

Determinants of Grain Size in Malting Barley

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Abstract

The influence of semi-dwarf genes, phenology, plant density and water supply on grain size of barley is being determined in a series of experiments in southeastern Australia.

Differences in the rate and duration of grain filling and in kernel weight have been measured in a range of tall and semi-dwarf genotypes. Cultivar differences occurred in grain weight and for the relative importance of rate versus duration of grain filling in achieving final grain weight. Genotypic ranking of these characteristics was consistent for sites in South Australia, Victoria and NSW. Two erectoid genotypes studied had small grain because of low grain filling rates despite long grain filling duration. Genotypes with a short stature from the ICARDA program in Mexico produced large grains, a result of both a high rate and long duration of grain filling (Yagan) or solely due to a high rate of grain filling (Kaputar). Known *sdw* genotypes were intermediate in all grain-filling characteristics, and similar to the standard height genotype Schooner. Franklin had the most variable grain filling characteristics of the *sdw* types, with short durations under harsh conditions. O'Connor differed from other genotypes by achieving high grain weight solely from a long grain filling period.

Large genetic differences were observed in grain numbers per spike, with genotypes with high numbers of grains per spike producing smaller grain size. Higher plant densities reduced grain numbers per spike but increased the variability in individual kernel grain weight as measured by a Single Kernel Characterisation System (SKCS). A strong association existed between the time for a genotype to reach the formation of awn primordia (maximum spikelet primordia) and the observed numbers of grains per spike at maturity.

Plant height at Condobolin amongst genotypes isogenic for a range of alleles for short stature and major phenological characteristics ranged from 53 to 96 cm, compared to 90 cm and 82 cm for the standard height recurrent parent Bowman and the control variety Schooner respectively. The seven tallest lines (> 80 cm) had kernel weights greater than 40 mg; only two lines shorter than 80 cm had kernels greater than 40 mg. These two exceptions carried either the *sdw-b* (40.1 mg) or *Ert-r* (44.8 mg) alleles and were 65 and 60 cm tall respectively; by comparison, Bowman and Schooner kernels averaged 41 mg. The kernel weight of the *sdw* isolate was 6.5% lower than Bowman in trials at Condobolin and Pinery. Confirmation that the *sdw* allele confers the short stature of the large grained variety Kaputar would indicate large grain size can be obtained by the use of this allele in an appropriate genetic background.

Introduction

Kernel size and uniformity are important determinants of malting quality. Both kernel size and shape influence water uptake and water distribution in the endosperm during germination and hence the rate and uniformity of malting. Small grains have low malt extract. Grain size

is under both environmental and genetic control. Under favourable grain filling conditions, there is less variation in grain size than in other yield components (Gallagher *et al.* 1975), as mobilisation of stem reserves and nitrogen can maintain grain filling under mild terminal stresses. However, in many Australian barley growing areas, periods of drought and high temperature frequently result in small grain and high screenings. Barley breeders therefore place major emphasis on selecting for large grain size.

The semi-dwarf character is associated with a number of traits that are important in barley cultivar improvement, namely, increased yield, greater straw strength and improved head retention. Four types of short stature barley has been described: *sdw*, brachytic, *uzu* and erectoide (Sears *et al.* 1981; Foster and Thompson 1987). The ICARDA program in Mexico has also developed germplasm with short stature, but unknown of genetic basis.

The *sdw* mutants are the short stature genes most widely used in Australian breeding programs. High yielding 2-row (Skiff and Tantangara) and 6-row (Yerong) cultivars have been released which are thought to incorporate the Vilticky (Haahr and von Wettstein 1976) and the Jotan (Mickelson and Rasmusson 1994) derived mutations, respectively. There has been no direct investigation of the suitability of incorporating different genes for semi-dwarfism into the Australian barley breeding programs, especially in regard to the potential effect of semi-dwarf genes on grain size. In a North American study comparing standard height and mutant semi-dwarf isotype pairs, a negative association was observed between semi-dwarf stature and 1000-kernel weight (Nedel *et al.* 1993). Brachytic mutants, conferred by genes *br₁* (in Aramir) and *br₂* (in Svanhals) are associated with reduced kernel size and shorter coleoptile (Swenson, 1940).

