather than MAFF. This left a gap which could not be filled from within existing resources of the Cereal Breeding Group. Selection for chemical composition obviously cannot be based on visual assessment, but requires many samples to be harvested for chemical analysis. The gap was temporarily filled by H-GCA funding of the present work under the new levy arrangements in the Cereal Breeding Group from 1987 to 1990.

The aims of the project were:

1. To develop the use of Near Infra Red Reflectance Spectroscopy (NIRS) for screening a large number of lines.
2. To develop selection strategies, such as the use of micro-plots and to determine the direction of further work.
3. To identify lines combining high protein (from *A. maroccana* derived material) and oil (from Pioneer, an old US cultivar) with high yield and other characters.

III. DEVELOPMENT OF NIRS

Near infra red reflectance spectroscopy (NIRS) has been used throughout the project to give rapid estimates of protein and oil contents of oat grain (see Marten, Shenk and Barton II, 1985 for an overview of NIRS). The instrument used was a Pacific Scientific NIR Scanner, model 4250. Suitable equations for protein and oil content in oats were developed by Mr R F Barnes, AGRI Hurley, using spectral and accurate wet chemistry data.

At the beginning of the H-GCA oat quality project (May 1987), it was clear that the project would generate thousands of data items. A standard system for labelling samples and storing data was developed. An IBM PC attached to the NIRS instrument was used to transfer files to the WPBS VAX computer (Butler-Stoney, 1990). Statistical analysis was undertaken using Genstat V.

Samples were prepared for NIRS as 10g of whole grain milled through a Casella knife mill with a 1mm sieve for 45 seconds. All material passing through the sieve was used as the sample for NIRS, while material not passing through the sieve was discarded. This may have led to some small bias in the results for husked grain, although in an experiment where samples of differing sizes were milled for different times, there were no systematic differences in protein or oil content indicated by NIRS. Each milled sample was placed in the instrument for one minute while spectroscopic data were collected.

IV. UNITS OF SELECTION

While NIRS can provide a rapid estimate of grain composition, the number of samples that can be processed is still very much less than the number of rows and individual rows assessed in the early stages of a conventional pedigree breeding programme where selection is being made for agronomic characteristics. The environmental variation associated with grain quality estimates of small samples make replicated experiments important and useful at an early stage in the breeding cycle. In order to achieve this with small amounts of seed available, 0.75m rows and replicated micro-plots were used as the units of selection in replicated experiments in this programme. In particular, micro-plots or hill plots (Frey, 1965), in place of 0.75 m rows, involved considerably less

land and seed, allowing a large number of replicated experimental plots to be accommodated in a small area.

Micro-plots were established at Gogerddan by sowing 25 seed lots through a plastic drain-pipe into furrows at 30 cm spacing. Because micro-plots were arranged in rows to fit into the standard nursery spacing, row numbers for the micro-plots were made to fit into the sequence of peg numbers used throughout the cereal breeding nurseries each year. Plots within each row were referred to as columns, and were designated by a separate number or by a suffix to the row number. At a column spacing of 30 cm, 12 micro-plots fitted within standard 3.75 m rows. 10 micro-plots per row were available for experimental use with micro-plots at the end of each row used as guard plots.

V. SCREENING OF OIL AND PROTEIN CONTENT IN DIVERSE BREEDING LINES

The spring and winter oat breeding programmes at WPBS contain lines derived from a wide range of material of diverse origin. Some of this material was introduced into the programmes because of grain quality traits, but much was introduced for other reasons. Diverse material was sampled from F3 and F4 generation nurseries.

A range of varieties and exotic lines were grown as controls in the nurseries were also examined. Early generation rows are rarely replicated, and therefore repetition of these control varieties provided the only information on the environmental variation within the nursery field. Statistical analyses of results from the controls gave estimates of the amount of variation between different parts of the nurseries and estimated the accuracy of the observations. (One control variety, Pennal, was omitted from the winter oat data because this variety showed more infection with oat mosaic virus than other

material in nurseries and this led to small stunted plants with high protein levels.) Analyses of variance of results for these control varieties (Appendix 1) showed that individual NIRS estimates had associated standard deviations of about 0.3% DM for oil content and 0.9% DM for protein content. These estimates, being based on rows from over the whole nursery area, included the effects of any environmental variation within the nursery field, and were very similar in two seasons (1987 and 1988) and for both winter and spring oats. Results showed that a major component of this variation was derived from the standard error of the calibration equations, environmental variation within the breeding nursery being no greater than variation in the NIRS analysis.

Information on individual F3 and F4 rows remained dependent on single samples and could only be considered as a guide to the potential of those rows. This was sufficient for a preliminary assessment, allowing a small number of crosses and parents with potential for producing high quality grain to be identified. The results of later sections suggest that it might be more efficient however to concentrate on genetic material containing known sources of high oil and/or protein.

