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GENETIC IMPROVEMENT OF OATS WITH SPECIFIC REFERENCE TO WINTER-HARDINESS AND LODGING RESISTANCE OF WINTER OATS AND IMPROVEMENT OF NAKED OATS

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by

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This is the final report of a thirty-nine month project which started in May 1992. In view of the preliminary nature of the information, a two year moratorium on publication was agreed between HGCA and the other sponsors (MAFF and Semundo) of the IGER oat breeding and research programme. In return, IGER included an update section which indicates the subsequent development of genetic material mentioned in the report. The work was funded by a grant of £325,119 from Home-Grown Cereals Authority (Project No. 0040/1/91).

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I SUMMARY

Excellent progress has been made in the genetic improvement of levels of grain yield, resistance to lodging and winter hardiness of winter oats and increasing the yield and naked expression of winter and spring naked oats. Each of these gains is important in improving the economic competitiveness of oats in relation to other cereals and reducing current limitations in production. In each case, the magnitude of improvement exceeds that which could be achieved by improved management practices, highlighting the value of breeding and genetic research in improving the competitiveness of the oat crop.

Lines combining improved winter hardiness and improved yield and agronomic characteristics. These lines have been used to initiate new crosses in order to generate superior lines capable of direct commercial development or to use in a convergent backcrossing programme in which several genetic factors for winter hardiness are brought together in a well adapted genetic background.

Two lines (85-47CnIII/2 and 87-61CnIII/1) with high resistance to lodging have proceeded to National list trials. The latter has good kernel content which is important for the premium milling oat market.

Promising dwarf oats are under development. These could conceivably have the same impact on the oat crop as did dwarf genes in wheat. Further work is being undertaken to obtain early maturity and larger grains in the dwarf types.

Improved naked oat varieties emanating from this project include Krypton and Lexicon (winter oats) and Ripon, Bullion and 11028Cn (spring oats). These represent advances in grain yield and other characteristics, higher oil (particularly Krypton) and higher expression of nakedness compared to existing varieties.

These and further advances are necessary in order to maximise the production and market opportunities for UK growers and processors.

II INTRODUCTION

The objective of this project was to improve the economic competitiveness of oats in relation to other cereals and to reduce current limitations of production. This should be achieved mainly through improvements in winter-hardiness and lodging resistance in winter oats and improvements in naked oats (Anon, 1991). Bearing in mind the significant progress that has been made recently in improving winter and spring oats, reasons for continued breeding effort in oats include diversification *per se*, the specific provision of an alternative cereal as a high yielding break crop meeting new market demands for human, livestock and industrial use and the replacement of imported sources of protein and energy (Valentine, 1990a; Anon, 1991). Of all the technological factors affecting the production of oats, plant breeding is perhaps the most important (Bennett, 1989). It is, after all, the main means by which the potential of a crop can be altered. For the genetic improvement of oats, a minor cereal, pre-competitive research at

IGER-WPBS is funded by MAFF; the work reported here, which is aimed at bringing material to a stage to which it can be developed, is funded by the H-GCA, while the near-market development of varieties is funded by industry in a unique tri-partite partnership. Past experience has shown that the uptake of previous work in terms of bringing promising lines to commercial development is high.

IGER-WPBS has a unique range of oat germplasm at various stages of development. Genetic sources may be in the form of unadapted genotypes from elsewhere in the world or wild species possessing specific characteristics. Breeding methods, utilising enhanced germplasm developed in the MAFF-funded programmes, range from backcrossing (to transfer simply inherited characters) and convergent backcrossing (transfer of many genes) to pedigree selection (selection for a range of characteristics) and accelerated generations procedures (to speed up breeding progress). Where possible, research is carried out to identify the magnitude of the effects of potentially useful genes and to identify any associated deleterious effects using contrasting genotypes. In addition, naked oat programmes rely heavily on the transfer of past and current gains being made for yield, disease and agronomic characteristics in conventional husked oats.

Current work is 5-13 years from the market. The last five years is the time it takes to complete National List and Recommended List trials and produce commercially significant quantities of seed.

III ENHANCED WINTER-HARDINESS

Following similar trends in wheat, barley and oilseed rape, winter oats is the preferred form of oats in southern Britain. The proportion of winter oats in England and Wales has actually risen from 15% in 1968 to 76% in 1989 (Valentine, 1990). There is a greater choice of varieties than ever before, with six varieties from IGER-WPBS (Image, Solva, Craig, Gerald, and two naked oat varieties Kynon and Pendragon) and two varieties from Serasem in France (Aintree and Mirabel) being available at the start of the project. Valentine (1984) listed the advantages of winter oats compared to spring oats as higher yield, earliness, greater tolerance of low soil moisture stress and cereal cyst nematode, the escape of severe mildew infection and higher kernel and oil contents. The main disadvantage of oats which becomes a limiting factor in northern England and Scotland is relatively low winter-hardiness compared to that found in barley, wheat, triticale and rye (in ascending order).

Levels of winter-hardiness of UK lines based on the old land race, Grey Winter, are significantly lower than those available in the winter oat gene pool in the USA (see Coffman *et al*, 1961; Coffman, 1964; Marshall, 1992 and Valentine, 1993). Past attempts to increase the winter-hardiness of UK lines have been unsuccessful for reasons given by Valentine (1993). However, more success has been obtained from the use of lines from Kentucky and Pennsylvannia identified as putative winter hardy sources in the early 1980's (Finkner, 1981; unpublished reports of the Uniform Winter Hardiness Oat Nursery, 1981 and 1982; Valentine and Middleton, 1983; Valentine, Middleton and Jones, 1984; Eagles, Williams and Toler, 1984). At the start of the project, we had completed two cycles of hybridisation and selection based on visual assessment of yield, agronomic characters and winter-hardiness in the field. The first cycle of a cross between Ky77-177 and Bulwark, a particularly winter-susceptible line, had resulted in lines with high levels of winter-hardiness, mean yield 91% of Bulwark and straw length similar to Bulwark (Table 1 reproduced from Valentine, 1993).

Table 1 Performance of a first cycle of selection for high winter-hardiness compared to parents and controls

	Yield (% Pennal)			Plant height (cms)	Winter survival[1] (%)
	1987 (2)	1988 (4)	Mean		
Ky77-177	-	-	-	-	97.0
Bulwark	101	100	100.4	142	0.5
81-87Cn15/1 Ky77-177 x Bulwark	86	93	90.7	139	79.5
81-87CnW/14/1 Ky77-177 x Bulwark	82	78	79.6	140	80.2
Solva (control)	112	108	109.3	132	7.7
Igri (winter barley)	-	-	-	-	100.0
Maris Otter (winter barley)	-	-	-	-	83.2

1 = survival in Pennsylvannia 1988-89
( ) = no. of trials

Table 2 Performance of a second cycle of selection for high winter-hardiness compared to parents and controls

	Yield (% Solva, Image, Craig)			Plant height (cms)	Survival of artificial freezing	
	1990 (2)	1991 (4)	Mean		-9°C	-11°C
KY77-177	-	-	-	-	90	65
Bulwark	-	-+	-		0	0
Solva	104	110	108.2	100	85	0
85-61Cn3/2	103	93	96.3	103	75	40
87-119CnII/1	-	-	-		90	55
87-119CnIII/1	-	-	-		75	45

( ) = no. of sites
85-61Cn = Solva x 81-87CnW/2
87-119Cn = Solva x 81-87Cn15
+ Bulwark in 2 locations yielded 92% of controls

Some of the best lines, particularly 81-87Cn15, 81-87CnW/14/1 and 81-87CnW/1, were used as parents from 1985 onwards to initiate a second cycle of hybridisation and selection. Evaluation of lines in 1990 and 1991 indicated good recovery of resistance to freezing and some progress in achieving high yields (Table 2 from Valentine, 1993).

The best lines were used to initiate a third cycle of hybridisation and selection. Sixteen crosses (92-59 to 92-74), involving a total of 286 hybrid grains, were made in 1992. The products of this cycle contained 6-12% of genes from the unadapted parents. The F1 generation of this material was in the glasshouse in 1993 and the best F2 plants selected in the field in 1994. Intercrossing of F1's was also be carried out in 1993 in order to concentrate factors conferring high winter-hardiness in high yielding backgrounds.

1992-93

Fourteen advanced cycle 2 lines derived from another promising source of very high winter-hardiness, Pennwin, obtained from Pennsylvannia State University were evaluated. Pennwin is a difficult source of winter-hardiness to utilise, although some derived lines have much better agronomic characteristics than those obtained from Ky77-177 (Valentine, Jones and Middleton, 1988). Thirty-nine cycle 2 lines based on other promising genetic sources were at an earlier stage of development (F4).

Lines were assessed in Pennsylvania, in southern Sweden and using artificial freezing tests. In Pennsylvania there was little winter injury because of protection from snow cover during the colder periods of the winter. Winter-kill was patchy and partly caused by snow mould (*Fusarium nivale*). Rows were scored on a 1-9 scale where 9 represented no dead plants and little if any leaf injury. Three replicates of each variety were sown.

In the Swedish test, two replicates were despatched but only one sown due to lack of space. Severe frosts (down to -10°C together with wind chilling) were experienced in late November and early December, with little snow cover. Only occasional and short frosty periods were experienced in January and February. A good range of winter-kill values (though patchy) was obtained. Rows were scored as above.

In the artificial freezing test, a glycol freezing tank was used in which the temperature was progressively lowered and samples removed at regular temperature intervals. The temperature at which 50% kill occurred (LD_{50}) is then calculated for each variety/line using probit analysis. The apparatus used is essentially that described by Jenkins and Roffey (1974) and Fuller and Eagles (1978). Paper pots were filled with a 50:50 mixture of JI No. 3 and peat compost, grown in a controlled environment at 15°C and 8 h photoperiod and transferred to 2°C at the same photoperiod to harden for 7 days. A freezing test was conducted in which the temperature is lowered over a 10.5 h period from 2°C to -12°C at a rate of cooling of 1.33°C/h. Samples of 20 plants per variety were taken out at -9°C, -10°C, -11°C and -12°C, transferred to a glasshouse (12°C/8 h supplementary light) and the number of live and dead plants recorded after 14 days recovery. The tests were carried out in four runs (in which there was 5 plants of each variety randomised in each temperature group) from 16-19 March 1993.

