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The influence of variety, year, disease control and plant growth regulator application on crop damage, yield and quality of winter oats (*Avena sativa*)

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SUMMARY

Yield, straw length, ripening, damage, grain composition and quality were determined on seven winter oat varieties included in trials grown in Northern Ireland between 1990 and 2000. Three management regimes were applied to the varieties in each year: (1) with fungicide but without plant growth regulator applications (+F−PGR); (2) with plant growth regulator and fungicide applications (+F+PGR); and (3) with neither fungicide nor plant growth regulator applications (−F−PGR). Disease control significantly improved yield, kernel content and the proportions of groats above 2·0- and 2·2-mm sieves but delayed ripening and increased the content of free kernels. Application of chlormequat significantly reduced straw length and the content of empty husks and increased the content of good oats but reduced kernel content. Specific weight, grain weight and the proportions of grain above 2·0- and 2·2-mm sieves were not significantly affected by either control of disease or application of chlormequat.

The combined effects of disease control and chlormequat significantly reduced leaning and brackling while lodging was reduced but not significantly. Rather than an increased incidence following disease control which was reduced by application of chlormequat, the two management strategies resulted in similar small incremental reductions in straw damage. In years with severe straw damage lower specific weight, grain weight and kernel content may have been attributable to the damage but quality was also poor in some years when there was little damage. Grain and groat size were only poor in those years when severe lodging or brackling occurred.

Year had the greatest influence on most characteristics and variety to a lesser extent. Disease control and to a lesser extent chlormequat application had smaller effects on fewer characteristics. While the effect of disease control on yield is of economic significance, the effect of chlormequat appears to be mainly of psychological significance.

INTRODUCTION

Oats, like wheat and barley, are detrimentally affected by lodging. Yields are reduced, harvesting is more difficult and prolonged, the poorly filled grain may have higher moisture content, lower specific weight and it may even have sprouted and be discoloured due to pathogenic activity. There is a widespread perception that because oats are taller, they are weaker and although fewer plant growth regulators (PGRs) are registered for use on oats compared with wheat and barley, their use is considered essential to management particularly when growing for the quality milling market. However, the increasing emphasis on environmentally responsible agriculture and concern about residues in foodstuffs has generated questions about the need for PGRs on oats and the possibility of growing oats without PGRs.

Knowledge of how variety, management and environmental conditions influence yield, quality characteristics of oats and their need for and response

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to fungicides and growth regulators is more limited than for wheat and barley. However, in recent years a commercial breeding company, Semundo Ltd., has taken a lead in collating and publishing results from experimental work on oats in the UK for the benefit of growers. In their most recent publication, 'Oats in a new era' (Anon. 1999), use of growth regulators was discouraged on short stiff varieties such as Gerald which, it was stated, did not show a positive response to PGRs in trials. The benefit to naked oats and taller varieties such as Kingfisher from PGR application was confirmed. Laverick (1997), in the earlier booklet, 'Winter Oats Agronomy Review', jointly published with the Home-Grown Cereals Authority, reported on ADAS experiments from 1992–94 with the varieties Aintree, Image and Pendragon, a naked variety. Although positive responses to PGR application were not obtained at all eight sites, yield increases of up to 1·56 t/ha were measured in one experiment. Evidence was presented that the magnitude of the response was associated with the reduction in lodging achieved.

Specific weight, screenings (proportion of the grain by weight which passes through a 2·0-mm sieve) and soundness of the grain, as judged by smell, are the main criteria currently most widely used by UK and Irish millers in defining quality for milling and for determining price per tonne. In describing experiments in the 1980s with the older varieties, Pennal, Peniarth and Bulwark, Laverick (1997) commented that chlormequat significantly reduced individual grain weight on some occasions. Chlormequat reduced specific weight slightly, by less than 1 kg/hl. Where lodging occurred the detrimental effect of chlormequat was smaller. A second, later, application of Terpal (2-chloroethylphosphoric acid + mepiquat chloride) resulted in a further reduction in specific weight with no additional benefit for lodging control.

Oats can be infected by a large number of pathogens of various types including fungi, viruses, nematodes and insects. The most frequently occurring are mildew (*Erysiphe graminis* f.sp. *avenae*), crown rust (*Puccinia coronata* f.sp. *avenae*) and leaf blotch (*Leptosphaeria avenaria* f.sp. *avenaria* (syn. *Septoria avenae*)). Control of these diseases would be expected to result in yield increases. Laverick (1997) reported on many experiments in which positive yield responses to a range of fungicides were recorded. With the exception of feeding value for animals, effects on grain quality characteristics were not reported. The effects of disease control on lodging and other types of damage were not reported.

As for agronomic research, much less effort has also been put into the breeding of improved varieties of oats than for wheat and barley. This is evidenced by the numbers of varieties which have been entered for National List trials in the UK, 294 up to and including 2001, compared with 1455 for wheat and 1875 for barley (R. Fenwick, *pers. comm.*). Shorter-strawed oat varieties have been introduced relatively recently compared with wheat and barley leading to concern about use of PGRs on such varieties (Anon. 1999; J. Valentine, *pers. comm.*).

In the present paper the benefits of disease control and PGR application to yield, agronomic and quality characteristics of seven winter oat varieties are examined and compared over an 11-year period in Northern Ireland.

MATERIALS AND METHODS

Winter oat variety trials were conducted in Northern Ireland during each of 11 years between 1990 and 2000 as part of the UK Recommended List Trials System funded by the HGCA. The trials were conducted according to protocols agreed by the three testing authorities in the UK, NIAB, Cambridge, SAC, Edinburgh and the Department of Agriculture and Rural Development in Northern Ireland. The trials were located at the Plant Testing Station, Crossnacreevy, near Belfast. In each year, the varieties were grown under three regimes: (1) with fungicide (F) but without plant growth regulator applications (+F−PGR); (2) with plant growth regulator and fungicide applications (+F+PGR); and (3) with neither fungicide nor plant growth regulator applications (−F−PGR). Each regime comprised a separate trial with three replications, individual variety plots within each replication being 36 m^2 in area and 1·5 m wide with inter-plot spacings of 0·45 m.