VI. SCREENING OF HIGH PROTEIN CONTENT IN *A. MAROCCANA* DERIVED MATERIAL

(a) Characterisation of lines

In order to investigate the extent of variation in protein content of *A. maroccana* derived spring oat lines and relationships with other characters under replicated field plot conditions, two experiments were set up in 1987. Experiment 1 contained 21 lines (two naked oats) and four controls (one naked oat) chosen from a stratified sample of lines of varying protein content found in a preliminary screen of field performance made in

1986 by Rogers & Thomas (1987). Experiment 2 contained 11 of the lines with the highest protein content and one control variety. In both experiments three different fertilizer treatments were applied. Both experiments were conducted using 0.75 m rows. Most plots contained three rows of the test genotype, of which only the middle one was harvested. For some genotypes in experiment 1 there was not enough seed available from the 1986 harvest to sow 27 rows. In these cases only the centre row of some plots contained the test genotype, the outer two rows being sown with a control variety. All plots of three rows were separated by a single row of Timmo spring wheat.

Each experiment was randomized as a split plot design with three replicates, three fertilizer treatments as whole plots and all the genotypes grown in one plot within each split plot. Fertilizer treatments consisted of 1) standard seedbed fertilizer only; 2) as 1 with an additional application of 30 kg N/Ha as 466 g Nitrochalk per 42 m traverse on 4th June 1987; 3) as 2 with a further application of Nitrochalk at the same rate on 24th June 1987.

Analysis of variance for these experiments are given in Appendix 2. The effects of fertilizer were generally small and the absence of significant fertilizer x genotype interactions indicate the similarity of the responses of different lines to fertilizer application. Mean values averaged over fertilizer levels are presented in Tables 1 and 2.

In experiment 1, the *A. maroccana* derived husked lines averaged 15.4% DM protein (Table 1). The best genotype had 16.9% DM protein. This was 2.8% DM more than Rollo and 4.0% more than Dula, the current most widely grown spring oat variety. Proportionally, this represents 19.9% more protein than Rollo or 31.0% more than Dula. Protein levels were also above those of a high protein selection, 07542Cn, identified in the spring oat breeding programme. On average, high protein lines were 13 cm taller

and 12% lower yielding than Dula and Rollo. The lines also had 0.9% DM more oil than Dula and Rollo, though no conscious selection for high oil content had been practised.

One of the two naked oat lines had a protein content of 18.7% DM, 1.8% DM above the commercially available spring naked oat cultivar Rhiannon. The other line had a protein content and yield similar to Rhiannon in this experiment, but had 9 cm taller straw. The oil content of both lines (mean 6.9% DM) was below that of Rhiannon (8.3% DM), which has a particularly high oil content for a spring naked oat.

Protein levels in experiment 2 were slightly lower than in experiment 1. The maximum protein level was 16.1%, 2.5% DM above Rollo. In this experiment, *A. maroccana* derived lines were 10.2% lower yielding than Rollo but had similar height and oil content overall. There was however a great deal of variation for grain yield, height and oil content.

Protein levels in both experiments were closely correlated with the levels observed in 1986 ($r = 0.73$, ***; 35 d.f.). Correlations between different characters for each experiment are given in Tables 3 and 4. There was an incomplete negative correlation ($r = -0.59$, **; 17 d.f.) between mean protein content and mean yield in experiment 1, and a negative but non-significant correlation ($r = -0.47$; 9 d.f.) in experiment 2. There were no associations between protein content or yield and oil content.

(b) Selection in the next cycle of breeding

Crosses between *A. maroccana* derived high protein lines of spring oats and varieties or advanced breeding lines of winter oats were made in 1987 and F1 plants grown in the glasshouse during the winter. F2 plants were spring sown in 1988 using the

NIAE walking seeder to sow individual seeds at a spacing of 100mm within rows and 150mm between rows. The most well grown individual plants provided sufficient seed for NIRS and for further evaluation, while smaller plants did not provide sufficient seed to make a sample for NIRS. For this material, the NIRS sample size was reduced to 5g from the standard 10g. Spaced plants were not considered suitable for winter sowing because previous experience at WPBS was that spaced plants were very susceptible to winter-kill. Protein contents ranged from 13.6 to 18.3% DM for winter oat parents and from 11.1 and 20.8% DM for the F2 plants. Progeny of plants with high protein content were grown in the glasshouse for another cycle of crossing to winter oats in the summer of 1989.

Crosses between *A. maroccana* derived spring oat lines were made in the summer of 1987 and F1 and F2 generations were grown in glasshouses. The F3 generation was then sown as spaced plants in the field in 1988. Strong plants were selected and their grain analyzed by NIRS. Protein contents ranged form 14.5% to 19.6% DM for the parent lines, and from 13.9 to 20.4% DM for the F3 plants. There seems little prospect of increasing protein content further than this from crosses between these particular lines.