Rasmussen *et al.* (1979) classified nine barley genotypes on the basis of the duration of grain filling as short (mean of 20.8 days), intermediate (mean of 25.9 days) and long (mean of 30.9 days), with the maturity only differing by four days when they were grown in the field. Metzger *et al.* (1984) found that the duration of grain filling period was influenced by environment but groups classified on this basis retained their ranking across environments.

The research reported here details three series of experiments. The first investigated the grain filling characteristics (rate and duration) and kernel size of 3 standard height cultivars and 7 semi-dwarf cultivars carrying either the *sdw*, the erectoide, or the unidentified ICARDA alleles for short plant stature. Trials were located at sites in each of the 3 states of South Australia (Pinery), Victoria (Horsham) and New South Wales (Condobolin). The second series of experiments investigated the influence of agronomic practice, namely sowing rate, on mean grain size and grain size variation of these genotypes. A third series of experiments compared the agronomic performance and grain size of isogenic lines differing in alleles influencing plant height and phenology.

Materials and Methods

Genotypes

The ten genotypes used in the first and second experiment included 3 standard height genotypes and 7 semi-dwarf genotypes. The semi-dwarf status, pedigrees and origin of the genotypes are detailed in Table 1. Dr. Jerry Franckowiak, University of North Dakota, USA, kindly provided the isogenic genotypes included in the third series of experiments, which were developed by backcrossing alleles for semi-dwarfism and major developmental characteristics into the recurrent parent Bowman. These lines are described in Table 7.

Table 1. Semi-dwarf gene status, country of origin and pedigree of three standard height and seven semi-dwarf barley genotypes.

Semi-dwarf status	Genotype	Country of origin	Pedigree
Standard height	Schooner	Australia (SA)	Proctor/Prior A//Proctor/CI3576
	O'Connor	Australia (WA)	ProctorCI3576(WI2231)/3/(XBVT212)
			Atlas57//(A14)Prior/Ymer
			Europa/IBON#7.148
<i>sdw</i>	Blenheim	United Kingdom	
	Franklin	Australia (Tas)	Shannon/Triumph
	Skiff	Australia (SA)	Abad Deba/3/Proctor/CI3576//CPI18197// Beka/4/Clipper/Diamant//Proctor/CI3576
CIMMYT semi-dwarf	Yagan	Mexico, via WA	
	Kaputar	Mexico, via NSW	
Erectoides	Cask	United Kingdom	
	VB9503	Australia (Vic)	Midas/Clipper/Noyep/Prior//CI3576/3/Union// Kenia/Research/4/Noyep//Prior/5/Elgina

Sites

The field trials were sown at Pinery in South Australia (34°08'S, 138°27'E), at Horsham, Victoria (36°42'S, 142°06'E) and at Condobolin, New South Wales (33°04'S, 147°11'E). Studies on grain filling duration were conducted at these locations in the 1996 season. Sowing rate and isogenic line experiments were conducted at these locations during 1997 and 1998 seasons, although the 1998 experiments at Horsham were lost due to frost damage.

Experiment 1: Rate and duration of grain filling

Trial design

The trial at Pinery, South Australia was sown on 1 July 1996 using plots 5 rows wide (0.75m; 1.1m centre-to-centre) and 4.2m long arranged in an alpha lattice design with 3 replications. Two sowing times, 9 June and 12 August 1996, occurred for trials at Horsham that were sown in alpha lattice designs with 3 replications, in plots 6-rows wide (0.90 m; 1.35 m centre-to-centre) and 12 m long. Trials at Condobolin were sown on 22 May and 28 July, 1996, in a split plot design with 3 replicates. Two water treatments were used; rainfed and a drip irrigation treatment that aimed to keep the soil moisture deficit below 50 mm during grain filling. These plots were 10 rows wide (1.80m; 2.10 m centre-to-centre) and 12 m long.

Observations and measurements

To follow the progress of grain filling 100 heads were tagged. This involved choosing plants whose main stem ears were at approximately the same stage of development (normally Zadok 55, and within the range of Zadok 53-57). It was anticipated there would be approximately 15 sampling times during grain filling, 20 plants in 5 groups were tagged in each plot. These 5 groups were spread over the whole plot and at each sampling time 1 plant was taken from each of the 5 groups of tagged plants. Sampling started at or soon after anthesis at all 3 sites. After sampling, the tagged ears were removed from each of the 5 plants and 10 spikelets (five on each side of the rachis) were removed. The awn was removed at its base from each of the spikelets, dried in an air forced oven at 40°C for 48hrs, cooled and weighed. Sampling took place at a frequency of 3 to 7 days during grain filling. The mean of these 5 plants was used as a value for each replication.

