Tetraploid Wheat—A Resource for Genetic Improvement of Durum Wheat Quality[1]

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ABSTRACT

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The tetraploid relatives (subspecies) of commercial durum wheat (*Triticum turgidum* L. subsp. *turgidum* conv. *durum* (Desf.) MacKey) offer a source of economically useful genes for the genetic improvement of durum cultivars. Tetraploid wheat subspecies show a wide diversity in grain protein composition and content, which are major factors determining the pasta-making quality of durum cultivars. In this study, the specific focus was the identification of accessions expressing one or more superior pasta-making traits. In all, 33 accessions were surveyed representing five different subspecies; var. *durum* (13 accessions), *polonicum* (7 accessions), *persicum* (3 accessions), *turanicum* (6 accessions), and *turgidum* (4 accessions). These accessions and the durum cultivars Wollaroi and Kamilaroi (in both years) and Yallaroi (in 1998 only) were grown at Tamworth, Australia in 1997 and 1998. Grain, semolina, and spaghetti cooking quality were evaluated using a range of tests. Several accessions were identified with larger grain size and protein content and higher semolina extraction. Although many of the accessions were weaker in dough strength, a few were equal to the commercial cultivars and produced pasta of comparable quality. The main disadvantage with these accessions was the low yellow color. These quality defects can be corrected by conventional breeding.

Durum wheat breeding in Australia is focused on producing cultivars that provide high grain yields, have superior disease resistance and tolerance to abiotic stresses, and offer high quality grain suitable for pasta making. There is a need to improve the quality of durum wheat to meet the ever-increasing demands of the market. Tetraploid relatives of commercial durum wheat may provide a reservoir of economically useful genes to extend the genetic diversity of quality traits available for breeding.

Research has shown that protein quantity and composition have a large influence on suitability of durum semolina for pasta making (D'Egidio et al 1990; Matsuo et al 1972). Protein composition has a major impact on end-use quality; therefore, an important limitation to improvement of the durum quality of commercial cultivars is the limited genetic variation in gluten protein composition in breeding populations (Liu and Shepherd 1996). Research has shown that greater variation in protein composition (particularly with respect to low molecular weight glutenin subunits) occurs in tetraploid wheats other than current durum cultivars (Liu and Shepherd 1996). Greater variation in high molecular weight glutenin subunits was found in *Triticum turgidum* L var. *dicoccoides* (Korn. ex Asch. & Graebner) Thell. than in durum cultivars (Levy et al 1988). Other research has established the link between allelic differences in the glutenin subunit composition and gluten strength in durum wheat (Vazquez et al 1996; Porceddu et al 1998). Thus, there is potential for the tetraploid species to provide useful genetic variation for pasta-making quality traits that could be incorporated to improve varietal quality. Genetic improvement of cultivated durum has been demonstrated with one tetraploid, *T. turgidum* var. *dicoccoides* (high grain protein), which was crossed with cultivated durum to produce lines with increased grain protein content, gluten strength, and spaghetti firmness and reduced pasta cooking residue (Kovacs et al 1998).

The aim of this study was to identify tetraploid germplasm with superior quality characteristics that would enhance the milling and pasta-making potential of Australian durum cultivars suitable for high quality markets. A selection of tetraploid subspecies were evaluated for grain and pasta-making qualities in comparison with three Australian durum cultivars grown under identical conditions over two years. Quality characteristics investigated included grain weight, hardness, protein content, semolina milling yield, semolina color, dough strength, and cooking quality of the pasta.

MATERIALS AND METHODS

Plant Material

In all, 33 accessions of tetraploid wheats were selected from the Australian Winter Cereals Collection, Tamworth, representing five different subspecies of *T. turgidum*: var. *durum* (13 accessions), *polonicum* (L.) MacKey (7 accessions), *persicum* ((Nevski *in* Kom.) A. Love & D. Love) (3 accessions), *turanicum* (Jakubz.) MacKey (6 accessions), and *turgidum* (4 accessions). These accessions and the durum cultivars Wollaroi and Kamilaroi (in both years) and Yallaroi (in 1998 only) were grown at Tamworth, Australia in 1997 and 1998 using a randomized complete block design (two replicates). Only one replicate from each year was tested. Kamilaroi AUS 21819 (Australian Winter Cereals Collection accession number) was the first of the three Australian durum cultivars released and is no longer widely grown. It has largely been replaced by higher gluten strength cultivars Yallaroi (AUS 23825) and Wollaroi (AUS 25926), which both dominate durum wheat production in Australia. The grain yields and quality of the check cultivars were typical of commercial grades reflecting adequate soil fertility and rainfall during the growing season.