Varieties were included in Recommended List trials because they were recommended or because they had been selected as candidates following inclusion in National List trials throughout the UK for a period of 2 years. They remained in trials as long as they continued to be recommended but if candidate varieties were not recommended, they were not included in subsequent trials. Therefore many varieties were only in trials for short periods of time. For the purposes of the present paper varieties have been selected for discussion which either were included in all or most years (Aintree, Image and Solva) and/or because they had particular features which distinguished them from the majority of other varieties. Aintree is early; Barra is grown for milling in the Republic of Ireland; Gerald is grown for milling in Northern Ireland and throughout the UK, having replaced Image; Jalna has gained a reputation for having good quality but erratic yields in more northerly and westerly parts of the UK; Kingfisher is very long-strawed yet without being excessively weak. Gerald was also the shortest-strawed variety included within this period, whilst Kingfisher was the tallest.

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Table 1. *Management of oat trials 1990–2000*

	Sowing date	Seed rate 1990–95/ Target plant population 1996–2000	Total N application (kg/ha)	P and K applications (kg/ha)	Harvest date
1990	12 Oct 1989	189 kg/ha	140	56 P, 113 K	6 Aug
1991	2 Nov 1990	189 kg/ha	160	56 P, 113 K	20 Aug
1992	24 Oct 1991	189 kg/ha	160	56 P, 113 K	Rnr*
1993	16 Oct 1992	189 kg/ha	140	66 P, 131 K	26 Aug
1994	16 Oct 1993	189 kg/ha	80	180 P, 180 K	30/31 Aug
1995	14 Oct 1994	189 kg/ha	140	89 P, 89 K	10 Aug
1996	21 Sep 1995	300 plants/m²	140	90 P, 90 K	30 Aug
1997	7 Oct 1996	300 plants/m²	140	90 P, 90 K	19 Aug
1998	21 Oct 1997	300 plants/m²	160	90 P, 90 K	−F−PGR 18 Aug +F−PGR 27 Aug +F+PGR 3 Sep
1999	15 Oct 1998	300 plants/m²	160	90 P, 90 K	11/12 Aug
2000	15 Oct 1999	300 plants/m²	160	90 P, 90 K	14/15 Aug

* Rnr, Record not recovered.

Details of sowing dates, seed rates, the total amounts of nitrogen, phosphate and potash applied and harvest dates for the trials are presented in Table 1. The active ingredients of the fungicides applied in the +F−PGR and +F+PGR regimes, their rates and dates of application are presented in Table 2. The fungicide programmes used were designed to keep incidences of all diseases below 0·05 (where 1 = infection of total leaf area). Severity of disease from year to year is shown by the infections on Image, which was included in all years, and the most severely infected variety if this was not Image (Table 3). The rates and dates of application of chlormequat chloride are presented in Table 4.

Straw length was measured at two points in each plot when the plants had reached their maximum height during grain filling. Crop damage was monitored frequently and assessed as the proportion (0–100) of the area of the crop affected by each type of damage either prior to harvest or earlier if present. Leaning is defined as deflection from the vertical by less than 45°, lodging as greater than 45° and brackling where buckling of the stem occurs at nodes more than 15 cm above the soil surface. Ripening in oats is difficult to determine by assessing the hardness of the grain because the husk is very stiff. Change of colour was therefore the method used and this was assessed on a 1–6 scale where 1 is early and 6 is late.

When all the varieties were mature the trials were harvested using a plot combine. Samples were retained for determination of moisture content, allowing yield at 850 g dry matter (DM)/kg to be calculated together with other quality characteristics. Following drying to 850 (±10) g DM/kg specific weight was determined on one sample from each plot using a chondrometer.

Grain weight, kernel content, grain composition and grain size were assessed manually using samples which had been bulked after drying to zero moisture content to determine moisture content of the harvested grain to give one sample per variety per trial. Grain weight was determined by counting and weighing two subsamples of 250 grains per variety. For the remaining characteristics two subsamples of 12 g per variety were drawn down. The proportions by weight of good oats, doubles, free kernels, empty husks, decayed grain and inert matter were determined by visual examination. From each of these two subsamples 150 good oats were retained for manual dehulling. Pressure applied at the base of each grain by the thumb was used to force the kernel out of the husk. The two fractions, i.e. hulls and kernels, were weighed and kernel content calculated as a proportion (g/100 g) of total weight. These two subsamples were also sieved both before and after dehulling to determine the proportions by weight passing through 2·0- and 2·2-mm sieves.

Throughout the period 1990–2000 the three trials were grown side by side and were managed identically with the exception of the fungicide and PGR treatments. However the lack of randomization of the three regimes does not permit differences between varieties in their response to the regimes or variation in the effect of the regimes from year to year to be tested statistically. Mean values for each variety in each year were used in the analyses of variance of the characteristics. Each regime was analysed separately using Genstat V. The significance of the effects of

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Table 2. *Fungicide treatments in oat trials 1990–2000*