VII. SCREENING FOR HIGH OIL CONTENT

Two lines, Pioneer and 78-34Cn5, were used as potential sources of high oil content in this work. Pioneer is an old North American variety somewhat similar to the British land race Grey Winter. Pioneer is tall (nearly 1.5 m grown in Aberystwyth) with weak straw and narrow grey grain but has high oil content (Welch *et al.*, 1983). The breeding line 78-34Cn5 is a high oil selection from an initial cross between Pioneer and Oyster

made in 1978. This line is a more agronomically acceptable type than Pioneer itself. Random sets of F3 progenies from Pioneer x Image (87 progenies) and 78-34Cn5 x Image (89 progenies) were grown as single rows in 1987 (Butler-Stoney, 1989). Seed from these rows and parent lines as controls were used to sow replicated experiments for harvest in 1988. The experiments were laid out separately for each cross using micro-plots. Parent lines were included multiple times to make up 100 treatment levels.

With the exception of ear emergence of Image x 78-34Cn5 lines, there were highly significant differences between lines for oil and protein content and important agronomic characteristics (Appendix 3). In all instances, variation appeared continuous. Mean values are presented in Table 5. All of the Pioneer x Image lines had oil contents in the range 6.9 to 8.8% DM. Figure 1 shows that values were generally nearer to Pioneer (8.0% DM) than Image (6.6% DM). Seven lines in fact had oil contents significantly greater than Pioneer. Both skewness in the direction of Pioneer and 'transgressive segregation' are encouraging evidence that good progress is likely to be made in selection for high oil content.

In the cross between Image and 78-34Cn5 oil content ranges from 6.5 to 7.9% DM, relative to Image with 6.8% DM and 78-34Cn5 with 7.1% DM. A number of lines exceeded the oil content of 78-34Cn5 (Figure 1), four lines significantly so. While, as expected, oil contents were generally lower than in the previous cross, which involved Pioneer itself, three of the four lines just mentioned had oil contents not significantly different from Pioneer. These results are again encouraging in relation to selection for high oil content.

For both crosses, correlations between characters were generally low (Table 6). As frequently observed, yield and height were positively correlated but the relationship

is more incomplete, probably as a result of breaking adverse linkage between genes, in the cross between Image and 78-34Cn5. Grain yield was not correlated with oil content in either cross, so that independent selection for both attributes should be possible. While selection for protein content would not be a primary objective in these crosses, it can be observed that yield and protein content were negatively related, particularly in the cross between Image and 78-34Cn5. Even in that cross however, the association was incomplete and accounted for only a small amount of total variation; on the one hand this may be thought of as a desirable effect, but on the other it might reflect the sensitivity of small increases in protein content to the overiding effects of environmental variation.

Of most interest, there were positive correlations between oil content and plant height in both crosses: high oil lines tend to be taller. This is shown graphically in Figure 1. Reduce in straw length while retaining high oil content will therefore be an important objective of further work to fully exploit this material.

The correlation between oil content of all the breeding lines in the 1988 experiments and the values observed in unreplicated rows in 1987 was high ($r = 0.84$, 174 d.f.).

VIII. CONCLUSIONS

The following conclusions can be drawn:

1. NIRS appeared to be a satisfactory method for the rapid simultaneous estimation of oil and protein content in oats. It is however relatively expensive technology and requires access to a high and continuous level of expertise to develop calibration equations.

2. Replicated micro-plots appear a very successful method for screening for high protein and oil content and other characters, involving considerably less land and seed than rows or plots.

3. Some progress in breeding for high oil and/or protein may be achieved by screening early generation material of diverse origin. It may be more efficient however to concentrate on genetic material containing known sources of high oil and/or protein such as Pioneer and *A. maroccana* derived lines.

4. The partial transfer of high protein from *A. maroccana* was a useful step towards producing cultivated oats with significantly improved protein levels, and, coincidentally increased oil content. On average, randomly drawn *A. maroccana* spring oat lines were taller, later maturing and lower yielding than currently available spring oat varieties Dula and Rollo. There were negative but incomplete associations between yield and protein content. Further pre-competitive breeding is necessary in order to combine high protein content with other characteristics.

5. A preliminary screen of winter and spring oat F2 spaced plants of the next cycle of breeding, in which it can be expected that more acceptable levels of yield and other agronomic characteristics can be achieved, produced encouraging variation in protein content. The best genotypes have again been used to start another cycle of pre-competitive breeding.

6. As there seems little prospect of increasing protein content for by intercrossing the best lines, further transfer of genes from *A. maroccana* or the use of other genetic sources with different genetic factors is justified. (Intercrossing may however be necessary to retain *existing high levels of protein*.)

7. Encouraging results were obtained in relation to selection for high oil content from Pioneer. Some transgressive segregants (oil levels significantly above the best parent) were identified. There were no adverse correlations with yield or protein content. A positive but incomplete association between oil content and height indicated that an important objective will be to identify recombinants having high oil and reduced straw length.

8. On the basis that an increase of 1% DM oil content gives an increase of about 25 MJ/kg DM in ME, the best high oil lines are likely to have ME increased by about 0.5 MJ/kg DM which would significantly raise the value of oats as livestock feed (Butler-Stoney, 1989).