Sample Preparation and Analysis

Samples of grain were cleaned on a Carter-Day dockage tester (Simon Carter Co., Minneapolis, MN). Hectoliter weight (HLW) was determined by a Schopper chondrometer equipped with a 250-mL cylinder. The 1,000-kernel weight (TKW) was obtained by counting 250 kernels randomly chosen after removal of broken grains using a grain counter (Numigral, Rouseau, Paris, France). The 250 kernels were weighed and the value expressed as the weight of a 1,000 kernels. Single-kernel weight (SK-WT), diameter (SK-DM), and hardness index (SK-HI) were measured using a single-kernel characterization system (SKCS 4100, Perten, Reno NV) (Martin et al 1993). Grain was milled into semolina by tempering the grains for 18 hr to 15.0% moisture and milling in an experimental mill (model MLU 202; Buhler, Uzwill, Switzerland) equipped with three break rolls and two reduction rolls (Approved Methods 26-41, AACC 2000). Semolina mill yield percentage (SY%) was expressed on a total products basis. Farinographs and extensigraphs were measured on the purified

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semolina (Approved Methods 54-21, 54-10). Mixing tests (duplicate determination per sample) were conducted with a 10-g mixograph (National Manufacturing Company, Lincoln, NE) with water absorption data obtained from the farinograph used to determine the amount of water to add to the semolina to give a constant mass of dough (16 g). MixSmart software supplied with the mixograph was used to determine mixograph dough development time (MPT) and the width of the curve at peak mixing time (WatP). Semolina was purified on an in-house-built small-scale purifier and this was used to prepare long pasta (spaghetti) using a Namad pasta extruder (Appar Laboratorio, Rome, Italy). Semolina was mixed with distilled water (30% by weight) in a premixing chamber for 10 min. The mixture was then extruded under partial vacuum (8 kPa) at 50°C through a Teflon-coated die piece, cut, looped over metal rods, and hung in a drying cabinet maintained at 25°C and 85% rh (diameter of dried pasta = 1.82 ± 0.025 mm). After the last sample was processed, the drying cycle commenced (65°C for 1 hr at 75% rh, 50°C for 13.5 hr at 60–65% rh, then equilibrated at 25°C for 12 hr at 55% rh). Pasta samples were stored at 22°C and 55% rh for at least seven days before analysis to ensure stable optimum cooking times.

Analytical Tests

For protein estimation, a subsample of cleaned grain was milled on a falling number mill (Perten, Reno, NV) and protein measured on the wholemeal by NIR (Infralyzer 450; Bran+Luebbe, Sydney, Australia) calibrated against Kjeldahl nitrogen (Approved Method 39-10, AACC 2000). Semolina color was evaluated by measuring *L* (brightness; 100 = white, 0 = black) and *b* (+yellow, –blue) parameters by means of a reflectance colorimeter (CR200 Chromometer; Minolta, Osaka, Japan) poured into the attachment provided. Values are the means of two determinations per sample. Starch damage was measured on semolina using a starch damage kit (Megazyme International Ireland Ltd., County Wicklow, Ireland) and was expressed as a percentage of the semolina on an as-is basis.

Pasta Quality Evaluation

Four tests were performed on the pasta: determination of the optimum cooking time, cooked pasta firmness, resilience, and stickiness. Details of these methods can be found elsewhere (Wood et al 2001), with the only variation being three replicate cooks or tests per sample. Firmness and resilience are defined

TABLE I
Grain and Semolina Properties of Tetraploid Wheat Accessions and Commercial Cultivars