	1st application	2nd application	3rd application	4th application
1990	1 l/ha propiconazole +tridemorph 28 Mar	1 l/ha propiconazole +tridemorph 4 Jun		
1991	1 l/ha propiconazole +tridemorph 26 Mar	1 l/ha propiconazole +tridemorph 23 May	1 l/ha propiconazole +tridemorph 17 Jul	
1992	1 l/ha fenpropimorph +0·9 l/ha prochloraz 27 Mar	1 l/ha triadimenol +tridemorph 20 May		
1993	1 l/ha fenpropimorph +0·9 l/ha prochloraz 29 Apr	1 l/ha triadimenol +tridemorph 4 Jun	1 l/ha triadimenol +tridemorph 21 Jun	
1994	1 l/ha fenpropimorph 19 Apr	1 l/ha fenpropimorph +0·9 l/ha prochloraz 9 May	1 l/ha triadimenol +tridemorph 10 Jun	1 l/ha triadimenol +tridemorph 28 Jun
1995	1 l/ha fenpropimorph 22 Mar	1 l/ha fenpropimorph +0·9 l/ha prochloraz 10 Apr	1 l/ha triadimenol +tridemorph 2 Jun	1 l/ha triadimenol +tridemorph 20 Jun
1996	1 l/ha triadimenol +tridemorph 22 Nov 1995	1 l/ha fenpropimorph 31 Jan	0·5 l/ha propiconazole +0·75 l/ha fenpropimorph 2 May	1 l/ha triadimenol +tridemorph 4 Jun
1997	1 l/ha fenpropimorph 12 Mar	0·5 l/ha propiconazole +0·75 l/ha fenpropimorph 16 Apr	1 l/ha triadimenol +tridemorph 30 May	
1998	0·5 l/ha propiconazole +0·75 l/ha fenpropimorph 19 May	0·5 l/ha triadimenol +0·5 l/ha tridemorph 3 Jun	0·5 l/ha triadimenol +0·5 l/ha tridemorph 22 Jun	
1999	0·33 l/ha cyproconazole +1·5 l/ha fenpropimorph +quinoxyfen 7 May	0·33 l/ha cyproconazole 8 Jun		
1999 +F+GR	0·3 l/ha quinoxyfen 17 May	0·3 l/ha quinoxyfen 3 Jun		
2000	0·33 l/ha cyproconazole +1·5 l/ha fenpropimorph +quinoxyfen 21 Apr	0·33 l/ha cyproconazole 22 May	0·5 l/ha triadimenol 13 Jun	

years and varieties were determined using the years × varieties interaction mean square as the residual term in the analysis. The significance of the effects of the three regimes was determined using the means of the seven varieties in each year and the years × regimes interaction mean square as the residual term in the analysis.

RESULTS

The influence of year and the differences between varieties in their characteristics are discussed using the results from the +F−PGR regime.

Yield, straw length and ripening

Yields in the +F−PGR regime across years varied between 6·7 and 8·5 t/ha at 850 g DM/kg (S.E. mean ± 0·22, $P<0·001$) (Table 5). Yields of the varieties in the +F−PGR regime varied between 6·7 t/ha in Jalna and 8·1 t/ha in Aintree (S.E. mean ± 0·18, $P \leqslant 0·001$) (Table 5). PGR application did not significantly affect yield (Table 6). Disease control resulted in a significant yield increase of 1·2 t/ha (S.E. mean ± 0·09, $P<0·001$) (Table 6).

Straw length varied between 112 and 151 cm across years in the +F−PGR regime (S.E. mean ± 2·09, $P<0·001$) (Table 5). Gerald, 121 cm, was the shortest

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Table 3. *Levels of infection (proportion of leaf area on a 0–1 scale) on Image with details in parentheses of the most severely infected variety if other than Image*

	Mildew	Crown rust	*Septoria avenae*
1990	0·40	Slight (i.e. <0·001)	No infection
1991	0·10	No infection	Slight
1992	0·17 (Gerald 0·37)	0·05 (Gerald 0·07)	No infection
1993	0·15 (Aintree 0·20)	0·04 (Gerald 0·06)	No infection
1994	No infection	0·00 (Solva 0·02)	Slight
1995	0·37 (Barra 0·37)	No infection	0·05 (Barra 0·15)
1996	0·13 (Barra 0·24)	Slight	0·02 (Gerald 0·04)
1997	0·33 (Barra 0·58)	Slight	0·37 (Barra 0·40)
1998	0·14 (Barra 0·18)	0·17	0·13 (Aintree 0·15)
1999	0·00 (Barra <0·001)	Moderate	<0·001 (Barra 0·01)
2000	0·02 (Barra 0·19)	0·27	0·13

Table 4. *Plant growth regulator treatments in oat trials 1990–2000*

Year	Treatment	Date
1990	2·5 l/ha Cycocel	3 May
1991	2·5 l/ha Cycocel	23 May
1992	2·5 l/ha Cycocel	20 May
1993	2·5 l/ha Cycocel	20 May
1994	2·3 l/ha Chlormequat 700	9 May
1995	2·3 l/ha Chlormequat 700	15 May
1996	2·3 l/ha Chlormequat 700	10 Apr
1997	2·3 l/ha Chlormequat 700	16 Apr
1998	2·3 l/ha Chlormequat 700	19 May
1999	2·3 l/ha Chlormequat 700	17 May
2000	2·3 l/ha Chlormequat 700	2 May

variety and Kingfisher, 140 cm, the tallest (S.E. mean ±1·67, $P<0·001$) (Table 5). PGR application significantly reduced height by 12·7 cm (S.E. mean ± 1·33, $P<0·001$) (Table 6). When disease was controlled, straw length was slightly, 2·4 cm, but not significantly longer (Table 6).

Ripening varied from year to year, being earlier in 1993 and 1997 and later in 1994 (S.E. mean ±0·35, $P<0·001$) (Table 5). Such differences may be circumstantial, as the score is relative and depends on the range in ripening amongst all the varieties in the trials which showed some variation from year to year. Despite this, comparisons between the varieties are valid. Aintree was the earliest variety to ripen, Barra, Image and Jalna were intermediate and Solva, Gerald and Kingfisher later to ripen (S.E. mean ±0·28, $P<0·001$) (Table 5). Ripening was delayed by disease control but PGR had no effect (S.E. mean ±0·09, $P=0·01$) (Table 6).