As well as improving the value of husked oats for feeding to ruminants, improvements in protein and oil content in naked oats would make them even more valuable as feed for monogastric animals as an alternative to expensive imports. In this context, raised oil content will be of great value on account of its high energy content. Apart from the high potential of oats with increased protein (and energy) for livestock use in place of imported vegetable and waste animal protein, increasing protein and oil or other components is also likely to increase the value of the oat crop for industrial fractionation, for which good scope exists in oats (Coombs, 1989).

In addition to selection for high protein and oil content, opportunities exist for the evaluation and modification of other grain quality traits. Apart from gross grain attributes such as kernel content, grain size and hectolitre weight which are important determinants of milling quality, variation doubtless exists for other chemical components of the grain such as beta-glucan (soluble fibre), phytate, lignin and emulsifier. The

development of NIRS equations to handle some or all of these attributes in addition to protein and oil would have the advantage that estimates for all the calibrations would be available with no additional handling of the sample.

IX. ACKNOWLEDGEMENTS

The contributions of Mr R Jones and Dr D I H Jones of the Forage and Soil Chemistry Group, WPBS and Mr R F Barnes, Biomathematics Department, AGRI Hurley, are gratefully acknowledged.

X. REFERENCES

ADAS (1986). Nutrition Chemistry, Feed Evaluation Unit, Stratford upon Avon.

Bennett, R.M. (Ed.) (1989). *The potential for the production and utilisation of oats in the United Kingdom*. H-GCA Research Review No. 14, 238pp.

Butler-Stoney, T.R. (1989). Increasing the oil content of winter oats. In: *Proceedings of the Welsh R & D Conference, Cardiff, March 1989* (abstract), p38.

Butler-Stoney, T.R. (1990). Using the EDIT directive to deal with awkward textual data. *Genstat Newsletter* No. 25, 57-58.

Coombs, J. (1989). *Industrial uses of oats.* In: *The potential for the production and utilisation of oats in the United Kingdom*. (Ed. Bennett R.M.) H-GCA Research Review No. 14, 63-95.

Doyle, C.J. & Valentine, J. (1988). Naked oats: An assessment of the economic potential for livestock feed in the United Kingdom. *Plant Varieties and Seeds* **1**, 99-108.

Frey, K.J. (1965). The utility of hill plots in oat research. *Euphytica* **14**, 196-208.

Hutchinson, W.G. & Cook, M.C.F. (1988). *Research Opportunities for Alternative Uses of Oats and Oat Products*. Occasional Studies in Agricultural and Food Economics. Economics and Statistics Division, Department of Agriculture, Belfast.

Hutchinson, W.G. & Cook, M.C.F. (1989). *The potential for oat production and marketing in Northern Ireland*. Occasional Studies in Agricultural and Food Economics. Economics and Statistics Division, Department of Agriculture, Belfast.

Hutchinson, J.B. & Martin, M.F. (1955a). The chemical composition of oats. I. The free oil and fatty acid content of oats and groats. *Journal of Agricultural Science, Cambridge* **45**, 411-418.

Hutchinson, J.B. & Martin, M.F. (1955b). The chemical composition of oats. II. The nitrogen content of oats and groats. *Journal of Agricultural Science, Cambridge* **45**, 419-427.

Jenkyn, J.F., Carter, N., Kerry, B.R., Gutteridge, R.J., Plumb, R.T. Christian, D.G., Darby, R.J., Harper, S.H.T., Mullen, L.A. & Ross, G.J.S. (1988). Factors limiting yield and quality of winter barley. *Annual Report of Rothamsted Experimental Station for 1987*, 17-19.

Marten, G.C., Shenk, J.S. & Barton II, F.E. (1985). Near Infrared Reflectance Spectroscopy (NIRS): Analysis of Forage Quality. US Department of Agriculture, Agriculture Handbook No. 643, 96pp.

Murphy, H.C., Aga Sadan, K., Zillinsky, F.J., Terrel, E.E. & Smith, R.T. (1968). *Avena magna*: an important new tetraploid species of oats. *Science* **159**, 103-104.

Prew, R.D., Beane, J., Carter, N., Church, B.M., Dewar, A.M., Lacey, J., Penney, A., Plumb, R.T., Thorne, G.N. & Todd, A.D. (1986). Some factors affecting the

growth and yield of winter wheat grown as a third cereal with much or negligible take-all. *Journal of Agricultural Science, Cambridge* **107**, 639-671.

Rogers, W.J. & Thomas, H. (1987). Use of interspecies hybridisation for increasing protein content in oats. *Progress reports on research and development* 1985/1986, H-GCA, London, 17-19.

Thomas, H., Haki, J.M. and Agangzeb, S. (1980). The introgression of characters of the wild oat *Avena magna* (2n=4x=28) into the cultivated oat. *A. sativa* (2n=6x=42). *Euphytica* 29, 635-640.