The lines consisted of (a) controls- Solva, Image, Craig, Bulwark and Mirabel; (b) primary genetic sources - Ky77-177, Ky78-443 and Pennwin; (c) the best of the lines from the 1st cycle of hybridisation and selection (see Valentine, 1993a); (d) 14 cycle 2 advanced lines derived from Pennwin; (e) 17 cycle 2 lines based on Ky78-443 and OK78602 and (f) 22 cycle 1 lines based on (g) new genetic sources from Pennsylvania (Pa 7617-3460, Pa 8014-840, Pa 8019-1 and Pa 8115-40). All lines were not present in each test.

Although results were not always clear-cut, Ky77-177, Pennwin, 81-62CnW/2 and 81-87CnW/14 were confirmed as having high winter-hardiness and cold tolerance. LD_{50} values in the freezing test were -12.2, -12.8, -14.1 and -11.1 respectively compared to -11.2 for Solva and -10.0 for Bulwark. Corresponding survival values at -11°C, where discrimination was highest, were 80%, 100%, 80% and 55% respectively compared to 65% for Solva and 30% for Bulwark.

The characteristics of two of the best cycle 2 advanced lines under test are shown in Table 3.

Table 3 Performance of the best lines from a second cycle of selection for high winter-hardiness based on Pennwin

	Yield (% Solva, Image, Craig) 1992 (1)	1993 (4)	Mean	Kernel %	Plant height (cms)	Survival Pennsylvania (9 = excellent)	Sweden	-9°C (%)	-11°C
Pennwin	-	-	-	-	-	9.0	5	100	100
Bulwark	-	-	-	-	-	5.3	3	80	30
Solva	115	101	102.8	74.6	146	7.7	4	90	65
87-142CnII/1	120	91	99.0	76.7	151	9.0	6	80	15
87-132CnII/1	-	94	-	-	157	8.0	7	95	80

( ) no. of sites
87-142Cn 85-64CnI/6/19 x Solva
87-132Cn 85-64CnI/4/7 x Solva
85-64Cn Solva x 81-62CnW/2
81-62Cn Bulwark x (07198CnI/3 x Pennwin)
The prefix (eg 87-) indicates the year in which the cross was made

From the parentage of these lines, 87-142CnII/1 and 87-132CnII/1 contain an average 6% of genes from the unadapted genetic source (including genes for winter-hardiness) and the balance being genes from Solva (75%), Bulwark (12%) and 07198CnI/3, a progenitor of Lustre, (6%). Good progress is therefore being made in retaining genes conferring high winter-hardiness while retrieving the yield and agronomic characteristics of the adapted variety.

The agronomic characteristics of the two lines based on the genetic source Pennwin appears better than the two lines from the second cycle of selection based on Ky77-177 (Table 2), undoubtedly reflecting the higher content of adapted genes in the Pennwin-derived lines (94%) compared to the Ky77-177 lines (75%).

The two lines were used to initiate ten new crosses, three of which have been accelerated using artificial lights and heating. F2 and F3 material will undergo initial selection in the field in 1995. Intercrossing of F1's will also be carried out in 1994 in order to concentrate factors conferring high winter-hardiness in high yielding backgrounds.

The crosses made in 1992 and 1993 can be viewed (a) independently, with the opportunity existing for the identification of superior lines, capable of commercial development, arising from each cross or (b) as part of a convergent backcrossing scheme (McKey, 1986) in which polygenic factors are inserted into a well-adapted genetic background by backcrossing followed by intercrossing of the resulting lines to bring as many polygenes as possible (genes of small effect) together in a well-adapted genetic background.

In general, the new cycle 2 lines had lower winter-hardiness than the advanced lines. None were selected for crossing in 1994, although lines of 89-128Cn were carried forward for agronomic assessment.

A number of the cycle 1 lines based on the new genetic sources from Pennsylvania were carried forward for further assessment. The two best lines were 89-152Cn2 and 89-153Cn1. The artificial freezing test showed the four genetic sources to have very high winter-hardiness at least equal to that of Pennwin. The generally disappointing levels of winter-hardiness retrieved after hybridisation and selection probably reflect the absence of severe winter conditions during the development of these lines and that the original lines were particularly poorly adapted and three-way crosses had to be used to increase the proportion of adapted genes at the expense of high winter-hardiness levels.

1993-94

Lines were sent to Pennsylvania and southern Sweden for testing in 1994. In Sweden, establishment was poor and no meaningful figure could be derived. In Pennsylvania, there was a relatively mild autumn with good amounts of moisture and well-tillered plants established. The first significant cold period was during late December when there was a light snow cover with a low of -19°C on the night of 28 December 1993. About 45 cm of snow fell on 4 January with plants being well protected from low temperatures during the remainder of the winter with many alternate layers of snow (total over 3 m for the winter) and sleet or freezing rain. The winter injury was associated with snow mould (*Fusarium nivale*) (Marshall, pers. comm.).

The lines consisted of (a) controls - Solva, Image, Bulwark, Gerald; (b) primary genetic sources - Ky77-177, Ky78-443 and Pennwin; (c) the best of lines from the 1st cycle of hybridisation and selection (see Valentine 1993); (d) five cycle 2 advanced lines derived from Pennwin which had also been tested in 1992-93; (e) two cycle 1 lines derived from Pa8014-840, a more recently used genetic source from Pennsylvania also tested in 1992 and 1993; (f) eleven new cycle 2 lines derived from Ky77-177, Ky78-443 and OK 78602 (from Oklahoma). There were two replicates. Results are shown in Table 4.

Table 4 Results of winter-hardiness tests in 1993-94

	Selection	Pennsylvania % survival
(a)	Controls	
	Solva	57.5
	Image	37.5
	Bulwark	1.0
	Gerald	20.0
(b)	Primary genetic sources	
	Ky 77-177	97.5
	Ky 78-443	80.0
	Pennwin	87.5
(c)	Cycle 1 lines derived from above genetic sources	
	81-62CnW/2	87.5
	81-87Cn15/1	82.5
	81-87CnW/14	85.0
	83-48Cn2/1	70.0
(d)	Cycle 2 lines (advanced lines tested in 1992-93)	
	86-74CnV/1/1	70.0
	87-130CnIV/1	92.5
	87-130CnV/1	91.5
	87-132CnII/1	84.0
	87-132CnV/3	67.5
(e)	Cycle 1 lines derived from Pa8014-840, also tested in 1992-93	
	89-152Cn	12.5
	89-153Cn1	0
(f)	New cycle 2 lines derived from Ky 77-177, Ky 78-443 and OK 78602	
	88-86Cn1	1.0
	88-86Cn2	10.0
	88-86Cn3	3.5
	F4 90-124Cn3	0
	F4 90-124Cn5	2.5
	F4 90-133Cn1	1.0
	F4 90-143Cn1	0
	F4 90-143Cn2	0
	F4 90-143Cn3	1.0
	F4 90-143Cn4	0
	F4 90-143Cn5	0

The marked advantage of the genetic sources (b) and the best 1st cycle 2 advanced lines (c) over presently available winter oats (a) was confirmed. The high winter-hardiness of the five cycle 2 advanced lines (d) which had been tested in 1992-93 was also confirmed and of these, 87-142CnII/1 and 87-130CnV/1 were used in a further nine crosses with oats adapted in other respects to UK conditions. F2 and F3 material from these crosses will undergo initial selection in the field and, by way of a new approach, under artificial freezing conditions in order to select the hardest plants at an earlier stage in the breeding progress.

The winter-hardiness levels found in the two cycle 1 lines derived from Pa8014-840 were low and no new cycle 2 lines with high winter-hardiness were identified among previously interested lines. Since the 1992-93 results confirmed these lines, in particular Pa8014-840 and Pa8115-40, to have superior cold tolerance to the genetic sources already used (the Ky lines and Pennwin), it was concluded that a proportion of the future enhancement of winter-hardiness should also be devoted to using individual plant selection under artificial conditions to exert a strong selection pressure towards high winter-hardiness.

1994-95

Lines were sent to Pennsylvania and southern Sweden as in previous years. No meaningful results were obtained from Sweden. In Pennsylvania, the winter was unusually mild, but there were a few days when the temperature dropped to -15 to -20°C with little or no snow cover, with wind chill temperatures lower than that during several periods. Survival was generally sparse (Marshall, pers. comm), but there were a number of lines with high survival.

The lines consisted of (a) controls - Solva, Image, Bulwark, Gerald (b) primary genetic sources - Ky 77-177, Ky 78-443, Pennwin, Pa8014-840 and Pa8115-40 (c)advanced cycle 1 and cycle 2 lines (d) 33 new F4 cycle 2 lines (e) 41 new F3 cycle 2 and cycle 3 lines.

The characteristics of the best lines are shown in Table 5, and in full in Appendix Table 3.

The marked advantage of the genetic sources and the best 1st cycle advanced lines over existing UK lines was confirmed. A number of further cycle 1 and cycle 3 lines with increased winter-hardiness over existing UK lines were also found. The winter-hardiness levels of the original genetic sources have not been fully retrieved, but as outline earlier, the intention is to inter-cross lines in future work in order to combine different genes for winter-hardiness in a good adapted background. 91-254Cn3 and Cn6 have been entered in the 1996 USA Uniform Winter-Hardiness Nursery together with 76-17Cn27/2, a progenitor of Solva for comparison with US lines and the original recurrent parent.

Table 5 Performance of the best lines and controls for winter-hardiness in Pennsylvannia in 1994-95.

Controls	% Survival
Solva	0.7
Bulwark	0
Genetic sources	
Ky 77-177	73.3
Ky 78-443	55.0
Pennwin	52.3
Cycle 1 lines	
81-87CnW/14	35.0
83-48Cn2/1	33.3
87-132CnII/1	21.7
89-116Cn2/1	15.7
Cycle 3 lines	
91-25Cn3	25.0
91-25Cn6	29.0
91-258Cn1	15.0
91-261Cn4	21.7
New genetic source	
Pa 8014-840	75.0

IV IMPROVED LODGING RESISTANCE IN WINTER OATS

Plant height is a major, though not sole, component of increased resistance to lodging in oats and other cereals. Current genetic advance centres on the accumulation of small genetic differences in plant height and transgressive segregation (the appearance of lines with shorter straw than either parent on the one hand and the incorporation of major dwarf genes on the other).