		Grain Characteristics[a]						Semolina Characteristics[b]		
Wheat	**Subspecies**	**HLW (kg/hL)**	**TKW (gm)**	**SY%**	**SK-WT (mg)**	**SK-DM (mm)**	**SK-HI**	**SD%**	***L***	***b***
Cultivar										
Wollaroi	*durum*	80.6	40.1	66.7	41.5	2.8	92.1	3.7	84.39	27.48
Kamilaroi	*durum*	80.5	40.1	68.0	40.7	2.8	99.8	4.2	84.71	27.18
Yallaroi	*durum*	78.6	38.0	67.0				4.4	84.30	27.18
Accession[c]										
AUS285	*durum*	79.0	33.6	50.0	34.7	2.4	37.5	1.2	91.12	7.74
AUS297	*durum*	72.4	39.5	62.6	43.8	3.0	87.6	4.4	82.97	18.09
AUS7812A	*durum*	78.4	53.9	70.4	53.3	3.3	99.8	5.3	79.71	14.93
AUS7829	*durum*	73.9	34.6	66.5	38.9	2.8	110.9	4.2	79.81	16.64
AUS7842	*durum*	79.4	37.5	68.3	38.7	2.6	97.6	4.1	81.62	16.83
AUS7922	*durum*	77.5	52.0	68.6	53.6	3.2	83.3	3.7	82.57	22.53
AUS16041	*durum*	80.3	45.0	71.6	45.1	3.0	98.5	4.3	82.81	19.65
AUS17045	*durum*	75.5	39.4	53.1	38.9	2.4	8.4	0.7	86.47	19.91
AUS17294	*durum*	79.5	42.6	69.5	42.5	2.8	98.3	4.0	83.76	23.95
AUS20677A	*durum*	78.2	59.8	71.0	59.8	3.2	87.5	3.8	83.03	21.75
AUS20677B	*durum*	78.5	66.3	70.9	61.2	3.3	87.9	3.8	83.81	19.14
AUS22300	*durum*	76.7	58.4	68.8	57.7	3.5	75.9	4.3	83.39	16.11
AUS22303A	*durum*	79.8	46.3	68.4	46.8	3.0	90.9	4.0	82.59	18.95
AUS3549A	*persicum*	73.3	38.3	69.7	40.5	2.8	97.2	5.0	79.59	18.14
AUS3830	*persicum*	74.2	24.8	65.8	26.4	2.2	106.1	3.7	81.03	16.68
AUS3838	*persicum*	77.2	26.8	66.8	27.8	2.2	104.2	4.6	80.87	13.96
AUS3824	*polonicum*	77.0	55.7	73.1	58.4	3.2	87.2	4.2	82.86	19.40
AUS3917	*polonicum*	76.3	24.0	66.1	25.9	2.2	105.7	4.0	82.12	14.60
AUS4049	*polonicum*	77.4	46.2	70.5	47.0	3.0	94.7	4.0	83.97	19.43
AUS5533	*polonicum*	77.0	53.2	73.0	57.3	3.2	88.1	4.4	82.60	19.51
AUS16133	*polonicum*	77.7	57.1	74.2	58.4	3.2	86.3	3.9	83.46	18.54
AUS22342A	*polonicum*	76.1	51.8	71.9	54.4	3.1	84.4	3.6	83.17	19.37
AUS22342B	*polonicum*	77.6	48.7	70.1	49.3	3.1	90.7	3.8	83.90	23.36
AUS3603	*turgidum*	77.8	36.9	66.0	37.3	2.8	97.7	4.3	82.88	20.72
AUS15914	*turgidum*	74.5	36.5	69.1	40.2	2.8	91.9	4.3	84.06	17.81
AUS18721A	*turgidum*	74.2	33.5	67.8	34.3	2.5	98.2	4.5	83.17	20.36
AUS18721B	*turgidum*	74.4	32.3	68.5	34.4	2.5	101.2	4.6	82.02	20.05
AUS7810	*turanicum*	72.3	49.2	71.3	49.4	2.9	102.2	5.9	84.44	18.51
AUS7812B	*turanicum*	79.4	52.9	71.8	54.3	3.3	93.1	5.3	78.59	14.88
AUS13539	*turanicum*	72.4	45.2	69.6	47.6	2.7	95.5	5.2	83.41	18.37
AUS15198	*turanicum*	72.8	45.0	69.1	46.4	2.7	93.4	5.0	83.43	18.75
AUS17210	*turanicum*	72.0	44.0	67.6	…	…	92.5	4.6	84.40	18.04
AUS14210	*turanicum*	73.6	49.6	70.2	49.0	2.8	98.9	5.9	85.30	17.95
LSD[d]	…	3.8	6.5	2.9	4.7	0.2	8.3	0.7	2.95	5.23
Year P[e]	…	0.209	0.387	**0.001**	0.293	0.417	**0.001**	**0.001**	0.304	0.641
Genotype P[e]	…	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.003**	**0.046**

[a] HLW = hectoliter weight; TKW = 1,000-kernel weight; SY% = semolina mill yield percentage; SK-WT = single-kernel weight, average of 300 kernel weights; SK-DM = single-kernel diameter, average of 300 kernel diameters; SK-HI single-kernel hardness index, average hardness index of 300 kernels.

[b] SD% = starch damage percentage; *L* = brightness (100 white, 0 black); *b* = color (+ = yellow, – = blue).

[c] A and B refer to selection from the AUS accession.

[d] Least significant difference ($P < 0.05$).

[e] Values in bold are significant at $P < 0.05$.

from the texture analyzer force versus time plot. The peak height of the first peak was defined as the firmness and the ratio of the peak height of the second to the first peak as the resilience Cooking loss was determined on the cooking water, two cooks per sample, and the means presented (Matsuo et al 1992).

Statistical Analysis

S-Plus 2000 (MathSoft Inc. Data Analysis Products Division, Seattle, WA) was used for analysis of variance (ANOVA), multiple comparisons, and calculation of correlation coefficients. Analysis of variance was used to determine the contribution to the variation in each parameter due to year, species, and genotype. Least significant difference (LSD) was calculated for each parameter using year as a replicate and this was used to test for significance ($P < 0.05$) between accessions.

RESULTS AND DISCUSSION

Grain Quality

HLW. The grain and milling characteristics measured are shown in Table I. HLW of the accessions were 72.0–80.3 kg/hL with a mean of 76.1 compared with the checks (the three cultivars) of 79.9. None of the accessions had a significantly higher HLW than the checks; some were statistically equivalent but many were lower. The average for each subspecies showed that the *turanicum* group had the lowest values compared with the checks.

TKW. There was much greater variation in TKW across the accessions, 24.0–66.3 g with an average of 44.3 compared with a mean of 39.4 for the checks. Four accessions had significantly smaller weights than the average of the checks (AUS 3830, AUS 3838, AUS 18721B, and AUS 3917), and these also had smaller kernel diameters and weights as determined using the SKCS-4100. However, 16 of the accessions had a significantly higher TKW than the checks. Accessions AUS 20677 (*durum*) and AUS 16133 (*polonicum*) had TKW values approaching 60 g and also had larger diameter kernels than the checks. As expected, there were high correlations between SKCS SK-WT, SK-DM, and TKW values, $r = 0.99$ and 0.91, respectively. Accessions AUS 20677 and AUS 16133 would be a good source of large grain genetic potential.