Valentine, J. (1987). Breeding cereals of high nutritional quality with special reference to oats and naked oats. *Aspects of Applied Biology* **15**, 541-548.

Valentine, J. (1990a). Oats: historical perspective, present and prospects. *Journal of Royal Agricultural Society of England* **151**, 161-176.

Valentine, J. (1990b). Naked oats. Proceedings of AAB Conference, Cereal Quality II. *Aspects of Applied Biology* **25**, 19-28.

Webster, F.H. (Ed.) (1986). *Oats: Chemistry and technology*. St Paul, Minnesota: American Association of Cereal Chemists.

Welch, R.W., Hayward, M.V. & Jones, D.I.H. (1983). The composition of oat husk and its variation due to genetic and other factors. *Journal of Science of Food and Agriculture* **34**, 417-426.

Table 1. Characteristics of Avena maroccana derived lines in Experiment 1.

	Ear emergence (days after 1 June)	Height (cm)	Lodging (1-5)[1]	Maturity (1-5)[2]	Total DM (g/row)	Grain yield (g/row)	Protein (% DM)	Oil (% DM)
Husked lines								
Av1893/2	29.9	123	2.6	1.7	263	47.3	16.2	6.3
Av3260/1/5/1	21.7	118	3.2	2.1	191	40.4	16.0	6.3
Av3260/3/1/1	30.3	123	2.8	2.1	264	45.7	14.7	5.5
Av3266/2/3/1	27.0	131	3.1	2.1	299	43.3	14.3	6.0
Av3281/2/1/1	31.1	129	2.5	2.4	268	37.2	16.6	7.4
Av3290/1/3/1	25.4	130	2.7	2.4	284	41.8	16.2	6.0
Av3290/2/9/1	27.7	130	3.1	1.9	314	45.0	15.3	6.4
Av3290/2/13/1	22.9	137	2.4	2.7	312	33.9	16.9	6.2
Av3290/2/19/1	24.1	132	3.0	2.1	323	45.8	15.0	6.3
Av3290/4/9/1	21.6	131	3.1	1.9	278	39.4	15.1	6.1
Av3291/1/5/1	27.1	125	3.3	1.9	241	44.6	15.1	6.5
Av3291/5/2/1	34.3	129	1.9	3.2	310	43.4	15.2	6.1
Av3291/5/4/1	32.6	132	2.0	2.3	276	43.3	15.1	6.4
Av3292/2/4/1	19.3	121	2.7	2.0	305	42.5	15.8	6.2
Av3294/3/3/1	29.9	132	3.2	1.8	308	41.8	14.6	5.9
Av3294/3/5/1	27.1	136	2.2	2.4	267	41.0	15.6	6.0
Av3322/11/10/1	26.4	115	2.3	1.9	265	47.5	14.8	5.7
Av3303/5/10/1	24.0	116	3.7	1.7	293	36.2	16.0	5.1
Av3688/4	25.6	124	2.5	2.1	280	43.2	14.5	6.0
Mean	26.7	127	2.8	2.1	281	42.3	15.4	6.1
Naked lines								
Av3291/4/4/1	26.9	125	2.7	2.8	269	35.1	15.6	7.4
Av3336/1/2/1	29.3	126	2.4	4.4	229	29.1	18.7	6.5
Mean	28.1	125	2.6	3.6	249	32.1	16.8	6.9
Control varieties								
07542Cn	27.3	113	2.8	1.9	270	46.4	14.7	5.6
Dula	26.6	114	2.7	1.7	232	47.6	12.9	5.1
Rollo	23.9	114	4.1	1.6	244	48.2	14.1	5.3
Rhiannon (naked)	28.0	116	3.0	2.4	221	34.8	15.9	8.3
Mean (excluding 07542Cn)	26.2	115	3.3	1.9	232	43.5	14.3	6.2
Mean of Dula and Rollo	25.2	114	3.4	1.7	238	47.9	13.5	5.2

[1] 1= no lodging; 5 = completely lodged
[2] 1 = early; 5 = late

Table 2. Characteristics of A. maroccana derived lines in Experiment 2.

	Ear emergence (days after 1 June)	Height (cm)	Lodging (1-5)	Maturity (1-5)	Total DM (g/row)	Grain yield (g/row)	Protein (% DM)	Oil (% DM)
Av1893/4	29.7	125	2.4	1.8	267	43.3	16.1	6.2
Av3290/1/6/1	28.4	132	2.1	3.1	327	42.5	14.8	6.1
Av3290/2/15/1	30.1	118	2.4	2.9	284	42.0	15.3	5.7
Av3292/1/6/1	27.4	120	2.2	2.7	316	48.8	14.4	5.6
Av3292/1/10/1	29.4	113	2.6	2.6	250	38.5	15.8	5.3
Av3293/1/1/1	28.1	120	3.6	1.6	227	45.0	12.1	5.9
Av3293/5/16/1	26.8	116	3.1	1.7	253	48.3	14.7	5.2
Av3294/1/6/1	29.9	124	2.6	2.2	293	43.6	14.0	5.5
Av3302/3/9/1	26.0	116	3.4	1.3	194	45.3	13.4	4.9
Av3323/6/6/1	25.9	111	2.4	1.4	160	43.0	14.4	4.5
Av3336/3/4/1	27.4	120	3.7	1.7	215	46.2	13.2	4.8
Mean	28.1	120	2.8	2.0	253	44.2	14.4	5.4
Rollo	24.7	119	3.4	1.3	264	49.2	13.6	5.4