Accumulation of small genetic differences in plant height

1992-93

The most recent example of the success of the former approach is the winter oat Gerald, first added to the UK Recommended List for 1993 (Anon, 1993). It is the shortest variety on the Recommended List, being about 10 cm shorter than

Image, which at the time of Gerald's introduction was the current most widely grown variety, and apart from being the shortest winter oat ever released by WPBS (now IGER), it has shorter straw than either of its parents. Like the older variety Pennal, its difference in height is also apparent during early vegetative development in terms of short leaves and prostrate habit (Valentine, 1992). The genetic basis of the shortness of either variety is unknown.

Gerald has been used as a parent of a number of crosses still in an early stage of development. Two crosses made in 1989 involving Gerald have been accelerated. The numbers of F4 multiple rows grown in 1992 and numbers advanced to the next generation sown in autumn 1992 are shown in Table 6.

Table 6 Number of lines selected in two crosses involving Gerald

Cross	No. of F4 multiple rows, 1992	No. of F5 multiple rows, 1993	No. of F5's in yield trials, 1993
89-26ACn	28	20	11
89-87ACn	26	17	2

The yield, lodging resistance and other characteristics of these lines in 1993 are summarised in Table 7.

Table 7 Performance of lines in 1993 from two crosses involving Gerald

	Ear emergence (days after 1 May) (3)	Height (cms) (3)	Lodging+		Mildew % 28.6	Crown rust % 5.7	Yield relative to controls				Kernel % Berriew	1000 grain wt (g) Berriew	
			a	b			Berriew Powys	Abbots Ripton Cambs	Gogerddan Dyfed	Mean			
Controls													
Solva	41.3	153	4.7	2.0	27.5	30.0	100	110	110	107	76.9	32.1	
Image	40.6	143	5.0	7.0	35.0	30.0	93	87	88	89	75.4	29.7	
Craig	42.2	143	1.0	7.0	30.0	20.0	107	103	101	104	-	-	
[Parents of 89-26Cn]													
Gerald	42.4	132	1.7	1.0	35.0	27.5	105	108	105	106	73.7	32.9	
Chamois (previously 81-40Cn5/1)	41.0	162	6.0	3.5	22.5	30.0	105	106	121	111	77.3	32.9	
Gerald derivatives													
89-26ACn F5 lines													
89-26ACn1	42.0	147	2.3	1.0	35.0	20.0	99	99	103	100	-	-	discontinued
89-26ACn4	39.3	147	3.7	3.5	25.0	7.5	109	105	121	112	76.7	31.0	
89-26ACn5	42.6	151	1.0	1.0	25.0	10.0	112	118	120	117	75.6	32.8	
89-26ACn6	39.9	154	2.7	1.5	20.0	15.0	115	114	112	113	76.4	36.3	
89-26ACn8	42.8	152	2.7	1.5	35.0	7.5	111	113	110	111	74.4	30.2	
89-26ACn10	40.3	153	1.0	1.0	30.0	0	109	112	124	115	-	-	discontinued
89-26ACn12	39.8	145	1.0	1.0	30.0	10.0	115	111	107	111	75.7	29.6	
89-26ACn13	40.8	149	2.3	1.0	35.0	15.0	112	112	110	112	75.3	36.7	
89-26ACn14	39.4	139	1.0	1.0	35.0	20.0	108	111	104	108	76.6	32.5	
89-26ACn18	42.3	159	1.7	1.0	22.5	0	113	109	117	113	75.2	36.3	
89-26ACn20	41.4	149	2.3	1.0	25.0	0	105	108	126	113	74.8	31.5	
89-87ACn F5 lines													
89-87ACn12	41.8	147	3.3	1.0	17.5	9.0	94	110	95	100	-	-	discontinued
89-87ACn15	39.9	147	3.0	1.0	6.5	12.5	103	102	116	107	75.3	36.5	

89-26ACn = Gerald x 81-40Cn5/1
89-87ACn = ($Solva^2$ x Av2983/7/4) x Gerald
+ 1-9 (1 = no lodging; 9 = completely lodged), a = Berriew 13.7.93, b = Abbots Ripton 29.6.93 throughout

The 1993 season and site was conducive to stem growth, with the plant height of Solva, Image and Craig (controls) ranging between 143 and 153 cm. In comparison, Gerald was 132 cm tall, while the plant height of Chamois was 162 cm. Current ratings for these varieties on the UK Recommended Lists for cereals are as follows: shortness of straw: Solva 5, Image 6, Craig 6, Gerald 8 and Chamois 4; standing power: Solva 6, Craig 6, Image 5, Gerald 7, Chamois 5. Despite its tall straw, Chamois, which was added to the UK Recommended List of winter oats for 1994 for special use in milling (Anon, 1994), yielded well over the three locations.

The generally excellent yields and standing power of the eleven lines derived from the cross 89-26ACn (Gerald x 81-40Cn5/1, a progenitor of Chamois) are apparent in Table 7. With the possible exception of 89-26ACn14, which had a height in trials of 139 cm, the lines had heights around or above the mean of the two parents (147 cm) and Gerald's short straw was not recovered. Surprisingly, most of the eleven lines from 89-26ACn had good to immune resistance to crown rust. Nine lines were continued to 1994 trials.

Two lines from the other cross (89-87ACn (Solva x Av2983Cn7/4) x Gerald) were also taller than Gerald, with plant height nearer to that of Solva, the taller parent. Yields were lower than those of the previous cross. One line was continued to 1994 trials. This line also had some resistance to mildew, possibly as a result of genes for mildew resistance from Solva and Av2983/7/4, containing the *A.barbata* recombinant mildew gene (neither of which are now resistant to mildew) having effects as minor or 'ghost' genes.

1993-94

In 1994, 46 lines from 15 different crosses involving Gerald as a parent were tested in yield trials.

Establishment was severely affected by *Fusarium nivale* at two locations, Gogerddan and Berriew. An attempt was made to use co-variance analysis to correct grain yield for plant population expressed as plants/m^2 but overall there was only a loose correlation. It was observed that several varieties including Chamois and Emperor had very good compensatory ability in giving high yields despite very low populations. Ear emergence and plant height but not grain yield results were used from these trials.

The yield and other characteristics of nine lines selected for continuation into 1995 trials are shown in Table 8.

In general, differences in grain yield were not as great as those obtained in 1993. The highest relative yields were obtained from 89-2Cn (Solva x Gerald). As in 1993, with the possible exception of 89-26Cn14/1, the short straw of Gerald was not recorded in derived lines. Due to generally good weather, lodging was not a problem and differences between lines for this characteristic could not be determined. The occasional line under test had very good adult plant resistance to mildew.

In the light of the difficulty of retrieving the short straw of Gerald from crosses involving the line as a parent, an experiment was carried out in 1994 to investigate the inheritance of this valuable characteristic. Random F2 plants from 3 crosses involving Gerald (50 plants of Gerald x 81-40Cn5; 50 plants of 81-40Cn5/1 x Gerald, the reciprocal cross; 100 plants of Gerald x Krypton), together with ten plants of each parent and 4 F1 plants of Gerald x 81-40Cn5/1 and 6 F1 plants of 81-40Cn5/1 x Gerald) were sown in Jiffy plots and transplanted to the field in autumn 1993 at 30 cm spacing. The material was covered with synthetic horticultural fleece as winter protection (necessary at wide spacing) and in the later stages netted to prevent bird damage. Plant height and date of ear emergence were recorded for each plant.

Classification of parents, F1 and F2 generations into various height classes (Fig 1) showed that plant height appeared to be normally distributed with a mean approximately mid-way between individual parents. Plants as tall as the taller parent (81-40Cn5/1 or Krypton) or, of more interest, as short as Gerald, could be identified. It made little difference whether Gerald was used as the female or male parent, so that cytoplasmic inheritance could be ruled out. Plant height was not correlated with date of ear emergence in any cross. The reason for the paucity of lines in trials with as short straw as Gerald is therefore unlikely to be genetic but is probably due to shorter plants being at a competitive disadvantage during the selection process. Accordingly, we have responded to this finding by drilling F2 populations involving Gerald in thinner stands so that short plants will not be crowded out and can readily be identified.

Table 8 Performance of lines in 1994 from crosses involving Gerald

	Ear emergence (days after 1 May)	Height (cms)		Mildew %	Crown rust % race 265	Yield relative to Solva and Image 1994				Yield 1993 Mean	Kernel %	1000 grain wt (g)
		b+	c			Stapleford Wilts	Abbots Ripton Cambs	Trerulefoot Cambs	Mean			
Ex trial 1											(3)	(3)
Solva	45.5	110	124	26.7	33.3	104	102	108	102	107	73.9	38.1
Image	45.0	117	121	40.0	50.0	100	98	98	97	89	75.4	38.0
Gerald	46.0	109	112	25.0	39.8	108	101	110	104	106	72.8	36.5
Chamois	46.0	133	136	15.0	36.7	111	97	100	101	111	75.6	38.2
89-26ACn6/1	45.0	120	128	6.7	33.3	104	98	120	104	113	74.7	41.1
89-26ACn12/1	44.0	118	122	25.0	39.8	106	97	114	103	111	73.8	38.4
89-26ACn13/2	45.5	120	115	15.0	38.3	98	101	116	102	112	73.5	37.1
89-26ACn14/1	45.0	114	110	20.0	46.7	106	99	111	103	108	73.8	39.1
Ex trial 2											(2)	(2)
Solva	46.0	117	123	33.3	33.3	102	103	-	102	-	74.3	40.3
Image	45.5	117	120	28.3	53.3	98	97	-	98	-	75.0	39.0
89-26ACn16	46.5	120	121	16.7	40.0	107	103	-	105	-	75.6	38.8
89-87ACn4	46.5	123	120	8.3	36.7	99	96	-	97	-	74.2	36.2
Ex trial 3											(2)	(2)
Solva	45.5	116	120	23.3	30.0	101	108	-	105	-	74.5	40.5
Image	45.0	125	122	40.0	43.3	99	92	-	95	-	75.2	39.6
89-2Cn2	47.5	124	116	22.7	39.8	109	104	-	107	-	72.5	37.9
89-2Cn3	45.5	130	118	13.3	40.0	107	108	-	108	-	72.4	38.0
89-2Cn12	45.5	123	116	9.3	26.7	107	113	-	110	-	72.0	39.6

+ treated with Cycocel 5c at growth stage 32
a = Gogerddan, Dyfed; b = Berriew, Powys; c = Abbots Ripton, Cambs

Kernel Content & 1000 grain weight

Trial 1 = mean of 3 sites - Berriew, Stapleford & Cornwall
Trial 2 = mean of 2 sites - Berriew & Stapleford

Other sources of non-dwarf resistance to lodging

In other parts of the breeding programme, selection has not been primarily for resistance to lodging but has given equal or greater weight to selection for grain yield, general agronomic characteristics, resistance to diseases and milling quality.