Grain hardness. Grain hardness values for the accessions were 8.4–110.9 SKCS SK-HI. Seven accessions were significantly softer than the average of the checks and three (AUS 7829, AUS 3830, and AUS 3917) were significantly harder. Sufficient hardness is re-

TABLE II
Dough Quality of Tetraploid Wheat Accessions and Commercial Cultivars[a]

Wheat	Subspecies	GP%	FWA	FDDT (min)	FB10 (BU)	EL (cm)	Rmax (BU)	MPT	WatP
Cultivar									
Wollaroi	*durum*	13.7	59.5	3.4	68	21.2	348	3.9	21.70
Kamilaroi	*durum*	13.2	60.9	2.6	85	21.0	200	2.99	17.35
Yallaroi	*durum*	12.2	58.9	3.3	65	15.4	320	4.81	19.50
Accession[b]									
AUS285	*durum*	13.4	56.0	2.3	88	19.3	180	3.01	11.35
AUS297	*durum*	13.3	58.0	2.1	148	17.9	115	2.45	11.35
AUS7812A	*durum*	16.6	64.7	2.0	180	15.9	148	1.75	9.40
AUS7829	*durum*	16.2	61.8	2.6	123	15.0	188	2.60	13.03
AUS7842	*durum*	16.3	61.0	2.8	105	15.6	185	2.01	10.65
AUS7922	*durum*	15.4	59.6	2.0	173	16.8	140	2.39	8.58
AUS16041	*durum*	15.4	63.1	2.6	138	14.3	140	2.59	14.35
AUS17045	*durum*	15.6	57.8	1.5	170	22.2	305	2.67	14.10
AUS17294	*durum*	13.6	61.9	3.0	75	19.5	335	3.62	19.80
AUS20677A	*durum*	15.7	63.3	2.4	105	14.5	165	2.50	11.00
AUS20677B	*durum*	15.6	61.4	2.0	100	14.9	195	2.46	11.58
AUS22300	*durum*	14.5	61.4	2.3	143	13.4	158	2.17	11.00
AUS22303A	*durum*	14.7	58.9	1.8	150	12.3	140	3.56	10.45
AUS3549A	*persicum*	14.1	60.9	1.6	185	15.9	165	1.94	11.53
AUS3830	*persicum*	16.3	58.9	2.6	103	13.4	203	2.46	11.50
AUS3838	*persicum*	15.4	59.4	2.0	163	16.0	170	1.75	9.23
AUS3824	*polonicum*	15.7	63.1	2.3	105	23.2	225	2.47	12.43
AUS3917	*polonicum*	16.3	61.1	1.8	185	16.1	120	1.60	10.68
AUS4049	*polonicum*	18.3	66.2	1.9	160	23.1	150	1.98	13.88
AUS5533	*polonicum*	15.4	62.6	2.3	85	23.2	280	2.81	11.70
AUS16133	*polonicum*	15.5	63.4	2.0	108	22.3	177	2.29	14.65
AUS22342A	*polonicum*	15.9	63.0	3.5	70	18.1	498	3.73	13.73
AUS22342B	*polonicum*	15.8	61.7	2.9	110	21.1	280	3.00	14.55
AUS3603	*turgidum*	13.3	58.5	1.8	165	…	170	1.84	9.83
AUS15914	*turgidum*	15.5	64.6	2.3	80	17.0	390	2.82	8.00
AUS18721A	*turgidum*	13.9	61.0	2.4	115	17.6	393	2.83	17.50
AUS18721B	*turgidum*	13.9	61.9	2.4	108	17.8	317	2.86	13.30
AUS7810	*turanicum*	13.9	65.3	2.5	120	14.1	188	1.57	7.35
AUS7812B	*turanicum*	16.7	64.7	1.8	180	11.8	180	2.28	10.45
AUS13539	*turanicum*	14.2	64.6	2.6	130	13.9	220	3.15	12.03
AUS15198	*turanicum*	14.5	65.2	2.6	118	14.2	193	3.30	14.00
AUS17210	*turanicum*	13.6	62.8	2.8	120	14.1	220	…	…
AUS14210	*turanicum*	13.7	65.0	2.5	120	13.5	220	3.08	12.10
LSD[c]	…	1.5	6.2	0.7	48	3.5	136	1.24	6.47
Year P[d]	…	**0.026**	**0.001**	**0.001**	**0.029**	0.753	**0.002**	0.569	**0.001**
Genotype P[d]	…	**0.001**	**0.004**	**0.002**	**0.001**	**0.019**	**0.008**	**0.053**	0.172

[a] GP% = grain protein percentage; FWA = farinograph water absorption (as-is); FDDT = farinograph dough development time; FB10 = farinograph breakdown after 10 min; EL = extensograph extensibility; Rmax = extensograph maximum resistance; MPT = mixograph peak development time; WatP = mixograph width of curve at peak mix time.