Data analysis.

Kernel growth over time was described for each genotype by a 4 parameter logistic model generated using the FITCURVE procedure in Genstat 5. These were of the form:

$$y = A + C/[1 + \exp(-B(x - M))]$$

where y is kernel weight, A is the lower asymptote, $A + C$ is the upper asymptote, B describes a rate parameter and M is the point of maximum rate of the logistic curve. The fitted curves were used to calculate values and standard errors for the maximum grain filling rate, the days from anthesis to the maximum rate, and the duration of filling estimated as the time from anthesis to 95 % of $(A+C)$.

Experiment 2: Influence of agronomic practice on grain size mean and variance

The influence of sowing rate on yield and grain quality were investigated at Horsham, Condobolin and Pinery in 1997 and 1998 using split plot designed trials with four sowing rates and three replicates. Plot size and management was generally similar to that for Experiment 1. Plants were sampled from the 1997 Horsham trial every 2 – 4 days from 30 days after sowing, to enable dissection of the shoot apex. Time to both double ridge and the formation of awn primordia (maximum primordia number) were recorded. Dry matter was harvested from 2m rows at maturity to determine average grain numbers per spike from 100 spikes. These spikes were hand threshed and the grain weight variability of 300 kernels assessed from the experiment at Horsham (1997) using a 4100 Perten Single Kernel Characterisation System (SKCS). Grain yield was recorded at each site, and samples retained for determining the percentage grain plumpness using a Sortimat dockage tester. Irrigation at two times during the growing season was applied as additional treatments at Condobolin in 1997.

The DISTRIBUTION directive in Genstat 5 (version 4.1) was used to calculate mean grain weight, and the skewness and kurtosis of the grain weight distribution. Skewness is defined by the average value of $(X-\mu)^3$ taken over the population. If low values of X are bunched close to the mean μ but high values extend far above the mean, this measure will be positive. Negative skewness occurs when the lower tail is extended (Snedecor and Cochran, 1989). Kurtosis is defined as $((X-\mu)^4 - 3)$. If kurtosis is positive, the distribution has longer tails than a normal distribution with the same σ . A “flat-topped” distribution will show negative kurtosis (Snedecor and Cochran, 1989). ANOVA using a split plot design was performed on the measurements of grain weight skewness and kurtosis from individual plot samples.

Experiment 3: Agronomic performance and grain size of isogenic lines differing in alleles for height and phenology.

The cultivars Bowman and Schooner and 19 Bowman isolines were sown in 10 row plots 10 m in length on 17 July 1998 at Condobolin, and at Pinery in 5 row plots, 4.2m in length. There was insufficient seed for full sized plots of two isolines and yield data for these is not presented. A RCB design was used with three replicates.

Results and Discussion

Experiment 1: Rate and duration of grain filling

Mean grain weights at maturity were estimated from the grain filling curves and varied across environments, from a low of 42 mg for early sown, dryland conditions at Condobolin to a high of 56 mg for the late sown Horsham site (Table 2). Averaged over the seven environments, grain weight was highest for Yagan, followed by VB9104, O'Connor and Kaputar. Schooner had moderate grain size followed by the *sdw* genotypes, Skiff, Blenheim and Franklin while the lowest average grain weights were recorded in the erectoide genotypes, Cask and VB9503.

Genotypic ranking of relative grain size at each site is also shown in Table 2; the consistency of ranking across a wide range of environments confirms the strong genetic control for grain size and suggests little genotype by environment interaction. Yagan and VB9104 had the highest and second highest grain weights, respectively, in all environments (Table 2). O'Connor was ranked third in all but one environment. Cask and VB9503 had the smallest grain size in almost all environments. There was more variation in the intermediate genotypes, Schooner ranking higher and Kaputar lower at Condobolin than at the other sites, and Skiff performing better than Blenheim and Franklin, at the later but not the earlier time of sowing, perhaps reflecting differences in phenology.

Table 2. Grain weight means for each genotype and environment, and ranking of genotypes for each environment.