The characteristics of two lines from this project that have proceeded into National List trials are shown in Tables 9 and 10. 85-47CnIII/2 is generally more resistant to lodging than Solva, with higher yield (Table 9). 87-61CnIII/1 has similar or better resistance to lodging than kernel quality and likely superiority for use in milling (Table 10).

Table 9 Performance of 85-47CnIII/2 in 1992 and 1993, on the basis of which (together with previous results) the line was entered into National List trials for 1994

(a) Agronomic and quality characteristics

	Ear emergence		Height (cms)		Lodging 1993 a	Lodging %		Mildew % 1993	Crown rust % 1993	Kernel %		1000 grain weight	
	1992 (3)	1993 (4)	(4)	(4)		Somersham 1992	Wilts 1993			1992 (3)	1993 (3)	1992 (3)	1993 (3)
Solva	40	41	127	146	3	3.3	23	25	30	76.6	75.8	38.1	36.2
Candidate	41	41	131	150	3	0	8	30	31	75.6	74.8	38.6	39.2

(b) Grain yield relative to controls

	1992				1993					Grand mean
	Somersham Cambs	Llwyngronwy Dyfed	Trerulefoot Cornwall	Mean	Berriew Powys	Abbots Ripton Cambs	Gogerddan Dyfed	Corton Wilts	Mean	
Solva	111	115	106	110.6	99	105	98	97	99.7	104.4
Candidate	113	117	107	112.5	112	111	102	101	106.5	109.1

Table 10 Performance of 87-61III/1 in 1993 and 1994 on the basis of which (together with previous results) the line was entered into National List trials for 1995

(a) Agronomic and quality characteristics

	Ear emergence		Height		Lodging a	Lodging %	Mildew %	Crown rust %	Kernel %		1000 grain weight	
	1993 (4)	1994 (4)	1993 (2)	1994 (2)	1993	Wilts 1993	1994	1994	1993 (3)	1994 (3)	1993 (3)	1994 (3)
Solva	41	45	143	117	3	10	27	33	75.8	73.9	36.2	38.1
Candidate	40	47	139	117	4.7	0	25	35	76.4	75.0	35.1	37.4

(b) Grain yield relation to controls

	1993					1994				Grand mean
	Berriew Powys	A.Ripton Cambs	Gogerddan Dyfed	Corton Wilts	Mean	Stapleford Wilts	A.Ripton Cambs	Trerulefoot Cornwall	Mean	
Solva	102	105	97	98	100.5	104	102	108	104.5	102.3
Candidate	107	104	102	99	102.8	100	88	102	96.8	100.2

Derivatives of S172, Omihi and Rosette

The winter oat S172, released by IGER-WPBS in 1939 (Griffiths, 1962), and its spring oat derivative Milford, released nine years later, contained a dwarf gene. S172 was probably Europe's first dwarf cereal. It was grown on the rich fen soils where resistance to lodging was an important requirement. At least eight varieties in the UK (Maris Quest), USA (Compact, Walken, Stout and Clintford) and New Zealand (Mapua and Omihi) have been produced from this source of dwarfness but none have been spectacularly successful (Valentine, Jones and Middleton, 1988). It appears that shortness in this, and other dwarf lines, is associated adversely with compact panicles, small grains and low yield.

Valentine, Jones and Middleton (1988) reported a line (81-117Cn2/1) with the compact panicles and short stiff straw of S172 but with improved grain size and number from Lustre. It was later shown that the basis of large grains in Lustre and 81-117Cn2/1 compared to S172 and Pennal (control) was greater cell size rather than number (S V Ruffle and Barry Thomas, unpublished University of Bath placement report). 81-117Cn2/1 has been used as a parent of several crosses. Details of lines selected for 1993 yield trials are shown in Table 11.

Table 11 Number of lines selected in three crosses involving 81-117Cn2/1, a S172 derivative

Cross	No. of F5 multiple rows, 1992	No. of F6 multiple rows, 1993	No. of F6 in yield trial, 1993
87-38	13	5	5
87-39	4	2	2
88-43A	9	4	3

(A = Accelerated)

The yield, lodging resistance and other characteristics of these lines are summarised in Table 12.

Six lines had plant height (range 129-138 cm) apparently lower than Solva (148 cm).

Three other lines were nearly as tall as, or taller (141-157 cm) than Solva. The short lines had the typical compact panicles of S172 while the panicles of the tall lines were lax in two cases and compact in the other. Shorter types also tended to be late in ear emergence (and maturity). Yields were also disappointing. Only two lines were continued into further trials.

Table 12 Performance of F6 lines in 1993 from three crosses involving 81-117Cn2/1 (S172 x Lustre) and from one cross involving 81-110Cn9

	Ear emergence (days after 1 May) (3)	Height (cms) (3)	Lodging		Mildew % 18.6	Crown rust % 5.7	Ear type	Yield relative to controls						Kernel %		1000 grain wt (g)		
			a	b				Berriew Powys	A.Ripton Cambs	Gogerddan Dyfed	Corton Wilts	Trerulefoot Cornwall	Mean	1992	1993	1992	1993	
					Trial 1													
Solva	39.5	148	1.0	1.0	25.0	30.0	lax	99	105	98	97	96	99	74.6	75.6	34.1	39.9	
Gerald	40.3	129	1.0	1.0	40.0	33.3	lax	99	107	95	109	95	101	-	73.3	-	35.9	
87-38CnI/1	38.3	141	2.0	1.0	40.0	31.7	lax	89	100	96	92	81	91	77.4	-	38.1	-	discontinued
87-38CnII/5	42.7	129	1.0	1.0	46.7	30.0	compact	98	100	100	98	84	92	76.6	-	33.6	-	discontinued
					Trial 2													
Solva	40.5	150	1.0	1.0	28.3	21.7	lax	102	105	97	98	-	100	-	75.6	-	38.2	
87-38CnI/4	40.5	135	1.0	1.0	36.7	0	compact	87	101	88	103	-	94	-	-	-	-	discontinued
87-38CnV/1	42.3	138	1.0	1.0	40.0	21.7	compact	95	104	103	105	-	102	-	75.8	-	30.9	
87-38CnVIII/3	44.2	132	1.0	1.0	40.0	36.7	compact	86	105	100	92	-	100	-	-	-	-	discontinued
87-39CnIII/2	44.3	134	1.0	1.0	46.7	1.0	compact	91	113	102	105	-	103	-	-	-	-	discontinued
87-39CnIX/1	40.3	133	1.0	1.0	40.0	12.7	compact	92	101	104	101	-	99	-	-	-	-	discontinued
87-52CnII/2	44.6	130	1.0	1.0	30.0	20.0	lax	92	102	112	92	-	100	-	-	-	-	discontinued
					Trial 4													
Solva	41.3	153	4.7	2.0	27.5	30.0	lax	100	110	110	-	-	107	-	76.9	-	32.1	
88-43ACnIII/2	40.8	157	3.0	2.0	35.0	0	lax	99	99	107	-	-	102	-	-	-	-	discontinued
88-43ACnIII/7	41.6	154	1.0	1.0	50.0	0	compact	99	105	107	-	-	104	-	77.0	-	35.1	

87-38Cn = 81-117Cn7/1 x Solva
87-39Cn = 78-1Cn3/2/1/2 x 81-117Cn2/1
88-43Cn = 81-117Cn2/1 x 82-39A/3/2 (Image x Lustre)
87-52Cn = 81-110-Cn9 x Solva

A S172-derived line, 81-110Cn9 (the New Zealand spring oat Omihi x Lustre) was identified in the mid 1980's which combined short straw, large grains with open (lax) rather than compact panicles. The line also had good tolerance to BYDV (derived from both parents) but was winter-susceptible. It was crossed with several parental cultivars in 1987. Most progeny, with low winter-hardiness, a marked tendency to produce albino tillers during the winter and low yields, have been discontinued. One advanced line, 87-52CnII/2 was present in yield trials in 1993. The shortness of the line was confirmed but yield was low and the line has been discontinued.

A third avenue to reducing plant height and increasing lodging resistance associated with compact panicles has been the use of the variety Rosette (LP 78-3). This line was a winter oat obtained from Lochow-Petkus in Germany, with S172 compact-type panicles, from the cross between Peniarth (from IGER) and Stammt (origin unknown but presumably the source of S172 type characteristics).

Among the other crosses, Rosette was crossed to Bardsey (an IGER line with compact panicles, an exceptionally high number of grains/panicle and medium length straw), in 1981 and the resulting F1 crossed again to the progenitor of Lustre (an IGER line recommended in 1987 and 1988 containing the American variety Cimarron in its parentage with exceptionally large grains (Valentine, Jones and Middleton, 1988)). Short-strawed lines from this particular cross were identified in 1986 and used to derive a second cycle of breeding material initiated in 1987. From one cross with an IGER breeding line, one highly promising line was present in yield trials in 1993 and 1994 (Table 13) and is proceeding to further trials prior to possible seed purification and subsequent entry to National List trials.

Table 13 Performance of a line derived from (Bardsey x Rosette) x Lustre in 1993 and 1994

(a) Agronomic and quality characteristics

	Ear emergence (days after 1 May)		Height cms		Lodging a	Lodging % Wilts	Mildew %	Crown rust %	Kernel %		1000 grain wt (g)	
	1993 (3)	1994 (1)	1993 (3)	1994 (2)	1993	1993	1994	1994	1993 (3)	1994 (3)	1993 (3)	1994 (3)
Solva	41	45	153	117	3	23	27	30	75.8	73.9	36.2	38.1
Gerald	42	46	132	111	1	0	25	33	73.3	72.8	34.9	36.5
Candidate	41	45	133	113	6	0	7	32	76.5	75.8	41.7	44.5

(b) Grain yield relative to controls

	1993					1994				Grand mean
	Berriew Powys	A.Ripton Cambs	Gogerddan Dyfed	Corton Wilts	Mean	Stapleford Wilts	A.Ripton Cambs	Trerulefoot Cornwall	Mean	
Solva	102	105	97	98	100.5	104	102	108	104.5	102.3
Gerald	99	107	95	109	102.2	108	101	110	106.5	104.1
Candidate	106	96	101	112	103.6	112	104	112	109.3	106.1

Dwarf oats from OT207

A promising open-panicled dwarf mutant, OT207, was described in 1980 (Brown, McKenzie and Mikaelson, 1980). It has a dramatic effect on plant height (20-50 cm reduction) which would make the oat crop far easier to manage. The gene, designated Dw6 (Simons *et al*, 1978), is dominant and does not incidentally suppress the naked oat characteristic so that it is also feasible to breed a dwarf naked oat. In Australia, cultivars of husked oats (Echidna and Dolphin) and naked oats (Bandicoot) containing this gene have been produced and very well received by farmers.