[b] A and B refer to selection from the AUS accession.

[c] Least significant difference ($P < 0.05$).

[d] Values in bold are significant at $P < 0.05$.

quired in cultivars to obtain a good semolina yield (correlation between SK-HI and SY% was r = 0.69) but this is not the only factor of importance. ANOVA showed a significant year effect (Table I). All samples had higher hardness in 1997 and this was reflected in almost all cases with higher SY%.

SY%. The accessions showed a large variation in semolina mill yield (50–74.2%), much wider than that found in the breeding populations (typically 66–70%). There were three accessions (*durum*) with lower yields (AUS 285 and AUS 17045 also had the lowest SK-HI) and 12 with significantly higher yield compared with the average of the checks. *Polonicum* accessions AUS 3824, AUS 5533, and AUS 16133 had yields of 73–74% compared with the average for the three checks of 67.2%, and all had large, heavy kernels. There were significant correlations between SK-WT, SK-DM, and SY% (r = 0.53 and 0.57, respectively). High semolina extraction is economically very important to a durum miller and the identification of accessions with these features is potentially quite valuable. Even a 1% improvement in yield represents a significant economic benefit to a miller and these accessions could provide considerable promise to a durum breeding program. Comparing the subspecies, the *polonicum* group had the highest average yields (71.2%) compared with the checks (mean 67.2%), suggesting that the screening of additional accessions from *polonicum* could identify more sources of valuable germplasm with better semolina extraction.

Starch damage. Starch damage (SD) more readily occurs when milling hard grains. The range for the accessions of 0.7 to 5.9% is wide, although the average of 4.2% was comparable to the checks (4.1%). Two accessions (AUS 285 and AUS 17045), subspecies of *durum,* had very low SD (1.2 and 0.7%, respectively) and were very soft-grain wheats. There was a high correlation between SK-HI and SD%, r = 0.82. The mean SD% was significantly higher in 1997, probably because the grain hardness was also higher in that year. Seven accessions had significantly higher SD compared with the average of the checks and were mainly from the *turanicum* group.

Semolina color. A bright yellow-colored semolina is desired by consumers; therefore, yellow color is a selection criteria in breeding programs, worldwide. It is not surprising, therefore, that the controls had significantly higher b values than all but three of the accessions (AUS 7922, AUS 17294, and AUS 22343B), which were equivalent (Table I). There were few accessions that had significantly different L values from the checks. Accession AUS 285 had a significantly higher L, probably because the b was very low. Some had lower $L,$ indicating dark-colored semolina, and this made very dark pasta. Utilization of accessions with low yellow color when

TABLE III
Pasta Quality Characteristics of Tetraploid Wheat Accessions and Commercial Cultivars

			Cooked Pasta Texture[a]			
Wheat	**Subspecies**	**OCT (min)**	**Firmness (g)**	**Resilience**	**Stickiness (g/sec)**	**CL%**
Cultivar						
Wollaroi	*durum*	13.3	405	0.76	5.8	5.6
Kamilaroi	*durum*	11.7	421	0.68	5.5	5.6
Yallaroi	*durum*	11.5	394	0.63	6.3	5.4
Accession[b]						
AUS285	*durum*	12.9	379	0.62	6.7	5.3
AUS297	*durum*	11.3	391	0.62	6.3	4.9
AUS7812A	*durum*	10.2	464	0.65	6.9	5.0
AUS7829	*durum*	11.0	422	0.50	6.1	4.9
AUS7842	*durum*	13.3	461	0.50	6.3	4.9
AUS7922	*durum*	11.7	292	0.78	5.8	5.2
AUS16041	*durum*	11.7	353	0.75	6.0	5.2
AUS17045	*durum*	11.0	303	0.67	5.6	5.0
AUS17294	*durum*	12.0	399	0.73	5.4	5.6
AUS20677A	*durum*	12.4	376	0.65	6.7	5.3
AUS20677B	*durum*	11.5	356	0.70	5.7	5.3
AUS22300	*durum*	11.3	333	0.70	6.2	5.4
AUS22303A	*durum*	12.3	348	0.58	6.2	5.1
AUS3549A	*persicum*	11.1	358	0.57	6.7	5.4
AUS3830	*persicum*	11.5	404	0.62	5.9	4.8
AUS3838	*persicum*	11.8	355	0.66	5.7	4.8
AUS3824	*polonicum*	11.3	398	0.69	6.4	4.9
AUS3917	*polonicum*	11.2	403	0.60	5.5	5.0
AUS4049	*polonicum*	10.4	486	0.62	6.1	4.9
AUS5533	*polonicum*	11.9	406	0.69	6.6	4.9
AUS16133	*polonicum*	12.5	423	0.76	14.7	5.2
AUS22342A	*polonicum*	12.3	490	0.61	5.8	4.7
AUS22342B	*polonicum*	12.5	364	0.69	5.6	4.8
AUS3603	*turgidum*	11.2	297	0.61	6.1	5.5
AUS15914	*turgidum*	12.0	320	0.88	6.3	5.3
AUS18721A	*turgidum*	11.9	369	0.73	5.5	5.7
AUS18721B	*turgidum*	11.7	395	0.70	6.1	5.7
AUS7810	*turanicum*	10.3	411	0.56	6.2	5.1
AUS7812B	*turanicum*	10.5	359	0.71	6.7	5.2
AUS13539	*turanicum*	11.8	318	0.75	6.2	5.4
AUS15198	*turanicum*	11.2	286	0.75	6.2	5.4
AUS17210	*turanicum*	11.5	310	0.61	6.1	5.3
AUS14210	*turanicum*	10.0	338	0.87	6.4	5.3
LSD[c]	…	2.0	107	0.16	5.9	0.4
Year P[d]	…	**0.003**	**0.001**	0.844	0.671	**0.002**
Genotype P	…	0.266	0.359	0.112	0.946	0.115