Height status	Genotype	Ranking for environments 1 to 7*							Genotype mean (mg)
		1	2	3	4	5	6	7	
Tall	Schooner	6	6	6	3	5	4	4	48.53
Tall	O'Connor	3	3	3	4	3	3	3	51.76
Tall	VB9104	2	2	2	2	2	2	2	53.70
<i>sdw</i>	Blenheim	7	5	7	5	8	5	8	45.92
<i>sdw</i>	Franklin	9	8	8	6	7	7	7	44.14
<i>sdw</i>	Skiff	5	7	5	8	6	8	5	46.80
CIMMYT	Yagan	1	1	1	1	1	1	1	63.68
CIMMYT	Kaputar	4	4	4	7	4	6	6	48.80
Erectoides	Cask	10	9	10	9	10	10	10	39.85
Erectoides	VB9503	8	10	9	10	9	9	9	42.08
Site mean (mg)		47.97	50.26	55.91	41.85	46.59	46.22	50.89	

*Environment key
 1. Pinery sown July 1
 2. Horsham sown June 9
 3. Horsham sown Aug. 12
 4. Condobolin sown May 22 rainfed
 5. Condobolin sown June 28 rainfed
 6. Condobolin sown May 22 irrigated
 7. Condobolin sown June 28 irrigated

The maximum grain filling rate for each genotype at each site was calculated from the logistic equations. Mean values for each genotype and site, together with the relative genotype ranking at each site are shown in Table 3. There were large differences among the data sets, emphasising the large effect of environmental conditions on grain filling rate. Averaged across all genotypes, the highest grain filling rate (2.74 mg/day) was recorded at the late sown, irrigated Condobolin site followed by the site at Pinery. The Condobolin late sown, rainfed site and the Horsham late sown site had similar grain filling rates (approximately 2.4 mg/day). The lowest grain filling rates occurred at the irrigated and rainfed early time of sowing at Condobolin (1.93 mg/day and 1.92 mg/day respectively), and at the early time of

sowing at Horsham (2.0 mg/day) perhaps reflecting the lower temperatures during grain filling.

Despite these major environmental effects, there were large and consistent genotype differences for grain filling rate. The highest average grain filling rates were for Yagan and Kaputar (2.60 mg/day). Schooner, VB9104, Franklin, Skiff, and Blenheim had average grain filling rates of approximately 2.3 mg/day. O'Connor's average grain filling rate was only 2.15 mg/day while both VB9503 and Cask were less than 2 mg/day. Genotypic ranking for grain filling rates was similar between sites.

Table 3. Maximum grain filling rate means for each genotype and environment, and ranking of genotypes for each environment

Height Status	Genotype	Ranking for environments 1 to 7*							Genotype mean (mg/day)
		1	2	3	4	5	6	7	
Tall	Schooner	6	6	6	2	1	2	5	2.35
Tall	O'Connor	7	4	8	9	7	7	7	2.15
Tall	VB9104	3	3	5	1	8	6	3	2.32
<i>Sdw</i>	Blenheim	5	8	7	8	4	5	6	2.22
<i>Sdw</i>	Franklin	9	7	3	5	5	1	8	2.29
<i>Sdw</i>	Skiff	4	5	4	6	6	8	2	2.28
CIMMYT	Yagan	1	1	1	4	2	3	4	2.60
CIMMYT	Kaputar	2	2	2	3	3	4	1	2.56
Erectoides	Cask	8	9	9	7	10	9	9	1.91
Erectoides	VB9503	10	10	10	10	9	10	10	1.78
Site mean (mg/day)		2.40	2.01	2.35	1.93	2.38	1.92	2.74	

* Environment key as for Table 2

Grain filling duration was also calculated from the logistic equations fitted to grain growth (Table 4). There were large differences between environments, ranging from 34 days, for late sown, rainfed trial at Condobolin, to 43 and 47 days for early and late sown trials at Horsham. Yagan had the longest average duration; this may have been partially related to Yagan's early anthesis date, enabling grain filling during a cooler period and contributing to Yagan's very large grain size. The tall, large grained genotypes O'Connor and VB9104 also had long duration of grain filling (44 days), while Franklin had the shortest duration of grain filling (35 days), perhaps reflecting Franklin's later flowering date. Grain filling periods for the late maturing Franklin, sown in June, and the early maturing Yagan, sown in August, coincided at Horsham, allowing a comparison of rate and duration of grain filling under similar climatic conditions. Large differences were apparent in both rate (Franklin 1.88 mg/day; Yagan 2.80 mg/day) and duration (Franklin 42.6 days; Yagan 48.7 days); it should be noted that total crop biomass was also dramatically different between the sowing dates. Duration of grain filling in the other *sdw* dwarfs was relatively short, averaging approximately 38 days, and being similar to Schooner. Perhaps most surprising were the rather long durations for the small grained erectoides genotypes and the short duration of Kaputar (35 days), considering its relatively large grain size.