Crop damage

Leaning in the +F−PGR regime varied between 0 and 11 (where 100 = leaning of the total area) across years (S.E. mean ±1·80, $P \leqslant 0·001$) (Table 7). Gerald had least leaning, less than 1, and Aintree and Barra most, 5·4–5·7 (S.E. mean ±1·44, P=NS) (Table 7). Disease control reduced leaning by 2 and PGR application by a further 2 (S.E. mean ±0·71, $P=0·002$) (Table 6).

Lodging was greater than 1 in only 3 years in the +F−PGR regime, 1992, 1996 and 1997 (S.E. mean ±3·06, $P<0·001$) (Table 7). Incidences of

Table 5. *The influence of year and variety on yield, straw length and ripening in the +F−PGR regime*

	Yield (t/ha at 850 g/kg dry matter)	Straw length (cm)	Ripening (1–6, where 1 = early)
1990	7·17	121·3	N/A
1991	7·79	124·8	N/A
1992	7·77	112·0	3·5
1993	7·53	148·0	2·5
1994	7·25	116·5	4·9
1995	7·76	132·6	N/A
1996	7·97	151·1	3·7
1997	7·40	143·8	2·2
1998	6·67	120·3	3·2
1999	7·04	133·5	N/A
2000	8·53	136·5	3·9
Aintree	8·09	128·7	1·8
Barra	7·30	131·3	2·7
Gerald	7·86	120·7	4·3
Image	7·46	132·0	2·9
Jalna	6·68	127·3	3·2
Kingfisher	8·05	140·3	4·8
Solva	7·32	136·3	4·0
S.E. mean			
Years	0·223	2·09	0·35
Varieties	0·178	1·67	0·28
D.F.	36	36	23

N/A: Ripening was not recorded in 1990, 1991, 1995 and 1999.

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Table 6. *Effect of chlormequat application and disease control on yield, agronomic quality and grain characteristics (means of seven varieties and 11 years)*

	+F−GR	+F+GR	−F−GR	S.E. mean	D.F.
Yield (t/ha at 850 g/kg dry matter)	7·53	7·67	6·70	0·086	20
Straw length (cm)	131·0	118·3	128·6	1·33	20
Leaning (proportion of plot area affected, 0–100 scale)	3·64	1·64	5·79	0·705	20
Lodging (proportion of area, 0–100 scale)	3·8	3·0	7·0	1·82	20
Brackling (proportion of area, 0–100 scale)	8·8	3·7	15·1	2·33	20
Ripening	3·4	3·3	2·9	0·09	12
Specific weight (kg/hl)	47·9	48·0	47·4	0·34	20
Grain weight (mg)	34·0	33·3	32·6	0·47	20
Kernel content (g/100 g)	76·8	76·0	75·8	0·190	19
Good oats (g/100 g)	91·2	93·1	92·2	0·41	18
Doubles (g/100 g)	0·55	0·46	0·52	0·149	18
Free kernels (g/100 g)	3·44	2·97	2·42	0·231	18
Empty husks (g/100 g)	3·25	1·96	3·03	0·225	18
Decayed grain (g/100 g)	0·42	0·47	0·35	0·065	18
Inert matter (g/100 g)	1·28	1·04	1·47	0·130	18
Grain (g/100 g) <2·2 mm	13·5	15·2	17·2	1·398	16
Grain (g/100 g) <2·0 mm	4·12	4·80	5·23	0·558	16
Groats (g/100 g) <2·2 mm	55·1	57·3	63·9	1·84	16
Groats (g/100 g) <2·0 mm	17·1	17·8	22·0	1·41	16

Table 7. *The influence of year and variety on incidences of crop damage in the +F−PGR regime*

	Leaning (proportion of plot area affected, 0–100 scale)	Lodging (proportion of area, 0–100 scale)	Brackling (proportion of area, 0–100 scale)
1990	1·95	0	0
1991	8·05	0	25·4
1992	0·95	3·8	51·5
1993	7·63	0	12·9
1994	2·20	0	1·5
1995	2·40	0	0·2
1996	3·72	7·55	1·8
1997	11·3	27·69	3·3
1998	1·43	0·24	0·2
1999	0	0·99	0
2000	0·40	0·99	0
Aintree	5·77	4·25	21·1
Barra	5·44	0	10·2
Gerald	0·67	0·69	2·1
Image	3·18	7·73	8·5
Jalna	4·54	0	8·4
Kingfisher	3·04	2·23	9·2
Solva	2·75	8·84	0
S.E. mean			
Years	1·80	3·06	5·96
Varieties	1·44	2·44	4·75
D.F.	36	36	36

lodging were less than 10 in all varieties, being lowest in Barra and Jalna, which had none, and Gerald, and highest in Image and Solva (S.E. mean ± 2·44, $P<0·02$) (Table 7). PGR application and disease control did not have significant effects on lodging (S.E. mean ± 1·82, $P=$ NS) (Table 6).

Brackling showed a very different pattern of incidence from year to year when compared with leaning and lodging, being most severe in the +F−PGR regime in 1991, 1992 and 1993 and with less than 5 in the other years (S.E. mean ± 6·0, $P<0·001$) (Table 7). Brackling was most severe in Aintree and least severe in Solva, which had none, and Gerald (S.E. mean ± 4·8, $P=$ NS) (Table 7). Since brackling occurs as the crop matures, this type of damage may have been most severe in Aintree because it was the earliest variety to ripen and therefore would have been prone to brackling over a longer period than the other varieties. PGR application reduced brackling by 5 and disease control by 6 (S.E. mean ± 2·3, $P=0·01$) (Table 6).