[a] OCT = optimum cooking time; CL% = cooking loss percentage of initial pasta weight.

[b] A and B refer to selection from the AUS accession.

[c] Least significant difference ($P < 0.05$).

[d] Values in bold are significant at $P < 0.05$.

breeding for a bright amber-colored pasta will require a breeding effort to improve the yellow color. This should not be difficult, because yellow color is highly heritable (Braaten et al 1962).

Protein Quantity and Quality

For good pasta quality, semolina protein above 10% and good dough strength and stability are important protein quality parameters (D'Egidio et al 1990, Matsuo et al 1972). In the Australian breeding program, dough strength is measured by the mixograph on early generation material and by the farinograph on advanced breeding lines. The dough should be strong and have good tolerance to overmixing.

Grain protein. Grain protein content for the accessions ranged from 13.3 to 18.3% with a mean of 15% (Table II). Nineteen of the accessions had significantly higher grain protein than the average for the checks (13.0%). Many of these belonged to the *durum*, *persicum,* and *polonicum* subspecies. There was a significant year effect on protein content, which is to be expected. Some of the high-protein accessions had significantly lower TKW compared with the checks, indicating a low proportion of starch in the kernel which would account for the higher grain protein content. There were 12 accessions with both significantly higher grain protein, SK-WT, and SK-DM than the checks. Of these, eight also had higher SY%. Accession AUS 7812B (*turanicum*) ranked the highest in these four parameters. Protein content was weakly correlated (Table IV) with cooked pasta firmness ($r = 0.32$) and negatively with cooking loss (CL%) ($r = -0.67$).

Dough rheology. There was a significant year affect on all the farinograph and extensigraph parameters, indicating a contribution of growing season to dough strength. There were no significant differences in farinograph water absorption (FWA) between the accessions and checks (Table II). A low water absorption could be a target for breeding because this reduces the time and energy needed to remove water during pasta drying. None of the accessions offered an advantage for FWA. Farinograph dough development time (FDDT), while less relevant to durum mixing than with bread wheats, does give an indication of dough stability. Significant correlations between FDDT and breakdown after 10 min of mixing past peak mixing time (FB10), extensigraph maximum height (R_{max}), and mixograph were found (Table IV). Generally, weaker doughs have shorter mixing times. Within the three checks, Kamilaroi was the weakest of the three checks and is used in the Australian breeding program as a low dough strength control; therefore, only comparisons between Yallaroi and Wollaroi with the accessions are relevant. Twenty-three of the accessions had significantly shorter FDDT compared with the checks. FB10 is used to score for strong and stable doughs in the breeding program. Once again, the majority of the accessions (20) had significantly larger FB10 values than the mean of Yallaroi and Wollaroi (66 BU), indicating that the accessions have poor dough stability. None had lower FB10 than these two checks. Dough strength is more accurately assessed using the R_{max}. Unfortunately, this parameter was very much affected by year and gave a large LSD value. For example, Wollaroi had an R_{max} of 425 BU in 1997 but only 270 in 1998. Only one accession (AUS 22342A, *polonicum*) had significantly higher R_{max} than the average of Yallaroi and Wollaroi (334 BU). This accession also had FB10, FDDT, and MPT comparable with the checks and also had excellent grain size, SY%, and pasta-making quality equivalent to the checks and would be suitable material for quality improvement. There were 20 accessions with significantly lower R_{max} than the average of the two checks, indicating that the majority of the accessions have inferior dough strength. Both FB10 and R_{max} are correlated ($r = -0.64$), so it is not surprising that those with moderate to low R_{max} had FB10 greater than checks. Eight accessions had a R_{max} significantly lower than Wollaroi and Yallaroi, consistent with their higher FB10 and lower FDDT values. Interestingly, many of the weaker accessions belonged to the *durum* group. Examination of the R_{max} data for each year separately cannot be rigorously assessed statistically but, knowing the reproducibility of the method (two standard deviations = 98 BU), it can be determined which accessions differed from the average of the controls. In 1998, the majority of the accessions had lower R_{max} values than the checks but there were six with equivalent strength. Of these, four (AUS 18721A, AUS 22342A, AUS 18721B, and AUS 17294) also had strength equivalent to the checks in 1998.