Work in the Cytogenetics Group has shown this gene is located on chromosome II (Mia, 1984). Various sources of this gene in spring oat backgrounds have been used in the winter and spring oat programmes. A number of crosses have been performed in order to increase the contribution of adapted genes and decrease the contribution of unadapted genes. Initial material was particularly susceptible to mildew, oat mosaic virus, leaf browning and winter-kill.

In addition to generating and selecting breeding material containing this gene, two field trials were carried out in 1993.

The first experiment, the aim of which was to quantify various characteristics including resistance to lodging and indicate rate of progress, compared DW6 derivatives containing 50% adapted:50% unadapted genes and 75% adapted:25% unadapted genes with control varieties (Solva and Gerald) at two rates of nitrogen. The trial was sown at Gogerddan. Nitrogen fertiliser rates were calculated taking into account crop type and soil nitrogen supply. Rates used were N1, the standard rate = 45 kgs/ha and N2, double rate = 90 kgs/ha. The trial was kept disease and weed free. A split plot analysis of variance design was used in which nitrogen was the main treatment and varieties the sub-treatments. There were three blocks. Results are presented in Table 14.

Table 14 Characteristics of Dw6 dwarf lines at two rates of nitrogen fertiliser application compared to Solva and Gerald i n 1993

	Ear emergence (days after 31 May)			Height (cms)			Lodging % 16.7.94			Yield (t/ha)		
	N1	N2	Mean	N1	N2	Mean	N1	N2	Mean	N1	N2	Mean
<u>Controls</u>												
Solva	7.0	7.0	7.0	164	163	164	29	75	52	[7.57[1]] *(84)*	[6.24[1]] *(73)*	[6.90[1]] *(78)*
Gerald	8.0	8.0	8.0	143	148	146	17	50	33	9.05 *(100)*	8.57 *(100)*	8.81 *(100)*
<u>50% adapted:50% unadapted</u>												
86-97Cn4/1	13.3	13.3	13.3	125	112	118	8	17	12	8.28 *(91)*	8.75 *(102)*	8.52 *(97)*
88-225ACnI	13.0	13.0	13.0	116	119	117	0	25	12	8.68 *(96)*	6.53 *(76)*	7.60 *(86)*
<u>75% adapted:25% unadapted</u>												
89-158ACn2	11.0	10.3	10.7	99	90	95	0	0	0	8.26 *(91)*	7.87 *(92)*	8.06 *(91)*
89-158ACn12	11.0	12.7	11.8	98	110	104	0	0	0	7.73 *(85)*	7.86 *(92)*	7.80 *(88)*
Mean												
Nitrogen												
Prob		NS			NS			0.015			0.024	
SED		0.26			2.6			2.1			0.090	
Variety												
Prob		<0.001			<0.001			<0.001			<.001	
SED		0.50			6.7			10.6			0.343	
Nitrogen x Variety												
Prob		NS			NS			NS			0.019	
SED		0.72			9.2			14.2			0.463	

[1] grain lost due to bird damage
( ) relative yield

In this trial, dwarf lines ranged from 95 to 118 cm tall, much shorter than presently available varieties (Solva 164 cm, Gerald 146 cm). Not surprisingly, therefore, dwarf lines have much better standing power. At the higher nitrogen rate, the two most advanced dwarf lines did not lodge at all while Gerald, the shortest and stiffest winter oat to be released by IGER-WPBS, was 50% lodged and Solva 75% lodged. The highest yielding dwarf in this experiment had a yield 97% of Gerald. Dwarf lines had later ear emergence than Solva and Gerald although introgressing more adapted germplasm improved earliness by 2-3 days.

The second experiment, the aim of which was to quantify the effect of the dwarf gene on yield and other characteristics, compared related tall and dwarf lines with 75% adapted:25% unadapted genes and control varieties (Solva and Gerald) in order to quantify the effect of the dwarf gene on yield and other characteristics. The related lines were obtained by bulking together non-segregating dwarf or tall F2 single plant progenies from groups of multiple rows grown in the field in 1992. There were three husked tall and dwarf comparisons and one naked tall and dwarf comparison. The experiment was grown at Gogerddan at a single rate of nitrogen application (45 kgs/ha). The trial was kept disease and weed free. There were three blocks. Results are presented in Table 15.

In the husked oat comparisons, dwarf lines were 60 cm shorter on average than their tall counterparts and consistently outyielded tall lines, on average by 22%. Dwarf lines did not lodge, whereas their tall counterparts were on average 65% lodged. On the other hand, dwarf lines were appreciably later than tall lines although there were 3 days difference between the earliest and latest dwarf lines. The earliest dwarf line had a similar time of ear emergence to Solva and Image. Despite lines having on average 25% unadapted genes, the dwarf lines yielded well in comparison to the newly released Gerald. One dwarf line had a yield 7% greater than Gerald.

In the single naked oat comparison, the dwarf gene clearly reduced height, improved resistance to lodging and delayed ear emergence. Surprisingly, however, the tall line outyielded the dwarf line. It should be borne in mind that this is a single comparison and it would be incorrect, let alone unlikely, to come to the conclusion that dwarf, naked oats have lower yield than their tall counterparts.

Table 15 Characteristics of related tall (dw6) and dwarf (Dw6) lines compared to Solva and Gerald in 1993

		Ear emergence (days after 31 May)	Height (cms)	Lodging % 16.7.94	Yield (t/ha)
Controls					
Solva		9.0	171	58	[5.57][1] *(71)*
Gerald		9.0	146	0	7.84 *(100)*
Husked oat comparisons					
89-158ACn5	dwarf	9.0	107	0	7.73 *(99)*
	tall	4.3	180	58	6.07 *(77)*
89-158ACn9	dwarf	12.0	112	0	7.45 *(95)*
	tall	6.0	178	75	6.45 *(82)*
89-158ACn14	dwarf	12.3	105	0	8.37 *(107)*
	tall	5.3	177	62	6.69 *(85)*
Mean	dwarf	11.1	108	0	7.85 *(100)*
	tall	5.2	178	65	6.40 *(82)*
Naked oat comparison					
89-166ACnI/1	dwarf	10.3	97	0	6.17 *(79)*
	tall	3.7	159	29	6.95 *(89)*
Variety					
Prob		<0.001	<0.001	<0.001	0.018
SED		0.50	3.4	28.3	0.717

[1] grain lost due to bird damage
( ) relative yield

One feature of dwarf oats based on the Dw6 gene is poor extrusion of panicles from the flag leaves. In the most extreme cases, panicles fail to emerge fully from the flag leaf sheaths due to short final internodes. Extrusion is probably better in winter rather than spring oats and is better in field rather than glasshouse-grown material. In the winter oat programme, a line (88-227CnII/2) of intermediate height referred to as a peduncle extender line, has been identified. A genetic study was carried out in 1993 to examine the genetic basis of peduncle extension.

100 F2 plants of two crosses between two different dwarf lines and the peduncle extender line, together with ten plants of each parent were sown in Jiffy Pots and transplanted to the field in autumn 1992 at 30 cm spacing. Plant height was recorded on 18 June 1993. Results are shown in Table 16.

Classification of the F2 generation of each cross revealed two discrete height classes for which there was no significant deviation from a classical 3:1 ratio for dwarf vs tall. This confirms that, as already known, dwarf is inherited as a single dominant gene, while tall is recessive. Of most interest, however, the intermediate height of the peduncle extender line is hardly retrieved. The trait is not, therefore, simply inherited. As plants with the peduncle extender phenotype have thin, fine straw and thin grains, cells were checked for chromosome abnormalities but none could be detected (J M Leggett, personal communication).

Table 16 Frequency distribution of plant height in two crosses involving dwarf lines and a peduncle extender line

	Plant height (cms)												
	40-50	50-60	60-70	70-80	80-90	90-100	100-110	110-120	120-130	130-140	140-150	150-160	Mean
Cross 1													
86-97Cn2			1	4	5								79.1
88-227CnII/2							4	5	1				113.2
F2 86-97Cn2 x 88-277CnII/2	2	1	18	44	13			1	9	11		1	86.9
Cross 2													
88-226CnII/9			5	5									70.0
F2 88-227CnII/2 x 88-226CnII/9		10	15	39	11	1		3	3	10	6		87.2

Chi-square analysis testing the deviation from 3:1 ratio

	Number observed	Number expected	Deviation	x^2	Prob
Cross 1					
Dwarf (<90 cm)	78	75.0	+3	0.120	-
Tall (>110 cm)	22	25.0	-3	0.360	-
Total	100	100.0	0	0.480	P = 0.50-0.40
Cross 2					
Dwarf (<100 cm)	76	73.5	+2.5	0.085	-
Tall (>110 cm)	22	24.5	-2.5	0.255	-
Total	98	98.0	0	0.340	P = 0.60-0.50

V INCREASED COMPETITIVENESS OF NAKED OATS

Naked oats thresh from a non-lignified husk during harvesting. The resultant grain has a high nutritional value for feeding to animals, particularly non-ruminants in terms of lower levels of fibre than barley or husked oats and higher levels of energy-rich oil and essential amino-acids than wheat, barley or husked oats. The crop also offers opportunities for food processors in terms of large potential savings on energy, equipment and labour particularly if larger amounts of naked oats were available (Valentine, 1990b, 1995; Doyle and Valentine, 1989; Valentine and Clothier, 1992).

The first commercial naked oat crops were grown in 1989 using the varieties Rhiannon (added to the National List in 1984) and Kynon (1986). Apart from the advent of suitable varieties, commercialisation followed from (1) circumventing the seed production problem (Valentine and Hale, 1990, (2) a clear, honest appraisal by the Superioat Company of chemical composition, yield, gross margins and other characteristics such as drying and storage, (3) the identification of specialised markets (Mason, 1992; Valentine and Clothier, 1992; Valentine, 1995).