Table 3. Correlations (17 d.f.) between means of husked A. maroccana derived lines in Experiment 1

	Height	Lodging	Maturity	Total DM	Grain yield	Protein %	Oil %
Ear emergence	0.19	0.46*	0.34	0.07	0.32	-0.20	0.19
Height		-0.26	0.47*	0.47*	-0.27	0.05	0.36
Lodging			-0.69**	-0.11	-0.16	-0.10	-0.22
Maturity				0.18	-0.26	0.23	0.28
Total DM					-0.06	-0.12	-0.13
Grain yield						-0.59**	-0.05
Protein %							0.31

Table 4. Correlations (9 d.f.) between means of A. maroccana derived lines in Experiment 2

	Height	Lodging	Maturity	Total DM	Grain yield	Protein %	Oil %
Ear emergence	0.45	-0.46	0.60	0.62	-0.54	0.46	0.68*
Height		-0.32	0.43	0.69	0.04	0.02	0.75**
Lodging			-0.77**	-0.67*	0.35	-0.73*	-0.45
Maturity				0.84**	-0.34	0.47	0.52
Total DM					0.02	0.36	0.74**
Grain yield						0.47	-0.12
Protein %							0.25

Table 5. Characteristics of random Pioneer-derived F_3 progenies

	Ear emergence (days after 1 June)	Height (cm)	Grain yield (g)	Oil (% DM)	Protein (% DM)
Pioneer x Image					
mean (n=85)	3.6	135	32.2	7.8	11.9
range	1.3-7.2	112-152	10.3-54.5	6.9-8.8	10.1-14.5
Pioneer					
mean (n=4)	2.1	142	36.1	8.0	12.1
range	1.8-2.4	140-145	32.9-42.2	7.9-8.1	11.9-12.4
Image					
mean (n=5)	3.5	112	41.2	6.6	11.2
range	3.3-3.9	107-118	35.3-46.1	6.5-6.8	10.6-11.7
78-34Cn5					
mean (n=3)	3.4	121	40.6	7.0	10.8
range	2.9-3.6	113-128	32.2-51.7	6.8-7.2	10.5-11.0
SED	4.74	0.9	8.35	0.19	0.46
Image x 78-34Cn5					
mean (n=89)	2.0	111	31.8	7.1	11.0
range	0.8-3.3	99-129	7.3-53.8	6.8-7.2	9.6-13.9
Image					
mean (n=6)	1.9	100	30.8	6.8	11.0
range	1.6-2.4	94-104	25.4-36.4	6.6-6.9	10.5-11.6
78-34Cn5					
(n=4)	2.0	108	37.3	7.1	10.6
range	1.8-2.2	103-111	30.2-44.5	7.0-7.2	10.2-11.0
Pioneer					
mean (n=1)	0.7	130	38.0	8.1	12.0
range	-	-	-	-	-
SED	0.58	4.05	7.97	0.21	0.59

Table 6. Correlations between means of Pioneer-derived random F_3 progenies

	Height	Grain yield	Protein %	Oil %
a) Pioneer x Image (85 d.f.)				
Ear emergence	-0.10	-0.18	-0.14	-0.15
Height		0.37***	-0.03	0.45***
Grain yield			-0.26*	0.17
Protein %				-0.31**
b) Image x 78-34Cn5 (87 d.f.)				
Ear emergence	-0.05	0.15	-0.11	-0.01
Height		0.21*	-0.41***	0.34***
Grain yield			-0.41***	0.00
Protein %				-0.12

Fig. 1. Relationship between grain oil content and plant height in Pioneer-derived material in 1987
a) Pioneer x Image random F_3 progenies (o), together with Image (+), Pioneer (*) and 78-34Cn5 (x)