Linkage between straw length and incidences of damage was not apparent amongst the varieties. Although Gerald had the shortest straw and low incidences of both leaning and lodging, Barra, which was most resistant to lodging in these trials, had straw of similar length to that of Solva and Image which had the highest incidences of lodging. Some linkage between straw length and incidences of damage across years is apparent. Lodging was most severe in

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1996 and 1997 in both of which the crops were tall. However, in 1993 when the crops were also tall there was little lodging, and brackling was most severe in 1992 when the crops were short.

Specific weight, grain weight and kernel content

Specific weight varied between 41·9 and 54·4 kg/hl across years in the +F−PGR regime (S.E. mean ± 0·70, $P<0·001$) (Table 8). Barra had the highest specific weight of 50·8 kg/hl, almost 2 kg/hl higher than those of Gerald and Image (S.E. mean ± 0·53, $P<0·001$) (Table 8). Jalna and Solva had low specific weights of 45·8 and 45·7 kg/hl, giving a range of 5 kg/hl amongst these seven varieties. PGR application and disease control had very little effect on specific weight, less than 0·5 kg/hl (S.E. mean ± 0·34, $P=$NS), a much smaller range than that of 12·5 kg/hl found across the 11 years of trials (Table 6).

Grain weight varied between 29·9 and 38·2 mg across years in the +F−PGR regime (S.E. mean ± 0·79, $P<0·001$) (Table 8). Kingfisher and Solva had the largest grain, *c.* 37 mg, and Aintree the smallest, 28·4 mg, with Barra also producing small grain (S.E. mean ± 0·63, $P<0·001$) (Table 8). PGR application and absence of disease control decreased grain weight slightly but not significantly, by 0·7 mg and 1·4 mg respectively (S.E. mean ± 0·47, $P=$NS) (Table 6).

Kernel content varied between 75·2 and 77·8 g/100 g across years in the +F−PGR regime (S.E. mean ± 0·38, $P<0·001$) (Table 8). Jalna had the highest kernel content, 79·1 g/100 g, and Aintree and Gerald the smallest of 74·7–74·9 g/100 g (S.E. mean ± 0·30, $P<0·001$) (Table 8). PGR application and disease control decreased kernel content slightly but significantly, 0·8 g/100 g and 1·0 g/100 g respectively (S.E. mean ± 0·19, $P=0·01$) (Table 6).

The extent of variation in kernel content both between years and in response to disease control and PGR application was much smaller than that in either specific weight or grain weight.

Grain composition

Grain lots of oats comprise a number of fractions: good oats, doubles (where the primary grain fails to develop and encloses the secondary grain), free kernels, empty husks, decayed grain and inert matter. Maximizing the good oats content is economically desirable as the other fractions detract from extract yield.

The good oats content varied between 85·9 and 94·8 g/100 g of the entire oat lot across years in the +F−PGR regime, with this being greater than 90 g/100 g in all but 3 years (S.E. mean ± 1·35, $P<0·001$) (Table 9). Jalna had a smaller good oats content, 84·0 g/100 g, than the other varieties which varied between 89·5 and 93·9 g/100 g (S.E. mean ± 1·08, $P \leq 0·001$) (Table 9). PGR application and disease control increased good oats slightly, by less than 2·0 g/100 g, but nevertheless significantly (S.E. mean ± 0·41, $P=0·02$) (Table 6).

Table 8. *The influence of year and variety on specific weight, grain weight and kernel content in the +F−PGR regime*

	Specific weight (kg/hl)	Grain weight (mg)	Kernel content (g/100 g)
1990	50·3	35·0	76·3
1991	50·6	30·6	76·5
1992	47·6	32·0	78·0
1993	47·4	32·4	78·5
1994	47·0	35·6	77·8
1995	48·0	36·1	77·1
1996	46·0	29·9	75·2
1997	43·6	34·2	75·9
1998	41·9	35·1	76·4
1999	49·9	38·2	76·4
2000	54·4	35·1	76·7
Aintree	46·9	28·4	74·7
Barra	50·8	31·9	78·0
Gerald	49·1	34·8	74·9
Image	48·9	34·2	77·1
Jalna	45·8	35·4	79·1
Kingfisher	48·0	36·8	77·5
Solva	45·7	36·5	76·4
S.E. mean			
Years	0·70	0·79	0·38
Varieties	0·56	0·63	0·30
D.F.	36	36	36

Free kernels were less than 5 g/100 g in 10 of the 11 years in the +F−PGR regime but in 1990 free kernels comprised, on average, 11 g/100 g of the grain lot (S.E. mean ± 0·49, $P<0·001$) (Table 9). It is clear that free kernels are a particular problem in some years. Solva had the highest content of free kernels, 5·2 g/100 g, and Aintree, with 1·5 g/100 g, the lowest (S.E. mean ± 0·39, $P<0·001$) (Table 9). PGR application and disease control decreased the proportion of free kernels slightly, by less than 1 g/100 g, but significantly (S.E. mean ± 0·23, $P=0·02$) (Table 6).

Empty husks comprised between 1·4 and 6·1 g/100 g of the grain in the +F−PGR regime across years (S.E. mean ± 0·91, $P=0·01$) (Table 9). Jalna had much greater contents of empty husks, 10·3 g/100 g, than other varieties, which varied between 0·7 and 3·4 g/100 g (S.E. mean ± 0·72, $P<0·001$) (Table 9).