The importance of the extensibility measurement in pasta making is unclear but the accessions selected here contain those that were significantly more (3 accessions) and less (14 accessions) extensible than the average of the three checks. Extensibility is only

TABLE IV

Correlation Coefficients of Quality Traits for Tetraploid Accessions (Combined Years)[a]

	HLW	TKW	SY%	SK-WT	SK-DM	SK-HI	SD%	GP%	FWA	FDDT	FB10	EL
HLW	1.00											
TKW	0.21	1.00										
SY%	0.02	0.52	1.00									
SK-WT	0.16	0.99	0.53	1.00								
SK-DM	0.25	0.91	0.57	0.93	1.00							
SK-HI	–0.12	–0.12	0.69	–0.11	0.04	1.00						
SD%	–0.32	0.15	0.74	0.18	0.27	0.82	1.00					
GP%	0.11	0.19	0.25	0.17	0.16	0.04	–0.08	1.00				
FWA	–0.20	0.44	0.54	0.46	0.37	0.24	0.46	0.40	1.00			
FDDT	0.07	–0.02	0.16	0.04	0.00	0.22	0.08	–0.29	0.06	1.00		
FB10	–0.14	–0.07	–0.07	–0.11	–0.01	0.00	0.14	0.34	–0.02	–0.77	1.00	
EL	0.11	0.10	–0.04	0.14	0.03	–0.30	–0.34	0.20	0.13	0.17	–0.34	1.00
Rmax	–0.06	–0.09	0.03	–0.04	–0.11	–0.13	–0.15	–0.18	0.03	0.58	–0.64	0.30
MPT	0.17	0.00	–0.08	0.09	0.02	–0.17	–0.18	–0.47	–0.17	0.67	–0.67	0.20
MPH	–0.30	0.01	–0.01	–0.03	–0.06	–0.07	–0.01	0.27	0.30	–0.16	0.10	0.02
WatP	0.30	–0.10	–0.03	–0.09	–0.09	–0.03	–0.18	–0.35	–0.16	0.58	–0.52	0.40
Firm	0.22	0.01	0.22	0.03	0.10	0.27	0.06	0.32	0.19	0.31	–0.27	0.42
Resil	0.04	0.25	0.21	0.25	0.18	–0.08	0.05	–0.11	0.27	0.09	–0.20	0.20
Stick	0.04	0.30	0.23	0.33	0.28	–0.05	0.01	0.08	0.20	–0.18	–0.04	0.17
OCT	0.40	–0.08	–0.12	–0.08	–0.12	–0.14	–0.40	–0.17	–0.34	0.43	–0.58	0.24
CL%	0.08	–0.04	–0.01	–0.07	–0.03	0.07	0.14	–0.67	–0.06	0.08	–0.20	–0.20

[a] Correlation coefficients above 0.42 are highly significant ($P < 0.01$); those over 0.32 are significant ($P < 0.05$). HLW = hectoliter weight, TKW = 1,000-kernel weight, SY% = semolina mill yield percentage, SK-WT = single-kernel weight, SK-DM single-kernel diameter, = SK-HI single-kernel hardness index, = SD% starch damage percentage, = GP% = FWA = farinograph water absorption, FDDT = farinograph dough development time, FB10 = farinograph breakdown after 10 min, EL = extensograph extensibility, Rmax = extensograph maximum resistance, MPT = mixograph peak development time, = MPH = WatP = mixograph width of curve at peak mix time, Firm = firmness, Resil = resiliency, Stick = stickiness, OCT = optimum cooking time, CL% = cooking loss percentage.

weakly correlated with all the parameters (Table IV). The range among the accessions (12.3–23.2 cm) was similar to that found in breeding material in the National Durum Wheat Breeding Program (data not shown). Extensibility may be important for laminated pasta, which includes much of the fresh pasta, where more extensible and weaker gluten are more suitable for sheeting.

Mixograph. The mixograph is another method used to assess gluten strength and is well correlated to R_{max} (mixograph peak time, r = 0.60; WatP, r =0.48). It was found, from over 20 years' usage of the mixograph in the Australian Durum Program, that a mix time of at least 3.5 min, good peak height, and a wide width of the curve at peak mixing are all indicators of strong gluten. *Durum* accession AUS 17294 was equivalent in strength to Wollaroi but all the others were weaker. Kamilaroi was the weaker of the three checks, with a shorter MPT and WatP, consistent with the farinograph and extensigraph data. Although MPT and WatP were significantly correlated to R_{max}, FDDT, and negatively to FB10, the r^2 values only range from 0.23 to 0.45; therefore, the mixograph does not give exactly the same measure as the other instruments (the mixograph has a different mixing action and imparts higher energy to the dough).

In summary, while each of the measures provide information about the gluten strength and dough rheological properties, the accessions are, in general, lower in gluten strength than the cultivars.