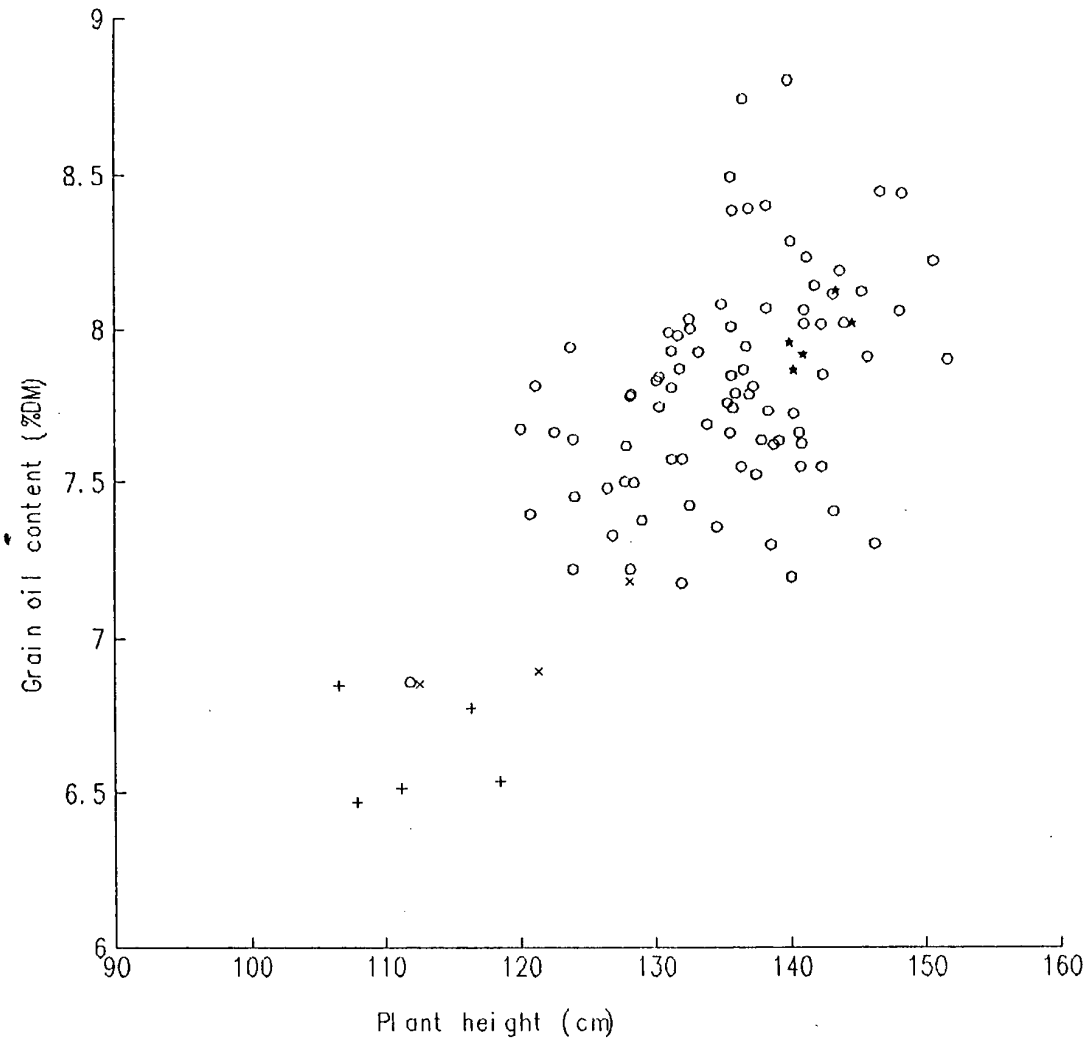
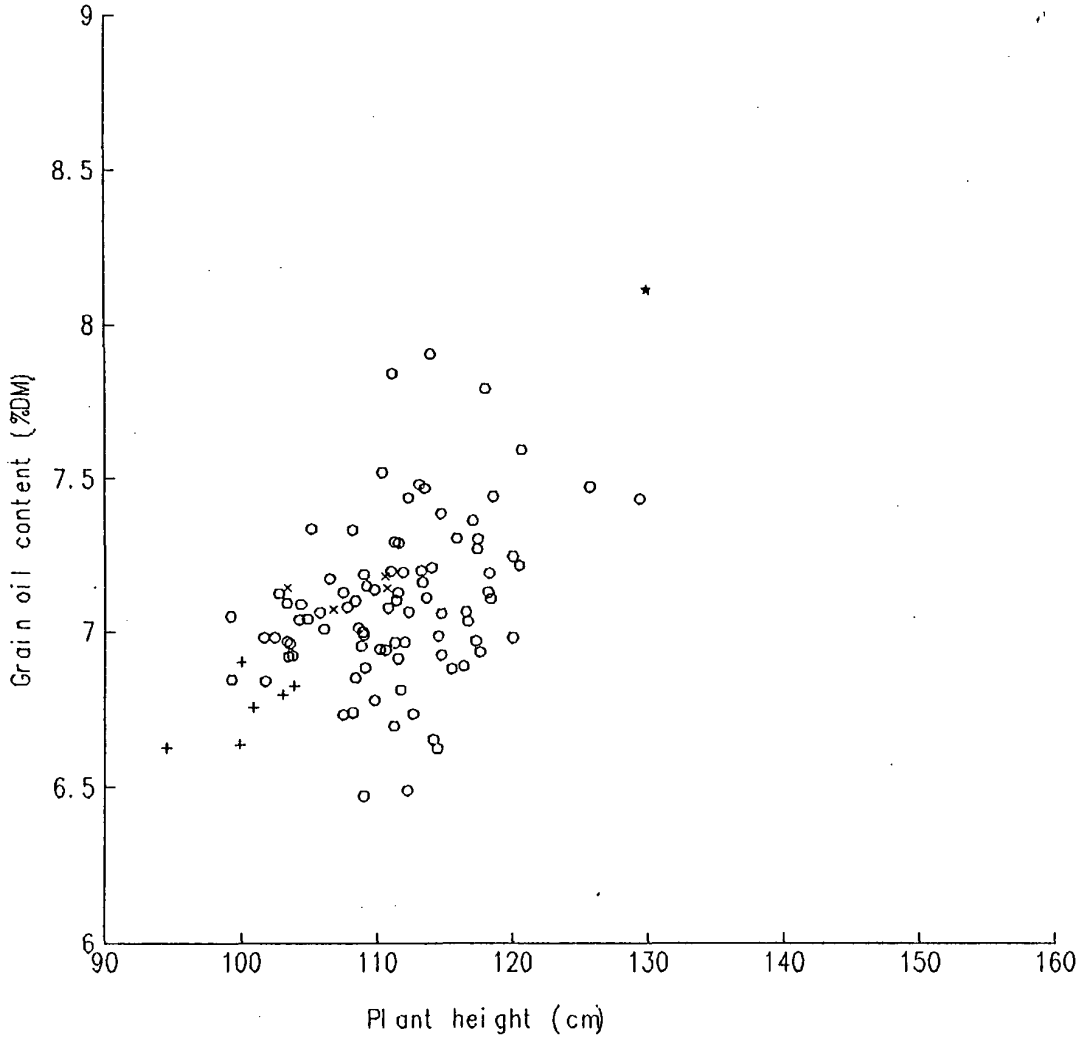