Contents of doubles, decayed grain and inert matter were all less than 3 g/100 g in all years in the +F−PGR regime (Table 9). None of the varieties had more than 1·5 g/100 g doubles (S.E. mean ± 0·45, $P=0·01$), 1 g/100 g decayed grain (S.E. mean ± 0·31, $P=$NS) or 2 g/100 g inert matter (S.E. mean ± 0·22, $P=0·004$) (Table 9). The effects of PGR application

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Table 9. *The influence of year and variety on grain composition of winter oats in the +F−PGR regime*

	Good oats (g/100 g)	Free kernels (g/100 g)	Doubles (g/100 g)	Empty husks (g/100 g)	Decayed grain (g/100 g)	Inert matter (g/100 g)
1990	85·9	11·04	0	2·83	0·16	0·63
1991	94·4	2·68	0	2·11	0·29	0·60
1992	94·8	1·65	1·02	1·36	0·59	0·50
1993	93·1	2·95	0	2·58	0·16	1·37
1994	92·6	2·59	0	2·97	0·75	1·43
1995	90·4	5·00	0	3·62	0·19	1·14
1996	96·0	1·08	0	2·13	0·02	1·06
1997	91·1	2·82	0·89	2·55	0·72	1·93
1998	88·3	2·24	1·15	6·13	0·59	1·66
1999	88·0	2·84	2·33	3·75	1·09	2·44
2000	89·4	2·92	0·62	5·67	0·05	1·35
Aintree	92·3	1·5	1·44	3·4	0·20	1·20
Barra	93·3	3·1	0·98	0·7	0·57	1·47
Gerald	93·9	2·9	0·08	1·9	0·64	0·84
Image	92·2	3·3	0·96	2·1	0·47	0·99
Jalna	84·0	4·3	0	10·3	0·11	1·83
Kingfisher	93·7	4·0	0	1·6	0·55	0·80
Solva	89·5	5·2	0·51	2·6	0·40	1·86
S.E. mean						
Years	1·35	0·49	0·56	0·91	0·40	0·28
Varieties	1·08	0·39	0·45	0·72	0·32	0·22
D.F.	36	36	36	36	36	36

and disease control on these fractions were small and non-significant (Table 6).

Grain and groat size

Millers check 'screenings' of oat lots at the point of purchase as material smaller than 1·5 mm is removed during milling and constitutes a reduction in extract yield. Cleaning of oat lots can benefit the grower as removal of smaller grains, etc. will reduce the penalties which could be incurred on sale to millers. Size of the grains also affects the milling process as the oats are separated into two or more streams based on grain size during milling to improve milling efficiency. Size of the groats produced can influence the type of product for which the oat lot is used. An indication of grain and groat size can be obtained from weighing the fractions passing through 2·0 and 2·2 mm sieves.

The proportions of grains passing through the 2·2 mm sieve varied between 3·6 and 31·2 g/100 g across years in the +F−PGR regime (S.E. mean ± 2·95, $P<0·001$) and between 0·7 and 12·2 g/100 g through the 2·0-mm sieve (S.E. mean ± 1·27, $P=0·02$) (Table 10). Aintree had the highest proportions of grain passing through both sieves and Barra the lowest (<2·2 mm: S.E. mean ± 2·36, $P<0·001$; <2·0 mm: S.E. mean ± 1·02, $P=0·02$) (Table 10). PGR application and disease control had small non-significant effects, increasing and decreasing, respectively, these proportions by less than 5 g/100 g (S.E. mean ± 1·4, $P=$NS) and 2 g/100 g (S.E. mean ± 0·6, $P=$NS) for the 2·2- and 2·0-mm sieves respectively (Table 6). The effects of environmental conditions were much larger than PGR application or disease control as shown by the extent of variation from year to year in these fractions (Tables 6 and 10).

The proportions of groats passing through the 2·2-mm sieve varied between 40·5 and 82·3 g/100 g across years in the +F−PGR regime (S.E. mean ± 4·47, $P<0·001$) and between 6·6 and 43·5 g/100 g through the 2·0-mm sieve (S.E. mean ± 3·58, $P<0·001$) (Table 10). As with the grain Aintree had the highest proportions of groats passing through both sieves and Barra had the lowest (<2·2 mm: S.E. mean ± 3·57, $P<0·001$; <2·0 mm: S.E. mean ± 2·85, $P<0·001$) (Table 10). PGR application resulted in smaller groats and disease control in significantly larger groats (<2·2 mm: S.E. mean ± 1·84, $P=0·01$; <2·0 mm: S.E. mean ± 1·41, $P=0·05$) (Table 6).

DISCUSSION

Incidences of lodging

In the current programme lodging was never catastrophic and could only be considered severe in 2 years, 1996 and 1997, giving a frequency of 2 years/decade. Yields and straw lengths were not uniquely high in

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Table 10. *The influence of year and variety on grain and groat size in the +F−PGR regime*

	Grain <2·2 mm (g/100 g)	Grain <2·0 mm (g/100 g)	Groat <2·2 mm (g/100 g)	Groat <2·0 mm (g/100 g)
1990	N/A	N/A	44·5	6·6
1991	15·0	3·42	70·5	20·3
1992	31·2	12·17	63·8	30·0
1993	9·6	3·62	40·5	12·3
1994	7·4	1·89	44·0	10·0
1995	7·4	1·29	48·2	10·3
1996	29·9	8·40	82·3	43·5
1997	11·5	3·23	56·6	21·4
1998	14·4	5·59	55·7	17·4
1999	3·6	0·70	50·2	7·2
2000	4·5	0·89	49·7	8·8
Aintree	28·4	7·73	89·4	37·4
Barra	7·6	2·52	42·0	9·0
Gerald	12·4	3·41	67·6	19·6
Image	12·5	4·64	46·6	16·4
Jalna	12·4	3·70	55·6	12·0
Kingfisher	12·4	3·33	45·2	14·4
Solva	8·5	3·52	39·3	10·8
S.E. mean				
Years	2·95	1·275	4·47	3·58
Varieties	2·36	1·017	3·57	2·85
D.F.	34	34	36	36

N/A: Characteristics were not recorded.

either 1996 or 1997. Similar frequencies of severe lodging of between 1 year/decade in Gerald and 4 years/decade in Image were recorded in SAC variety trials 1992–2001 (Cranstoun, *pers. comm.*). In both the programme being reported in this paper and the SAC programme, incidences of lodging were both less frequent and less severe than might have been expected in winter oats. In comparison, winter wheat is reported to suffer severe lodging every 3 to 4 years (Berry *et al.* 2002). Oats are more susceptible to brackling than wheat and in the present programme brackling was observed in varieties which were unaffected by lodging and occurred in years when lodging was not severe. Since brackling in oats can cause similar difficulties to lodging at harvest and can have similarly detrimental effects on grain condition the general perception that oats are very susceptible to lodging may be based on a much broader definition of damage which includes brackling.