Table 4. Grain filling duration means for each genotype and environment, and ranking of genotypes for each environment

Height Status	Genotype	Ranking for environments 1 to 7*							Genotype mean (days)
		1	2	3	4	5	6	7	
Tall	Schooner	6	5	4	6	9	8	9	37.6
Tall	O'Connor	1	2	1	2	4	5	3	44.6
Tall	VB9104	3	3	3	5	3	3	2	44.0
<i>Sdw</i>	Blenheim	8	4	6	3	8	7	8	38.6
<i>Sdw</i>	Franklin	10	7	10	8	7	10	5	34.7
<i>Sdw</i>	Skiff	5	9	7	7	5	6	7	38.3
CIMMYT	Yagan	2	1	2	1	2	1	1	49.5
CIMMYT	Kaputar	7	8	8	9	10	9	10	34.8
Erectoides	Cask	9	10	9	10	1	4	4	39.1
Erectoides	VB9503	4	6	5	4	6	2	6	41.1
Site mean (days)		38.2	43.1	43.1	37.8	33.9	46.64	35.2	

* Environment key as for Table 2

The results highlight genotype differences in both grain weight and in the relative importance of filling rate and duration in achieving that grain weight. Both the erectoides types had small grain because of low filling rates and despite a long duration. The CIMMYT material had large grains, as a result of both a high rate and a long duration in one case (Yagan) but only because of a high rate in the other case (Kaputar). The *sdw* genotypes tended to be intermediate in all characteristics, as was the tall genotype Schooner. Franklin was the most variable of the *sdw* types, with short durations under harsher conditions. O'Connor was different to other genotypes in that its high grain weight resulted solely from a long grain filling period.

Experiment 2: Influence of agronomic practice on grain size mean and variance

Sowing rates were used to establish plant populations of 80, 160, 240 and 320 plants per m². Increasing sowing rates reduced grain weights in six of the seven environments (Table 5) and reduced the percentage of plump grain (retained above a 2.5mm screen) in five environments. Large genetic differences existed in both mean grain weights and mean percentage plump grain; interactions between genotype and sowing rate for both grain weight and percentage plump grain occurred at three environments (Horsham 97, Pinery 98 and Condobolin 98). At Horsham 97 and Pinery 98, despite most genotypes having reduced grain size, percentage plump grain for most genotypes was increased slightly at 160 plants per m² compared with a plant density of 80 plants per m². The highest plant densities reduced grain plumpness. Franklin was an exception at Horsham, and Cask an exception at Pinery 98, with a reduction in the percentage of plump grain at the higher plant densities. Generally the percentage of plump grain was reduced with increasing plant densities in the other environments although the effect was less pronounced for those genotypes with inherently large grain size.

Large environmental influences on grain plumpness were observed. Mean grain plumpness for all genotypes varied from 86.1% (mean grain weight 47.0 mg) at Horsham in 1997 to 50.6% (mean grain weight 35.7 mg) in the dryland trial at Condobolin, 1997. Irrigation was applied as a treatment to the May and July sown trials in 1997 at Condobolin, increasing mean grain plumpness (from 50.6%) to 62.2% and 69.0% respectively. Despite the use of irrigation in these trials, the grain plumpness for all genotypes was lower than in the dryland trial at

Horsham in 1997. Mean daily temperatures during the grain filling period were 12.3°C at Horsham and 17.3°C at Condobolin. Grain yields were 1.0 – 1.5 t/ha higher in the irrigated trials at Condobolin.

Increasing plant densities from 80 to 160 plants/m² increased ($p < 0.05$) grain yields in three environments (Horsham 97, Pinery 98 and Condobolin 98) by an average of 18%. Plant density did not have a significant effect on grain yield in the other environments.