Pasta Quality

Optimum cooking time. The optimum cooking time (OCT) for all the pastas was within a narrow range (10.0 to 13.3 min), with no difference between the mean of the checks and accessions (Table III). The OCT is largely affected by protein content, pasta diameter, and drying conditions, and the latter two were kept constant.

Firmness. A wide range in firmness values for the accessions was obtained: 286 to 490 g with an average of 375 g compared with the checks of 407 g. A higher firmness is preferred from a sensory point of view and our test resembles the first bite in sensory analysis. There was a highly significant year effect on the firmness measurement, which caused a large LSD. None of the accessions produced pasta that was firmer than the average of the checks (407 g), but there were three accessions that were significantly less firm. While the test error has a 2 standard deviations of ± 50 g, there is quite a large environmental influence on the firmness measurement (year effect was highly significant, with higher overall average firmness across all samples in 1997 than in 1999; 419 vs. 328 g). It is possible to rank the accessions with respect to the mean firmness for the checks for each of the two years. In 1997, accessions AUS 4049 and AUS 7812A had significantly higher firmness than the mean of two controls, but not in 1998. No accessions had a higher firmness than the checks in 1999. In contrast, there were 12 accessions with lower firmness in 1997, 6 of which also had significantly lower firmness in 1998. Thus, it is possible to rank the samples but, in general, the accessions were either equivalent or lower in cooked firmness than the checks. Firmness was weakly negatively correlated with resilience (r = –0.46) and CL% (r = –0.36) and positively correlated with grain protein (r = 0.32) (Table IIV). Although these were all significant, they only explained a small percentage of the variation in firmness. Protein contributes to pasta firmness; therefore, as protein increases the pasta would be expected to become firmer and, therefore, less resilient. Protein composition also affects pasta firmness (D'Egidio et al 1990, Matsuo et al 1972) and this differed between the accessions (data not shown).

Resilience. Resilience is probably related to the elasticity of the pasta, which could be measured by tests like the alveograph or viscoelastograph. The requirements for fresh, long, and short dried goods pasta in terms of elasticity are likely to vary. While resilience measured here using the TA.XT2 gives some measure of elasticity, it is unknown how this relates to end product requirements. Resilience varied from 0.5 to 0.9, with an average the same as the checks. Two accessions (AUS 15914 and AUS 14210) had higher resilience than the checks (0.69) which could be an advantage for some types of pasta. There is a weak negative correlation between resilience and firmness (r = –0.46), so that a firmer pasta would have a lower resilience. The cultivars from the Australian breeding program have resilience values generally greater than 0.85, but this may make them less desirable for certain end products requiring more elasticity. Further research is needed to understand the relationship between end product requirements and textural measurements.

Stickiness A low stickiness is desired in cooked pasta. The average stickiness for the accessions was 6.4 versus 5.9 for the checks and there were no significant differences between any of the samples. The only exception was AUS 16133, which had an extremely high value in 1997, which cannot be explained. These accessions do not have inferior pasta stickiness. The cause of stickiness is not clear and could be related to the amount of amylose and amylopectin leaching onto the surface of the pasta during cooking. Stickiness was poorly correlated with all other parameters, indicating that the surface condition of the pasta is being measured, a feature reflected in none of the other test measurements.

CL%. A low CL% is also a desirable feature of good quality pasta. The CL% of the accessions was 4.7 to 5.7%, a relatively narrow range. Although there were no accessions with higher CL% than the checks, there were 14 accessions that had significantly lower CL%. All but one of the *polonicum* accessions had lower CL% than the average for the checks. However, the differences were still very small and probably not worth consideration in a breeding program because CL% is already acceptable. CL% was significantly but weakly negatively correlated with grain protein (r = –0.67) and firmness (r = –0.36).

CONCLUSIONS

Diversity was found both for grain and pasta-making quality in the tetraploid accessions, differing from that observed in the three Australian durum cultivars. This variation in quality traits has the potential to be valuable in the genetic improvement of future cultivars. Superior grain protein, grain size, and semolina mill yield were identified in some of the tetraploid accessions consistently over two seasons. Genes for these enhanced quality traits have been

TABLE IV (continued)
Correlation Coefficients of Quality Traits for Tetraploid Accessions (Combined Years)[a]

	Rmax	MPT	MPH	WatP	Firm	Resil	Stick	OCT	CL%
Rmax	1.00								
MPT	0.60	1.00							
MPH	0.06	–0.11	1.00						
WatP	0.48	0.68	–0.34	1.00					
Firm	0.13	–0.05	–0.05	0.21	1.00				
Resil	0.30	0.27	–0.08	0.19	–0.46	1.00			
Stick	–0.17	–0.13	–0.26	–0.01	0.15	0.15	1.00		
OCT	0.33	0.42	–0.11	0.32	0.08	0.11	0.14	1.00	
CL%	0.19	0.31	–0.28	0.43	–0.36	0.42	–0.04	0.09	1.00

introgressed into the breeding populations. The work has shown that it is beneficial to screen accessions of tetraploid subspecies for potential quality improvement. Other benefits may include agronomic properties, disease resistance, and better adaptation to abiotic stress.

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