It is also widely believed that crops with high yield potential are more likely to lodge. Although yield in terms of the weight of the ear/panicle is not explicitly included in the Berry *et al.* (1998) model of lodging, height of the centre of gravity does reflect the loading at the top of the shoot. In both the present programme and that of SAC (Cranstoun, *pers. comm.*), there were years when yields were high, 8·5 t/ha in 2000 in the present programme and 9·2–10·9 t/ha in 1996 in the SAC programme, and lodging was minimal. Chalmers *et al.* (1998), in a programme examining the effects of nitrogen fertilizer on yield and lodging of winter oats, also stated that yield was not related to the extent of lodging at individual sites. Therefore it would seem that, depending on weather conditions, high-yielding crops can be successfully grown without a proportionate accompanying incidence of lodging.

Lodging and disease control

With cereals the beneficial effect of disease control on yield usually necessitates the application of PGRs to offset the detrimental effects of an increased risk of lodging from the increased loading due to higher yields. In the present programme, increased height as well as increased yield resulting from disease control would have increased the risk of lodging yet crop damage was reduced when disease was controlled (Table 6). Characteristics of the crop shoot–root system involved in determining the risk of lodging may have benefited from additional photoassimilate being available as a result of disease control. For example, the anchorage provided by the root system may have been improved by increased production of roots when disease was controlled. Another possibility is that leverage of the shoot and plant as influenced by the

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radius, wall width and material strength of the stem may have been reduced when disease was controlled because of beneficial effects of greater amounts of photoassimilate on the size and structure of the cells of the stem internodes. Reduction or elimination of direct effects of pathogenic organs and tissues on the structural integrity of the plant cells and tissues may also have contributed to this response. A growth retarding effect of some triazole-type fungicides was reported by Rademacher (2000) but this was based on work done with seedlings rather than mature plants (Buchenauer & Röhner 1981; Saishoji *et al.* 1998). The conclusion of practical import from the present programme is that disease control was associated with the reduction of mechanical damage and further work is needed to determine causal factors.

Lodging and PGR application

PGRs are applied to crops primarily because of their benefits for control of lodging, with a positive effect on yield being the intended outcome. Overall, PGR application generally had small but non-significant beneficial effects on crop standing, taking all types of damage into account, but did not reduce damage completely (Table 6). Reduction in straw length is considered to be one of the major, if not the main, mechanisms by which chlormequat application results in a beneficial effect on lodging. The reduction in mean overall straw length of 13 cm was smaller than the decreases of up to 36 cm reported by Leitch & Hayes (1989). However, application of chlormequat does not always result in reduced straw length and therefore its effect on this characteristic may not always contribute to a reduction in the risk of lodging. Increase in straw length in response to chlormequat application has been observed in other experiments, for example Leitch & Hayes (1990) who, in their experiments with the winter variety Bulwark, found that some early applications resulted in increases in straw length. Compensatory growth was suggested as the mechanism but was not explained further by these workers.

The effects of chlormequat on characteristics of the crop shoot–root system other than height which are involved in determining the risk of lodging are beginning to be understood. Crook & Ennos (1995) reported that neither 5C Cycocel nor Terpal had an effect on bending strength of stems of wheat and that applied sequentially they actually reduced stem rigidity. Also working with wheat, Berry *et al.* (2000) commented that the effectiveness of the New 5C Cycocel was counteracted by an associated reduction in material strength of the basal internode. Thus there is evidence that effects of PGRs on some characteristics may increase the risk of lodging. Given the inherently greater height of oat plants compared with both wheat and barley and the different structure of the inflorescence (a panicle in oats and a spike in wheat and barley), detailed work is needed on the effects of agronomic factors on characteristics determining the risk of lodging in oats.

The results in the present programme show that chlormequat application is not always necessary when lodging does not occur, nor is it always effective when it does occur. Leitch & Hayes (1989) found that yield of winter oats was reduced on a number of occasions following chlormequat application. If avoidance of chlormequat application is considered desirable, then results of the present work suggest that sometimes, though not always, yield may be lost by not applying the PGR, and also that the effect on lodging is not indispensable.

Varieties

Yields of Aintree in the present programme were higher, Gerald lower and Jalna much lower than expected from their performances across the whole UK presented in the 1998 and 1999 Recommended Lists (Anon. 1997, 1998) (Table 5). The low yields of Barra in the present programme were in keeping with its performances in the Irish Recommended List, when, even in 1996, it was only 98 % of the controls (Anon. 1996). Straw lengths of the varieties in the present programme followed the same order as in the 1998 and 1999 UK Recommended Lists. Combining leaning (× 1/3) with lodging to give standing power produced values where Gerald had the strongest straw (0·9), Aintree intermediate (6·2) and Image weak (8·8) in keeping with their ratings in the 1998 UK Recommended List (Table 7). However, Solva had more total damage (9·7) than Image when it would have been expected to have been intermediate and similar to Aintree. On the other hand Kingfisher (3·3) and Jalna (1·5) had less total damage than expected from the ratings for their standing power on the 1999 UK Recommended List. The possibility that different types of lodging, i.e. stem and root lodging, occurred to differing extents in trials throughout the UK compared with trials in Northern Ireland was not examined in the current trial and cannot be ruled out. Given that brackling was more severe than both leaning and lodging in all varieties except Solva it may be necessary to include this type of damage in the calculation of standing power and in research and modelling of straw strength in oats.