Table 5: Mean grain weight (mg) of semi-dwarf and standard height genotypes grown in seven environments during 1997 and 1998 at four different plant densities. Days to maximum primordia number (MPN) are the mean of sowing rate treatments. Mean grains per spike determined from two environments.

Genotype	Plant/m ²				Mean	Days to MPN	Mean grain no. per spike
	80	160	240	320			
Blenheim	42.0	40.5	38.5	38.5	39.9	86.3	25.3
Cask	37.1	35.7	34.8	33.4	35.2	86.8	25.1
Franklin	38.6	37.0	35.0	33.8	36.1	89.6	23.8
Kaputar	42.8	41.9	40.8	40.5	41.5	74.7	19.5
O'Connor	45.9	43.1	43.7	42.3	43.7	73.3	19.5
Schooner	42.1	40.9	39.2	39.1	40.3	75.6	17.8
Skiff	41.1	40.3	39.1	38.9	39.9	75.6	19.4
VB9104	48.4	47.0	46.6	45.4	46.9	76.7	17.4
VB9503	38.3	37.2	36.5	35.8	37.0	80.8	22.9
Yagan	51.1	48.7	48.4	48.4	49.1	65.5	15.7
Mean	41.9	40.5	39.5	38.9			
Lsd (5%)						2.1	1.25

Lsd (5%) = 1.28 when comparing mean grain weight between varieties.

Lsd (5%) = 0.77 when comparing mean grain weight between sowing rates.

Lsd (5%) = 2.56 when comparing mean grain weight between sowing rates for individual genotypes.

Further increases in plant populations beyond 160 plants/m² caused little or no change in grain yield but generally reduced mean grain size. Highest grain yields were obtained at Condobolin in 1997, with mean yields of 3.46t/ha and 3.18t/ha in the two irrigated treatments, and the lowest mean yield of 1.79t/ha occurred at Pinery in 1998. Genotypic grain yield differences occurred in five environments. The early maturing Yagan, the midseason Schooner and the very late maturing Franklin were consistently amongst the lowest yielding entries in all environments indicating the diverse range of environments and the absence of a strong relationship between maturity and yield performance in these trials. The semi-dwarfs, Skiff, VB9503 and Cask, and the tall genotypes, O'Connor and VB9104, were the higher yielding genotypes across all environments.

Highly significant genotypic differences occurred in the mean grain numbers per spike with little variation in ranking of genotypes between sites. The semi-dwarf genotypes Blenheim, Cask, Franklin and VB9503 had the highest average grain numbers per spike. However, this characteristic appears to be independent of plant stature with the other semi-dwarf genotypes, Kaputar and Skiff, having relatively low grain numbers per spike. Measurements of the pre-anthesis phenological phases of development indicated a strong association between the time for a genotype to reach the formation of awn primordia (maximum spikelet primordia) and the

observed numbers of grains per spike at maturity (data not presented). Grain numbers per spike were strongly influenced by both environment and plant densities. Plant density also influenced the variability in grain numbers per spike (data not presented), with a reduction in variation apparent.

The SKCS allowed changes in grain size variability to be quantified from the 1997 trial at Horsham. Calculation of kurtosis for each sample population (grain from a single plot) provided a quantitative description of the grain weight distribution. Higher values of kurtosis (Table 6), or a grain size distribution with greater variability, occurred with increasing plant densities. This is despite the observation in this trial that moderate increases in plant density improved the percentage of plump grain. Large genotypic differences also existed, without any consistent relationship with the inherent grain size. Both Kaputar, with an inherently large grain size, and VB9503, with an inherently small grain size, had high kurtosis values, whilst O'Connor and Blenheim, with inherently large and small grain size respectively, had the lowest kurtosis values.

Table 6: Kurtosis in the distribution of individual grain weights for semi-dwarf and standard height genotypes grown at different plant densities at Horsham during 1997.