Specialised markets include feed for racehorses, pet food, malting for use in the food industry and milled oat products. Other potential markets include oil extraction for industrial use (Green, 1992; Mason, 1992), piglet creep feed and fractionisation (Burrows *et al*, 1992). Over 20,000 t of naked oats were produced in 1992, representing 10% of industrially processed oats.

Naked oats are still at the early stage of development as a modern crop. Producers and feed companies have positive attitudes towards the crop (Loader, 1991). The existence of diverse markets buffers crop development but also should, by providing larger quantities of grain, facilitate the penetration of larger general markets such as non-ruminant animal feed (Valentine, 1995) and be beneficial to UK arable farmers. Similar developments are taking place elsewhere in the world although UK is the furthest ahead in commercial development (Valentine, 1993). Burrows (1986) envisaged naked oats as a valuable, transportable crop supplementing world grain products.

The development of naked oats in the UK is still largely based on Kynon and Rhiannon which were released in the 1980s. Pendragon, added to the National List in 1991 with better winter-hardiness and resistance to mildew then Kynon, but only marginally greater yield than Kynon, has made little impact. Harpoon and Neon have been added to the new Recommended List for 1995 (Anon, 1995). However higher yielding varieties, with better expression of nakedness than existing ones, are urgently needed to make the economics of growing naked oats more attractive and the penetration of additional markets easier.

A summary of the yield and other characteristics of naked oats coming through from the beginning of the project are shown in Tables 17-24.

The winter naked oats Krypton and 86-142CnIII/3 emanating from this project have substantially improved yield compared to Kynon, Pendragon and Harpoon (Table 17). Krypton entered National List trials in 1993 and 86-142CnIII/3 (provisionally named Lexicon) in 1994.

On the basis of these figures, neither variety is an improvement on existing varieties for the degree of nakedness (Table 8). Four other naked oat lines being re-tested in 1995, had 100% naked expression. A difference between 96.7% (Kynon) and 100% may not seem very significant. When it is expressed however in terms of the number of husked grains - 33 husked grains in a 1000 grain sample of Kynon and none for the four other varieties - this represents a large difference in quality for those markets (such as human consumption), where virtual freedom from husked oats is required. Further testing is necessary to confirm the high expression of these lines.

For 1000 grain weight, Harpoon (29.4 g) and a number of lines tested for the first time represent sizeable gains achieved during the project. 89-187Cn4/1 is notable in apparently having a 1000 grain weight (36.9g) equally or exceeding this of husked oats (Table 19).

The new variety Krypton has an oil content above that of Kynon, Pendragon and Harpoon (Table 20).

In naked spring oats, three potential varieties emanating from the project have reached National List trials. These are Ripon, entered into NL1 in 1993, and now in Recommended List trials, Bullion (NL1 in 1994 and now in NL2) and 11028Cn (NL1 in 1993). The yields of these varieties are 109.1, 114.4 and 110.9 relative to Rhiannon (100) (Table 21). All three varieties represent major improvements (98.6 - 99.6%) over Rhiannon (95.4%) in terms of the degree of naked expression. Very good progress has also been in increasing 1000 grain weight, with Bullion and 11028Cn (33.1g and 31.2g respectively) having about 20% larger grains than Rhiannon (25.9g). For oil content, Ripon, Bullion and 11028Cn have lower levels than Rhiannon (7.3, 6.6 and 6.6 compared to 8.9%).

Table 17 Yield of winter naked oats continued to 1995 trials (relative to Kynon)

	1992		1993			1994 Trial 4		1994 Trial 7		Mean
	Somersham Cambs	Llwyngronwy Dyfed	Berriew Powys	Abbots Ripton Cambs	Gogerddan Dyfed	Stapleford Wilts	Abbots Ripton Cambs	Gogerddan Dyfed	Berriew Powys	(No. of trials)
Kynon	100	100	100	100	100	100	100	100	100	100 (9)
Pendragon	111.8	123.8	100.4	109.8	100	110.6	106.1	106.1	101.4	107.8 (9)
Harpoon	112.0	133.4	104.5	99.4	102.0	97	114.5	96.6	100.7	106.7 (9)
Krypton	113.8	155.2	102.0	113.6	95.4	117	124.8	-	-	117.4 (7)
86-142CnIII/3	135.6	149.5	112.7	108.6	108.7	106	118.9	99.5	107.7	116.3 (9)
89-139Cn2/1	-	-	-	-	-	-	-	96.6	82.9	89.7 (2)
89-173Cn1/2	-	-	-	-	-	-	-	98.9	97.9	98.4 (2)
89-187Cn4/1	-	-	-	-	-	-	-	89.3	77.4	83.3 (2)
89-224Cn3/1	-	-	-	-	-	-	-	106.2	95.2	100.7 (2)
89-224Cn4/1	-	-	-	-	-	-	-	101.0	100.3	100.6 (2)
89-224Cn10/2	-	-	-	-	-	-	-	88.8	92.6	90.7 (2)
89-226Cn1/1	-	-	-	-	-	-	-	97.5	92.3	94.9 (2)
89-269Cn6/1	-	-	-	-	-	-	-	92.1	88.4	90.2 (2)

Notes 1. Yield at Dundee and Trerulefoot in 1992 not presented as Kynon not present in trial
2. Yield results at Berriew in 1992 had a CV >10% and therefore not presented

Table 18 Percent nakedness (by number) of winter naked oats continued to 1995 trials

	1992				1993		1994			Mean
	Trial 1			Trial 2	Trial 3	Trial 5	Trial 4		Trial 7	(No. of trials)
	Dundee	Trerulefoot Cornwall	Berriew Powys	Berriew Powys	Berriew Powys	Berriew Powys	Berriew Powys	Stapleford Wilts	Berriew Powys	
Kynon	-	-	-	94.7	93.3	99.3	100	94.7	98.0	96.7 (6)
Pendragon	98.7	99.3	96.7	96.7	97.3	100	98.7	98.0	99.3	98.3 (9)
Harpoon	76.7	94.0	93.3	96.7	94.0	97.3	98.0	88.0	-	92.2 (8)
Krypton	84.7	96.0	96.7	91.3	94.7	100	99.3	94.0	98.7	95.0 (9)
86-142CnIII/3	-	-	-	97.3	96.7	-	99.3	96.7	-	96.5 (5)
89-139Cn2/1	-	-	-	-	-	-	-	-	99.3	99.3 (1)
89-173Cn1/2	-	-	-	-	-	-	-	-	99.3	99.3 (1)
89-187Cn4/1	-	-	-	-	-	-	-	-	96.0	96.0 (1)
89-224Cn3/1	-	-	-	-	-	-	-	-	100	100.0 (1)
89-224Cn4/1	-	-	-	-	-	-	-	-	96.7	96.7 (1)
89-224Cn10/2	-	-	-	-	-	-	-	-	100	100.0 (1)
89-226Cn1/1	-	-	-	-	-	-	-	-	100	100.0 (1)
89-269Cn6/1	-	-	-	-	-	-	-	-	100	100.0 (1)

Table 19 1000 grain weight (g) of winter naked oats continued to 1995 trials

	1992				1993		1994			Mean
	Trial 1			Trial 2	Trial 3	Trial 5	Trial 4		Trial 7	(No. of trials)
	Dundee	Trerulefoot Cornwall	Berriew Powys	Berriew Powys	Berriew Powys	Berriew Powys	Berriew Powys	Stapleford Wilts	Berriew Powys	
Kynon	-	-	-	25.6	23.5	23.3	23.9	24.5	27.0	24.6 (6)
Pendragon	22.6	24.3	28.9	28.8	27.4	28.4	32.1	27.9	31.9	28.0 (9)
Harpoon	26.5	28.3	26.9	30.7	29.6	28.2	33.5	31.3	-	29.4 (8)
Krypton	24.9	22.9	24.9	24.9	23.6	22.1	26.3	25.5	29.1	24.9 (9)
86-142CnIII/3	-	-	-	23.1	25.8	-	26.9	24.1	-	25.0 (4)
89-139Cn2/1	-	-	-	-	-	-	-	-	22.9	22.9 (1)
89-173Cn1/2	-	-	-	-	-	-	-	-	28.8	28.8 (1)
89-187Cn4/1	-	-	-	-	-	-	-	-	36.9	36.9 (1)
89-224Cn3/1	-	-	-	-	-	-	-	-	31.7	31.7 (1)
89-224Cn4/1	-	-	-	-	-	-	-	-	30.7	30.7 (1)
89-224Cn10/2	-	-	-	-	-	-	-	-	28.7	28.7 (1)
89-226Cn1/1	-	-	-	-	-	-	-	-	31.9	31.9 (1)
89-269Cn6/1	-	-	-	-	-	-	-	-	27.6	27.6 (1)

Table 20 Oil content (%DM basis) of winter naked oats continued to 1995 trials (relative to Kynon)

	1992				1993		1994		1994	Mean
	Trial 1			Trial 2	Trial 3	Trial 5	Trial 3	Trial 3	Trial 7	(No. of trials)
	Dundee	Trerulefoot Cornwall	Berriew Powys	Berriew Powys	Berriew Powys	Berriew Powys	Berriew Powys	Stapleford Wilts	Berriew Powys	
Kynon	-	-	-	7.2	8.0	8.0	8.4	8.4	8.1	8.0 (6)
Pendragon	8.9	8.3	7.1	7.1	8.0	8.2	8.3	7.9	7.9	8.0 (9)
Harpoon	7.9	7.8	7.1	7.1	7.9	7.8	7.6	7.7	-	7.6 (8)
Krypton	9.3	8.5	8.1	7.8	9.1	9.1	8.8	8.4	7.8	8.5 (9)
86-142CnIII/3	-	-	-	7.7	7.4	-	8.5	8.2	-	8.0 (4)
89-139Cn2/1									8.9	8.9 (1)
89-173Cn1/2									8.7	8.7 (1)
89-187Cn4/1									7.7	7.7 (1)
89-224Cn3/1									7.1	7.1 (1)
89-224Cn4/1									7.2	7.2 (1)
89-224Cn10/2									7.7	7.7 (1)
89-226Cn1/1									8.5	8.5 (1)
89-269Cn6/1									7.8	7.8 (1)

Table 21 Yield of spring naked oats continued to 1995 trials (relative to Rhiannon)