Fig. 1. (cont.)
b) Image x 78-34Cn5 (Pioneer x Oyster) random F_3 progenies (o), together with Image (+), 78-34Cn5 (x) and Pioneer (*)



Appendix 1 Analyses of variance for grain quality components in WPBS breeding nurseries

Source of variation	Winter oats 1987		Spring oats 1987		Winter oats 1988	
	d.f.	M.S.	d.f.	M.S.	d.f.	M.S.
Oil content (% DM)						
Variety	10	3.454***	21	0.770***	7	4.688***
Residual	124	0.096	29	0.085	34	0.090
S.D.		0.31		0.29		0.30
Protein content (% DM)						
Variety	10	24.845***	21	1.108	7	6.762***
Residual	124	0.582	29	0.918	34	0.746
S.D.		0.76		0.96		0.86

***, P<0.001; **, P<0.01; *, <0.05 throughout the tables.

Appendix 2. Analyses of variance for A. maroccana derived lines in

Experiment 1

Source of variation	d.f.	Ear emergence	Height	Lodging	Maturity	Total DM	Grain yield	Protein %	Oil %
Blocks	2	0.01	306.3	0.564	0.591	19150	3707	2.755	0.009
Fertilizer	2	7.45	60.4	31.580**	0.138	6750	3788	17.366**	0.819**
Error 1	4	15.58	77.7	0.818	1.058	4320	983	0.876	0.036
Genotype	24	112.94***	485.8***	2.253***	3.333***	9800***	3402***	11.197***	4.571***
Fert. Genotype	48	1.17	36.7	0.428	0.221	5800	1257	0.846	0.177
Error 2	144	1.76	35.0	0.335	0.185	3380	900	0.757	0.201

Experiment 2

Source of variation	d.f.	Ear emergence	Height	Lodging	Maturity	Total DM	Grain yield	Protein %	Oil %
Blocks	2	0.84	29.15	0.287	0.398	3870	1589	0.885	0.084
Fertilizer	2	3.01	7.15	7.510	2.565	3230	1246	0.689	0.024
Error 1	4	7.34	19.20	4.343	0.968	2010	1118	1.473	0.012
Genotype	11	28.15***	279.10***	2.795***	3.673***	21650***	4988***	11.672***	2.627***
Fert. Genotype	22	1.33	32.08*	0.449	0.262	1560	364	0.131	0.048
Error 2	66	1.02	16.01	0.274	0.303	2310	625	0.283	0.060

Appendix 3. Analyses of variance for Pioneer-derived F_3 progenies grown as micro-plots

Source of variation	d.f.	Ear emergence	Height	Yield	Oil %	Protein %
Pioneer x Image						
Blocks	2	54.45***	556***	154	1.22***	0.45
Genotype	99	3.29***	230***	162**	0.545***	1.77***
Error	198	1.09	48	103	0.09	0.49
Image x 78-34Cn5						
Blocks	2	5.92***	1222***	5061***	0.055***	4.92***
Genotype	99	0.71	112***	193***	0.221***	1.31***
Error	198	0.56	28	96	0.068	0.64