Genotype	Plants/m ²				Mean
	80	160	240	320	
Blenheim	0.203	0.643	0.430	0.487	0.441
Cask	0.470	2.363	1.893	1.987	1.678
Franklin	0.523	0.250	1.210	1.713	0.924
Kaputar	0.993	2.103	1.423	1.697	1.554
O'Connor	0.257	0.877	1.250	1.047	0.857
Schooner	0.623	0.590	0.973	2.167	1.088
Skiff	1.327	1.763	1.300	0.693	1.271
VB9104	0.220	1.483	2.523	2.147	1.593
VB9503	1.430	2.270	1.907	2.387	1.998
Yagan	0.623	1.623	0.750	1.010	1.002
Mean	0.667	1.397	1.366	1.553	

Lsd (5%) = 0.831 when comparing genotype means

Lsd (5%) = 0.436 when comparing sowing rate means

Lsd (5%) = 1.427 when comparing sowing rate means between individual genotypes

The skewness of the distribution of grain weights in samples of both Franklin and Cask increased with the higher plant densities, indicating a sample with a high number of smaller grains and a number of larger grains causing an upper tail in the distribution (data not presented). Plant density had no effect on the skewness of grain weights in samples from the other genotypes.

Experiment 3: Influence of genes controlling stature on grain size

There was a large range in crop height among the Bowman isolines, from a low of 53 up to 96 cm, compared to 90 cm for Bowman and 82 cm for Schooner (Table 7). There was also considerable variation for other characteristics including tillering and time to anthesis. Short stature genes usually shorten internode length but there can also be variation in the total number of internodes (related to leaf number at anthesis) or the number of internodes which elongate. For example, the *sdw* allele can result in the extension of the stem at a higher

internode (Kirby, 1993). The number of elongated internodes and the length of the internodes was measured on main stems of each genotype. In all but one genotype, there were four or five internodes that elongated; the one exception had seven internodes. Average length of the three upper internodes ranged from 98mm in the shortest genotype to 220 mm in the tallest genotypes.

Table 7. Height, yield, kernel weight, spikelet number, number of extended internodes and average length of the upper three internodes for Bowman isolines grown at Condobolin in 1998.

Genotype	Allele*	Height (cm)	Yield (t/ha)	Kernel weight (mg)	Spikelet no./ear	Internode no.	Internode length (mm)
I90-207-1	<i>gra</i>	53	3.02	34.7	25.5	5	98
I90-344-1	<i>Ert-r</i>	60	2.25	44.8	28.4	4	179
I90-343-1	<i>mn?</i>	62	2.83	29.6	22.1	7	102
I90-200	<i>uz</i>	63	na	36.6	29.0	5	163
I90-340-1	<i>br?</i>	64	2.20	37.4	29.2	5	152
I90-206-1	<i>sdw-b</i>	65	na	40.1	24.7	5	145
I90-347-1	<i>ari-e</i>	65	2.74	33.8	24.0	4	167
I89-529-1	<i>sdw</i>	66	2.98	38.0	27.7	4	167
I90-431-1	<i>ert-k</i>	71	2.92	38.1	25.9	4	196
I90-93-1	<i>ert-a</i>	73	2.73	37.2	27.1	4	196
I90-239-1	<i>glo-a</i>	77	3.05	36.6	25.7	4	202
I90-136-1	<i>v</i>	79	2.96	26.2	71.7	5	209
I90-179-1	<i>glo-d</i>	80	2.88	38.6	31.5	5	186
I89-592-1	<i>fus</i>	80	3.04	43.3	27.8	4	222
Schooner	Control variety	82	3.47	40.6	28.1	5	189
I89-343-1	<i>Ea</i>	83	3.09	41.0	27.3	5	218
I90-483-1	Com?	84	2.93	43.3	28.3	4	221
I90-479-1	<i>ert?</i>	85	3.60	40.1	28.5	4	205
I90-94-1	<i>ert-d</i>	86	2.70	43.2	32.4	5	208
Bowman	Recurrent parent	90	3.13	41.8	27.7	5	224
I90-192-1	<i>sld</i>	96	2.65	44.2	28.3	5	216
lsd (5%)		10	0.46	1.91	1.84		

* Gene symbols from BGN16:81-121. (?) indicates simply inherited gene not mapped or studied in allelism tests.

Within the two row genotypes, there was a weak relationship between height and kernel weight. The seven tallest genotypes (> 80 cm), compared to only two genotypes shorter than 80 cm, had kernel weights greater than 40 mg. The two exceptions carried *sdw-b* (40.1 mg) or *Ert-r* (44.8 mg) alleles and were 65 and 60 cm tall respectively; by comparison, Bowman and Schooner kernels averaged 41 mg. The ranking of genotypes for kernel weight was similar to that recorded in a similar trial at Pinery in 1998 (data not presented) suggesting that G x E for this character is not large within these isolines.