	1991		1992			1993				1994					Mean (no. of trials)
	Morfa Dyfed	Sarn Powys	Aberdeen Grampian	Hytesbury Wilts	Sarn Powys	Morfa Dyfed	Aberdeen Grampian	Hytesbury Wilts	Sarn Powys	Morfa Dyfed	Aberdeen Grampian	Stableford Wilts	Abbots Ripton Cambridge	Sarn Powys	
Ex trial 1 1994															
Rhiannon	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100 (14)
10730Cn (Bullion)	94.7	102.3	118.7	104.6	106.4	124.2	139.2	132.8	119.0	128.9	111.6	114.2	109.0	96.0	114.4 (14)
11028Cn	96.3	101.7	-	-	111.4	121.7	-	-	129.3	116.0	106.2	112.5	107.3	106.6	110.9 (10)
Ex trial 3 1994															
Neon (10026Cn)	97.0	100.0	-	-	108.9	122.3	-	-	106.9	111.9	-	98.0	106.4	101.4	105.9 (9)
11556Cn83	-	-	-	-	-	117.7	-	-	118.6	77.4	-	100.0	106.4	114.1	105.7 (6)
11556Cn104	-	-	-	-	-	116.9	-	-	121.6	115.5	-	102.0	103.3	95.6	109.2 (6)
11564Cn	-	-	-	-	-	121.0	-	-	113.2	98.7	-	83.0	123.5	92.8	105.4 (6)
11585Cn	-	-	-	-	-	120.0	-	-	-	107.1	-	-	-	97.0	108.0 (3)
11587Cn	-	-	-	-	-	119.5	-	-	115.4	104.8	-	-	-	74.1	103.4 (4)
11595Cn	-	-	-	-	-	112.6	-	-	-	109.4	-	100.0	117.0	92.8	106.4 (5)
Ex trial 8 1994															
Ripon (10687Cn)	113.4	96.7	109.4	109.2	103.9	122.9	-	-	116.9	110.2	-	-	-	99.0	109.1 (9)
11590Cn	-	-	-	-	-	108.1	-	-	-	115.5	-	-	-	116.5	113.4 (3)

Table 22 Percent nakedness (by number) of spring naked oats continued to 1995 trials

	1992		1993		1994	Mean (no. of trials)
	Sarn	Nursery	Sarn	Morfa	Morfa	
Ex trial 1 1994						
Rhiannon	93.6	96.5	94.0	93.5	99.5	95.4 (5)
10730Cn (Bullion)	99.5	99.5	96.8	98.0	99.0	98.6 (5)
11028Cn	99.6	99.5	-	99.4	100.0	99.6 (4)
Ex trial 3 1994						
Neon (10026Cn)	99.6	98.0	-	99.6	99.5	99.2 (4)
11556Cn83	-	-	-	98.0	98.0	98.0 (2)
11556Cn104	-	-	-	98.4	100.0	99.2 (2)
11564Cn	-	-	-	95.2	97.5	96.4 (2)
11585Cn	-	-	-	99.2	99.5	99.4 (2)
11587Cn	-	-	-	99.4	99.5	99.4 (2)
11595Cn	-	-	-	98.0	99.5	98.8 (2)
Ex trial 8 1994						
Ripon (10687Cn)	98.0	99.0	0	98.8	98.5	98.6 (4)
11590Cn	-	-	-	99.2	98.5	98.8 (2)

Table 23 1000 grain weight (g) of spring naked oats continued to 1995 trials

	1992		1993		1994	Mean (no. of trials)
	Sarn	Nursery	Sarn	Morfa	Morfa	
Ex trial 1 1994						
Rhiannon	23.6	26.4	29.6	24.5	25.3	25.9 (5)
10730Cn (Bullion)	35.4	34.3	32.5	32.4	31.0	33.1 (5)
11028Cn	33.6	30.3	-	31.7	29.4	31.2 (4)
Ex trial 3 1994						
Neon (10026Cn)	30.4	27.8	-	29.2	25.1	28.1 (4)
11556Cn83	-	-	-	37.2	27.0	32.1 (2)
11556Cn104	-	-	-	32.8	24.3	28.6 (2)
11564Cn	-	-	-	35.9	32.6	34.2 (2)
11585Cn	-	-	-	27.5	26.2	26.8 (2)
11587Cn	-	-	-	36.1	28.0	32.0 (2)
11595Cn	-	-	-	31.2	282.1	29.6 (2)
Ex trial 8 1994						
Ripon (10687Cn)	27.5	29.7	-	29.5	26.3	27.9 (2)
11590Cn	-	-	-	33.7	26.2	30.0 (2)

Table 24 Oil content (% DM basis) of spring naked oats continued to 1995 trials

	1992		1993		1994	Mean (no. of trials)
	Sarn	Nursery	Sarn	Morfa	Morfa	
Ex trial 1 1994						
Rhiannon	9.3	8.1	9.0	9.5	8.6	8.9 (5)
10730Cn (Bullion)	6.8	6.2	7.0	6.5	6.6	6.6 (5)
11028Cn	6.8	6.1	-	6.8	6.8	6.6 (4)
Ex trial 3 1994						
Neon (10026Cn)	9.0	7.3	-	8.5	9.5	8.6 (4)
11556Cn83	-	-	-	9.9	9.0	9.4 (2)
11556Cn104	-	-	-	8.9	10.0	9.4 (2)
11564Cn	-	-	-	8.2	8.6	8.4 (2)
11585Cn	-	-	-	8.2	8.9	8.6 (2)
11587Cn	-	-	-	8.2	9.4	8.8 (2)
11595Cn	-	-	-	7.4	7.1	7.2 (2)
Ex trial 8 1994						
Ripon (10687Cn)	7.2	6.2	-	7.1	7.5	7.3 (2)
11590Cn	-	-	-	6.1	6.8	6.4 (2)

VI CONCLUSIONS

Valentine (1993) pointed out that the full resuscitation of the oat crop is likely to arise only via radical genetic improvement. Major genetic improvements which could have a major impact on the oat crop included increased winter-hardiness, which would improve the stability of the crop and extend its range; higher yielding, early maturing spring oats; dwarf or lodging resistant oats; better naked oat varieties and oats with high oil content.

Building upon gains made in the USA and the UK since the early 1980's, successive cycles of hybridisation and selection have aimed at combining winter-hardiness and high grain yield. High yielding lines with significantly higher levels of winter-hardiness than currently available winter oat varieties have been achieved but further work is still necessary to recover higher levels of grain yield. The opportunities exist for the identification of superior lines capable of commercial development arising from each cross or as part of a convergent backcrossing scheme (McKey, 1986) bringing together polygenic factors into a well adapted genetic background by intercrossing superior lines. The absence in recent years of 'hard' winters has hindered selection for winter-hardiness. For this reason another approach that we have started using is individual plant selection under artificial conditions to identify superior progenies in early generations.

Increased lodging resistance is mainly being brought about by reduction in plant height. The recently released variety Gerald, the shortest winter oat variety produced by IGER, is being used as one source of shortness. During the project, we have shown that short types are being lost through competition and we are now sowing some F2 populations at lower density in order to retain more Gerald type plants. Nevertheless, some lines with high resistance to lodging and grain yield have been identified. Two lines with high resistance to lodging that have proceeded to National List trials are 85-47CnIII/2 and 87-61CnIII/1. The latter has good kernel content which is important for the extremely important premium milling oat market.

Compact panicled dwarfs have provided another avenue for short straw. One very promising line has been identified which has straw almost as short as Gerald, high grain yield and exceptionally large grains.

Open panicled dwarf varieties containing the Dw6 gene are also under development. In one trial, one dwarf line had a yield of 7% greater than Gerald. Dwarf lines have extremely good standing power but tend to be late and have small grains. Further work is being undertaken to rectify these faults. Commercially acceptable dwarf varieties could conceivably have the same impact on the oat crop as did dwarf genes in wheat.

Naked oats open up new markets to oats, particularly for feeding to non-ruminants, by virtue of unparalleled nutritional value. The crop also offers opportunities for food processors in terms of large potential savings on energy, equipment and labour, particularly if larger amounts of naked oats were available.

A welcome development is the introduction of Recommended Lists for naked oats, this forming part of NIAB's HGCA funded work.

Improved naked oat varieties emanating from this project include Krypton and Lexicon (winter oats) and Ripon, Bullion and 11028Cn (spring oats). These represent advances in grain yield and other characteristics, higher oil (particularly Krypton) and higher expression of nakedness compared to existing varieties.

There remain further opportunities for genetic improvement in these characteristics. Other opportunities include increased resistance to diseases, in particular mildew, and improved value for human and industrial markets. These advances are necessary in order to maximise the production and market opportunities for UK growers and processors in the face of likely stern competition from other countries, particularly the Scandinavian countries. In this context, however, the UK is fortunate in being able to grow winter oats which tend to have better kernel and oil content than spring oats.

VII UPDATE

Since writing the original report, work in a number of areas has come to fruition. As with all plant breeding, some avenues proved more successful than others for genetic and other reasons.

Gerald has gained market share from 35.7% in 1995-96 to 47.8% in 1996-97 plantings. This is a much larger share of its market than any other cereal of any significance, a measure of its popularity with growers (by virtue of its short, stiff straw) and millers.

Chamois (81-40Cn5/1) has been promoted from PG to G on the UK Recommended List. This variety has high milling quality. **Emperor** is in its second year of provisional recommendation on the List. This variety has the highest level of yield and also disease resistance (with the exception of the naked oat Lexicon).

Two lines (**89-26Cn6/1** and **14/1**) involving Gerald and an immediate progenitor of Chamois in their parentage (from among the lines in Tables 7 and 8) are now in their second year of National List trials. One line is as short as Gerald.

The two lines mentioned in Tables 9 and 10 (87-47CnIII/2 (**Stampede**) and 87-61CnIII/1 (**Smuggler**)) entered into National List trials were withdrawn after two years of testing.

All of the lines containing S172 (Tables 11 and 12) have been discontinued. It proved impossible to combine high grain yield, short straw and earliness. One shorter-strawed naked oat containing the more open-panicled 81-110Cn9 is in 1997 NL1 trials.

Two sister selections of the line derived from (Bardsey x Rosette) x Lustre (Table 13) are currently showing exceptional promise and have been entered into 1997 NL1 trials. One selection has been named **Millennium.**

Major progress has also been made in selecting dwarf oats. Following on from the encouraging results obtained for lines containing the DW6 dwarf gene (Tables 14 and 15), two dwarf winter oats (one husked and one naked) are at the Seed Purification stage.