Specific weights of the varieties in this programme were lower than those presented in the 1998 and 1999 UK Recommended Lists, which probably reflects differences in processing of the grain following harvest and before determination of specific weight (Table 8). Of greater significance are relative differences amongst the varieties, with Aintree, Jalna and Solva having lower specific weights than the other varieties when compared with the 1998 and 1999 UK

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Recommended Lists. On the other hand grain weights and kernel contents of all the varieties were higher in this programme than on the 1998 and 1999 UK Recommended Lists (Table 8). The amount of grain $<2{\cdot}0$ mm was much lower in this programme than on the 1998 and 1999 UK Recommended Lists and in particular Jalna did not have such high screenings relative to other varieties (Table 10). The analysis of grain composition showed that Jalna had high proportions of empty husks without accompanying free kernels (Table 9). This suggests that the kernels had been shed prior to harvest and this may account for lower yields in Jalna in this programme. The reason for the retention of the empty husks in the absence of the free kernels is not known and is surprising because in 1990 when free kernels were high compared with later years there was no accompanying increase in empty husks (Table 9).

Barra was notable in having no lodging although it had greater incidences of leaning and brackling than all other varieties except for Aintree. Despite having low yields it produced grain which had high kernel content, the highest specific weight and the smallest proportions of small grain, confirming its value for milling.

Quality

Chlormequat application (or non-application) had little or no effect on ripening and minimal effects on specific weight and grain weight. The detrimental effect of chlormequat application (or beneficial effect of non-application) on kernel content was small, less than 1 g/100 g. Grain composition was also minimally affected by chlormequat application (or non-application) with the exception of the good oats fraction which increased and empty husks which were reduced when chlormequat was applied. The effect of chlormequat application on grain size and groat size was negligible. This is surprising since there is a widespread perception that grain size is smaller and screenings are increased when PGRs are applied.

Surprisingly, although the beneficial effect of disease control on quality characteristics and grain composition was slightly larger than that of chlormequat application, it was still quite small. This was in contrast to its effect on yield, crop damage and grain size distribution, where the beneficial effects were large and unambiguous. A small effect of disease control on specific weight and grain weight and a large effect on yield were also found by Haigh & Bradshaw (1998) in experiments with winter and spring oats at three sites over 3 years.

Although, statistically, variation in the influence of PGR application and disease control from year to year cannot be determined from the results of the present study because of the design of the experiments, it is apparent that the influence of year is dominant compared with the small and relatively consistent effect of both disease control and PGR application. Although variety had large and consistent effects on most characteristics across the three regimes, the large effect of year on most characteristics could not be ameliorated by either management or variety and would affect profitability in terms of both yield and attainment of purchase standards for quality characteristics. The strong influence of environment found in the present programme is in agreement with conclusions drawn by Doehlert *et al.* (2001) from a study of 12 spring oat varieties grown at four sites over 3 years. They found that specific weight and kernel content, determined mechanically, were 'about equally' affected by environment and variety, based on mean squares from the Analysis of Variance. In their work, yield was more strongly influenced by environment than by variety. However disease was not controlled and variation in the incidence of crown rust was considered to be an important factor contributing to the variation observed. In the experiments conducted by Haigh & Bradshaw (1998), grain weight, but not specific weight, of winter oat varieties was found to vary between years.

Comparison of quality and grain characteristics in years when lodging was severe, 1996 and 1997, with the remaining years enables some development of understanding of the effects of lodging although these are confounded with weather and soil effects. Quality characteristics, namely specific weight, grain weight and kernel content, were lower when lodging was severe but were also low in some of the years when there was little or no lodging. For example, in addition to 1996 and 1997, specific weight was also low in 1998, grain weight in 1991 and kernel content in 1990, 1991, 1998 and 2000. Chalmers *et al.* (1998) found that grain weight was not related to the amount of lodging. In the present study there seemed to be no major detrimental effect of lodging on grain composition since proportions of doubles, free kernels, empty husks, decayed grain and inert matter were not higher in years when lodging occurred than in other years. Grain size was affected by lodging since in 1996, along with 1992 when brackling was most severe, greater proportions of smaller grains and groats were produced (Tables 7 and 10). Thus screening losses influencing sale price and output from the mill and management of the grain lot during milling, which is based on grain size, will be affected by lodging.

CONCLUSION

Variation in incidence of lodging between years was quite large and was only affected to small extents by variety, disease control and chlormequat application. Preventative action in the form of a PGR application will not therefore always be necessary. The need to identify crop characteristics which predispose crops

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to lodging remains an important goal for crop science research and the Berry *et al*. (1998) model is a useful way forward. Development of a predictive model allowing characteristics of the crop to be measured in the field early enough in the life cycle to enable the risk of lodging to be predicted is of vital importance (Easson *et al*. 1992; Berry *et al*. 1998).

Results from the present study indicate that it is possible to produce high yields from tall crops of oats without concurring severe crop damage. Chlormequat application, whilst producing a consistent straw shortening effect, had relatively few beneficial effects on agronomic and quality characteristics of the seven varieties included in the present analysis. Indeed, detrimental effects on kernel content would be of concern to the miller. However, given the widespread reliance on chlormequat application, confidence in growing oats without PGRs will need to be encouraged. More detailed experimental work using a wider range of active ingredients and varying rates, timings and combination of ingredients is also needed. Development of a prediction scheme assessing the risk of lodging at stages in the crop cycle when action such as reduction in application of nitrogen fertilizer could be taken would also encourage a move away from dependence on PGRs in oats.

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