Spikelet number per ear varied widely within the two row types, ranging from 22 to 32. This character was not strongly related to crop height although the genotypes with the greatest number were 80 and 86 cm tall. Interestingly, high spikelet number was not associated with smaller grains; the two genotypes with the largest kernels had 28 spikelets per ear.

Grain yield ranged from 2.2 to 3.6 t/ha and a number of the genotypes with short stature performed well at Condobolin but the relative genotypic yield ranking at the Pinery site was quite different (data not presented). This interaction may have been linked to changes in phenology.

The *sdw* gene has been used widely in feed barley genotypes in Australia but there have been concerns that it is associated with small grain size and high screenings. In this study, kernel weights for genotypes carrying the gene were 6.5% lower than for Bowman at both sites. The Golden Promise erectoide (*ari-e*) isolate also had small grain.

Conclusions

Studies in wheat in Western Australia (Whan *et al.*, 1996), had suggested rate of grain growth is more important than duration of grain filling, as duration is influenced to a much greater extent by environment. In our results, a variation of approximately 40% in both grain filling rate and grain filling duration was observed between environments. These studies indicate large grain size can be achieved either through a rapid rate of grain filling (eg Kaputar) or by a long duration of grain filling (eg O'Connor). The exceptional grain size of Yagan results from the combination of a high rate and long duration of grain filling. Genotypes dependent on a long duration of grain filling to achieve a large grain size were not adversely effected (relative to the other genotypes) by late sowing, despite late sowing markedly reducing grain filling duration. Similarly, the grain size ranking of genotypes dependent on a rapid rate of grain filling for achieving large grain size was not influenced by sowing date, despite mean (daily) grain filling increasing with delayed sowing date. Although the influence of plant biomass, and the relative value of pre and post anthesis assimilates to grain filling has not been considered in this paper, these studies have occurred in conjunction with the described research and will be reported elsewhere.

The identification of semi-dwarf alleles with the potential for use in breeding programs without adversely effecting grain size was the primary objective of this study. Grain numbers per spike, which are negatively associated with grain size, are intrinsically linked to the developmental time to reach the maximum primordia number (awn primordia development). However, this characteristic is independent of the presence of the alleles for short stature included in these studies. Nevertheless, the variation in grain size amongst the Bowman isolines indicates the presence of these alleles do have a negative influence on grain size. The potential for incorporating these alleles into a genetic background that masks their adverse effect is more difficult to establish. Probably, despite their high yield potential, the erectoide genotypes should be precluded from use by Australian malting barley breeding programs due to the very low rate of grain filling associated with the erectoide allele and the resultant small grain size, particularly in stressful conditions. The *sdw* allele, assumed to be present in Skiff and Blenheim, may be more useful. Grain filling rates and duration were not too dissimilar to the standard height variety Schooner. This allele may be present in Kaputar, and determining the genetic basis of the semi-dwarf trait in Kaputar should assume high priority. If the short stature of Kaputar is determined by *sdw*, a sense of optimism should exist amongst barley breeders. Existence of a *sdw* Kaputar type, indicates selection amongst the large numbers of *sdw* derived genotypes within Australian barley breeding programs can realistically combine the *sdw* allele with high rates of grain filling and hence plump grain size. Continued effort is required to combine the *sdw* allele with longer duration of grain filling, and selection should target those crosses between *sdw* semi-dwarfs and genotypes with long duration of grain filling, such as O'Connor and VB9104. Advanced semi-dwarf breeding

lines in national trials (eg WI3102, WB236), with similar grain size to taller varieties such as Schooner, indicate progress may already have been made in this area.

Given the relative small grain size of current semi-dwarf varieties, and the importance of grain size uniformity to the malting industry, variation in plant density was investigated as a means of improving grain quality. It was expected that increases in sowing rates would reduce tillering resulting in fewer, and more uniform, spikes per plant whilst increasing spike numbers per m². In some environments small improvement in grain plumpness did occur by increasing plant densities, but these increases were generally from very low plant densities to levels generally adopted in commercial practice. The very high plant densities generally resulted in a deterioration of grain quality. The quantitative measure at one location of grain size uniformity using a SKCS indicated improved grain plumpness associated with modest increases in plant density might not necessarily be associated with improved grain uniformity for malting purposes. These studies need to be extended to include additional locations before a final conclusion can be drawn.

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