Naked winter oats (Tables 17-20) accounted for nearly 7% of the certified winter oat seed produced in 1996. A new generation of naked oats have emanated from the project. Both the winter oats **Krypton** (deferred from 1996) and **Lexicon** were added to the most recent UK Recommended List. Krypton has already ousted Kynon as the No. 1 naked oat. It is 11% higher-yielding than Kynon in fungicide-treated trials and a massive 18% higher-yielding in untreated trials. The latter figure is very close to the yield advantage of Krypton (17.4%) presented in Table 17 for breeders' trials between 1992 and 1994. Krypton has excellent resistance to mildew and crown rust. It has tall straw but similar lodging resistance to Image. Lexicon (86-142CnIII/3) has similar yield and disease resistance, but is slightly shorter. **Harpoon**, a naked oat with large grains, has been transferred from category P (provisionally recommended for general use) to category G (fully recommended for general use).

The naked spring oat **Bullion** (10730Cn in Tables 21-24) was also added to the UK Recommended List. This variety is 7% higher-yielding than Rhiannon in fungicide-treated trials and 13% more in untreated trials. Moreover, it has far better expression of nakedness, about 98% compared to Rhiannon. **Neon** has been transferred to category G.

The higher yield of these varieties is a very significant boost to the economics of growing naked oats and their penetration into further markets.

One of the least successful areas of progress has been the improvement of winter-hardiness in order to improve stability of the crop and extend its range. Winter conditions have not been severe enough to select for high winter-hardiness and retrieval of yield has been accompanied by a general erosion of winter-hardiness. In the 1995-96 USDA Uniform Winter-Hardiness Nursery sown in 16 locations in USA and four European locations, one line (91-254Cn3) did reasonably well (ranked 12^{th}, mean survival = 61.5%) compared to the best entry (mean survival = 70.3%) and its recurrent parent, 76-17Cn17/2 (ranked 22^{nd}, mean survival = 45.7%). This and other lines have been recycled within the winter oat programme. At the same time, we are introducing new genetic variation and examining fresh ways, such as gene mapping, of tackling the problem.

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APPENDIX

Table 1 Results of winter-hardiness tests and artificial freezing test 1992/93

	Selection	Pennsylvannia USA 0-9 9=hardy	Landskrona Sweden 1-10 10=hardy	Artificial freezing test LD50	-9°	-10°	-11°	-12°
(a)	Controls							
	Solva	7.7	4	-11.2	90	100	65	15
	Image	7.3	2					
	Craig	7.0	3					
	Mirabel	7.7	5					
	Bulwark	5.3	3	-10.0	80	50	30	0
(b)	Primary genetic sources							
	Ky77-177	9.0	4	-12.2	100	90	80	65
	Ky78-443	4.7	2					
	Pennwin	9.0	5	-12.8[1]	100	100	100	85
(c)	Cycle 1 lines							
	81-62CnW/2	8.7	6	-14.1	90	85	80	70
	81-87Cn15/1/1	9.0	7	-9.7	85	90	0	0
	81-87CnW/14	8.3	9	-11.1	95	80	55	25
	83-48Cn2/1	9.0	5	-10.8	100	90	30	10
(d)	Cycle 2 lines (advanced lines)							
	86-74CnV/1/1	8.3	5	-10.6	90	75	50	0
	87-142CnI/1	8.3	4	-9.4	60	35	20	0
	87-142CnII/1	9.0	6	-9.8	80	40	15	0
	87-142CnII/2	9.0	5	-10.1	90	60	15	0
	87-144CnV/1	8.7	4	-10.6	90	75	45	5
	87-119CnV/1	9.0	7	-9.1	55	10	0	0
	87-130CnIV/1	9.0	6	-10.8	90	85	55	5
	87-130CnV/1	8.3	7	-10.6	90	60	65	0
	87-132CnII/1	8.0	7	-12.1	95	95	80	50
	87-132CnV/3	8.7	5	-11.3	80	70	85	20
	87-139CnIII/1	8.7	8	-10.9	85	85	50	15
	87-141CnI/2	8.3	7	-9.9	75	40	30	5
	87-141CnIII/2	8.0	4	-11.2	95	90	40	35
	87-142CnV/1	8.7	6	-10.2	75	60	40	5
(e)	Cycle 2 lines (F4)							
	89-128Cn1 15706	8.0	5	-10.8	90	75	50	15
	89-128Cn2 15708	4.0	4	-10.4	90	40	50	15
	89-128Cn3 15718	7.7	2	-10.0	65	65	20	10
	89-128Cn4 15758	6.3	3	-10.8	75	80	40	25
	89-128Cn5 15762	5.3	4	-9.6	55	55	55	10
	89-137Cn2 15848	8.0	2					
	89-137Cn3 15857	8.3	3					
	89-137Cn4 15867	8.0	3					
	89-137Cn5 15871	8.3	1					
	89-137Cn6 15887	7.7	3					
	89-137Cn7 15890	8.7	2					
	89-138Cn1 15914	7.7	2					
	89-138Cn2 15918	8.7	3					

	89-138Cn3	15926	8.7	3						
	89-139Cn1	15946	8.0	1						
	89-139Cn2	15983	7.0	2						
	89-139Cn3	15992	7.3	3						
(f)	Cycle 1 lines (based on Pa 7617-3460 etc)									
	89-148Cn1	16371	5.0	1	-10.0	60	60	40	10
	89-149Cn1	16391	7.7	3	-9.5	65	25	45	15
	89-149Cn2	16393	5.0	4	-8.9	35	10	10	0
	89-149Cn3	16429	7.3	4	-9.8	75	45	20	0
	89-149Cn4	16434	7.3	3	-9.4	60	30	15	0
	89-150Cn1	16446	5.3	1	-10.6	90	65	40	15
	89-150Cn2	16453	7.3	2	-10.4	80	55	45	15
	89-152Cn1	16481	7.3	3	-11.2	70	80	65	25
	89-152Cn2	16487	8.3	5	-10.4	70	55	55	15
	89-152Cn3	16512	8.3	6	-10.4	80	50	45	20
	89-153Cn1	16523	8.0	4	-10.3	75	40	60	15
	89-153Cn2	16540	7.3	4	-10.2	70	65	35	10
	89-153Cn3	16543	7.7	3	-9.7	50	45	10	25
	89-153Cn4	16550	7.3	4	-10.6	95	70	30	15
	89-154Cn1	16568	6.0	3	-9.3	60	30	5	0
	89-154Cn2	16571	7.3	4	-9.6	80	20	20	0
	89-154Cn3	16579	6.7	4	-10.5	95	70	30	5
	89-156Cn1	16666	7.0	3	-9.2	60	15	10	0
	89-156Cn2	16687	5.0	3	-9.3	60	25	25	0
	89-156Cn3	16693	5.3	4	-9.3	75	0	10	0
	89-156Cn4	16695	7.0	7	-9.8	85	15	30	10
	89-156Cn5	16704	6.7	4	-8.0	15	5	0	0
(g)	New genetic sources								
	Pa 7617-3460				-12.6	100	100	95	75
	Pa 8014-840				-14.3[1]	100	100	90	90
	Pa 8019-1				-12.1	70	90	80	35
	Pa 8115-40				-13.0[1]	100	100	100	90

[1] slope not significantly different from zero

APPENDIX

Table 2 Results of winter-hardiness tests 1994/95

Selection	Pennsylvannia USA 0-9
Solva	0.7
Image	0.7
Bulwark	0
Gerald	0
Ky 77-177	73.3
Ky 78-443	55.0
Pennwin	52.3
81-62CnW/2	14.0
81-87Cn15/1	3.3
81-87CnW/14	35.0
83-48Cn2/1	33.3
87-119CnII/1	0.7
87-142CnII/1	0
87-132CnII/1	21.7
87-130CnV/1	0.3
Pa 8014-840	75.0
Pa 8115-40	3.0
Fringante	0
89-115Cn4/1	0
89-115Cn4/2	0.3
89-116Cn1	15.7
89-152Cn2/1	0
89-153Cn1	0
Cycle 2 F4 selections	
90-4Cn1	0
90-4Cn3	2.7
90-38Cn2	0
90-39Cn2	0
90-119Cn1/1	0
90-119Cn1/2	0
90-120Cn1	0
90-121Cn1	0
90-121Cn2/1	0
90-121Cn2/2	0
90-121Cn4/1	0
90-121Cn4/2	1.7
90-121Cn5/1	0
90-121Cn5/2	0
90-121Cn6/1	0
90-121Cn6/2	0

90-121Cn7/1	0
90-121Cn7/2	1.7
90-122Cn1	0
90-122Cn2	0
90-124Cn1	0
90-124Cn2	5.7
90-124Cn7	0
90-124Cn8	0
90-125Cn1	6.7
90-125Cn2/1	0
90-125Cn2/2	0
90-128Cn1	0
90-128Cn2/1	0
90-128Cn2/2	0
90-130Cn1	0
90-130Cn2	0
90-130Cn3	0
90-133Cn2	0
90-133Cn5	0
90-133Cn6	0
90-40Cn1	0
Cycle 2 F3 selections	
91-21Cn1	7.3
91-21Cn2	3.0
91-43Cn1	10.0
91-43Cn2	0
91-45Cn1	1.7
91-46Cn1	0
91-46Cn2	0
91-47Cn1	0.7
91-47Cn2	4.0
91-47Cn3	0.7
91-47Cn4	0.7
91-48Cn1	0
91-124Cn1	0
91-126Cn1	0
Cycle 3	
91-254Cn1	5.3
91-254Cn2	4.7
91-254Cn3	25.0
91-254Cn4	0.7
91-254Cn5	7.3
91-254Cn6	29.0
91-254Cn7	6.7
91-258Cn1	15.0
91-258Cn2	5.0

91-259Cn1	6.7
91-259Cn2	0
91-259Cn3	0
91-259Cn4	5.0
91-259Cn5	1.7
91-259Cn6	0.7
91-259Cn7	0
91-259Cn8	0
91-260Cn1	0
91-260Cn2	0.7
91-260Cn3	0
91-260Cn4	0.3
91-261Cn1	6.7
91-261Cn2	0.7
91-261Cn3	0
91-261Cn4	21.7
91-261Cn5	5.3