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Variation of Seed Dormancy and After-ripening in Tetraploid Wheat (*Triticum durum, T. turgidum, T. turanicum, T. carthlicum, T. polonicum*)

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ABSTRACT

In western Canada, durum wheat cultivars (*Triticum durum*) have low to moderate levels of seed dormancy and are susceptible to pre-harvest sprouting. The aim of this study was to evaluate the dormancy level of Canadian durum wheat cultivars and to identify tetraploid wheat accessions with elevated levels of seed dormancy. First, the level of seed dormancy and length of after-ripening of 17 North American durum wheat cultivars were evaluated. The plants were grown under field conditions in 1995 and 1996, harvested at maturity (Zadok's Growth Stage 92, ZGS 92), dried at room temperature for one week, and assessed for level of seed dormancy over seven weeks of after-ripening at 20°C. Seed dormancy was characterized by the extent of germination at 20°C. The results indicated that five durum cultivars exhibited moderate levels of seed dormancy at maturity while the remaining cultivars were non-dormant. Likewise, a rapid loss of dormancy (within 2-3 weeks of after-ripening) was characteristic of all durum cultivars. In a second experiment, 78 accessions of *T. turgidum, T. turanicum, T. carthlicum, T. polonicum, and T. durum* from the USDA germplasm collection grown under field conditions in 1995 and 1996 were evaluated for seed dormancy with the idea of identifying potential sources of increased seed dormancy. At ZGS 92, eighteen accessions were classified as dormant. Accession 93-282 was the only highly dormant genotype in this study. The seven most dormant accessions, identified in two years of field tests, were tested for length of the dormancy period. Accession 93-282 was the only genotype that had a longer period of dormancy than the durum cultivar, Kyle. The intensity of seed dormancy was quantified at five germination temperatures. A dormancy index was calculated from germination data at 10 and 20°C. The dormancy indices of tetraploid accessions 93-62 and 93-177 were 37% higher than that of the durum cultivar Kyle.

Keywords: After-ripening, Dormancy index, Seed dormancy, Seed germination, Temperature, Tetraploid wheat.

INTRODUCTION

Dormancy in wheat caryopses (*Triticum* spp.) is an important agronomic trait. Lack of dormancy can result in pre-harvest sprouting under wet climatic conditions, which adversely affects end-use quality. In contrast, excessive dormancy results in poor stand establishment (Derera, 1989).

Primary dormancy in cereal caryopses arises during the development of the grain on the mother plant. The intensity of dormancy varies greatly, and this variation may be genetic in origin, but influenced by the environmental conditions occurring during grain development (Simpson, 1990). Primary dormancy in cereals is temperature dependent. Primary dormancy is generally displayed only above certain critical tem-

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peratures, usually around 17-20°C in the germination medium. Freshly harvested caryopses may not germinate when placed under optimum environmental conditions and will only germinate after a period of dry storage referred to as after-ripening (Bewley and Black, 1994).

In western Canada, a low level of grain dormancy and a short period of after-ripening are undesirable because, occasionally, untimely rains at harvest cause sprouting of the grains in the spike before the wheat can be harvested. Durum wheat cultivars (*Triticum durum*) have low to moderate levels of dormancy and are susceptible to pre-harvest sprouting. Economic losses resulting from sprouting in wheat (prairie-wide) are estimated at 5.25% per annum (Wahl and O'Rourke, 1993). Based on that estimate, losses in the Canada Western Amber Durum crop average $36 million per annum. Moreover, millers are reluctant to purchase sprouted durum, and the commercial grade standard tolerates only low amounts of visible sprouting. In Canada, a maximum of 0.5% of kernels with visible sprouts is permitted in the top durum grade (Canadian Grain Commission, 1991).

It is generally accepted that the long-term solution to the pre-harvest sprouting problem lies in the development of cultivars that resist the damaging effects of rain during the period between maturity and the completion of harvest. In order to breed new cultivars with higher levels of grain dormancy and reduced sprouting damage, the levels of dormancy in existing cultivars or germplasm needs to be identified.

Reported studies on dormancy and after-ripening in tetraploid wheat are few in number and only a limited number of genotypes have been investigated (Clarke *et al*., 1994, Hare *et al*., 1988). The objectives of this study were to determine: levels of dormancy and length of after-ripening in five tetraploid and one hexaploid wheat species and the temperature sensitivity or response to temperature of wheat genotypes differing in dormancy level.

MATERIALS AND METHODS

Length of Seed Dormancy Period in Durum Cultivars

Plant Materials: For this experiment, 17 durum cultivars (*Triticum durum*) and three common wheat (*Triticum aestivum* L.) controls were used. This experiment was conducted at two locations, the University of Saskatchewan's Seed Farm (Saskatoon) and Kernen Crop Research Farm (6 km east of Saskatoon) in 1995 and 1996. The soil types at the Seed Farm and Kernen Farm were an orthic-dark-brown Bradwell clay-loam and Sutherland clay/clay-loam, respectively. At each location, a randomized complete block design (RCBD) with four replications was used. Each plot consisted of four 2.4m long rows spaced 30 cm apart and was sown at approximately 250 seeds per m^2. Sowing dates were 4 and 17 May in 1995 and 13 and 28 May in 1996 for the Seed Farm and Kernen Farm, respectively. Fertilizer (11-51-0) was drilled with the seed at approximately 50 kg ha^{-1} and all experiments were conducted on fallow land.

For all experiments, spikes were harvested when plants reached Zadok's growth stage (ZGS) 92 (Zadoks *et al*., 1974). The spikes were held at room temperature (23±2°C) for 7 days, then placed in a freezer at -20°C (Mares, 1983). For this particular experiment, 40 and 50 spikes were harvested per plot in 1995 and 1996, respectively.

Laboratory Experiments: At least 15 intact spikes per plot (collected from the field) were threshed by hand. Seeds were stored in sealed paper envelopes at -20°C and removed from the freezer at one-week intervals and kept at room temperature (23±2°C) for seven weeks. Germination tests were conducted with 50 seeds. Seeds were placed in Petri plates (9 cm diameter) lined with a double layer of filter paper (Whatman No.1) containing 5 m of double distilled water. Germination tests were conducted for seven days in an incubator at 20°C under dark conditions. A RCBD (coincident with the

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field experimental design) was used in this experiment. Each plot within a block consisted of 50 seeds placed on a Petri plate. A Hotpack model 352632 illuminated environmental chamber (Hotpack Corporation, Philadelphia, Pennsylvania) was used. The relative humidity inside the chamber was 45-50%. Germination tests were conducted within two months of harvest. After seven days, germinated seeds were counted and removed. Ungerminated seeds were treated with 1 mM of gibberellic acid (GA_3) solution (Hou and Simpson, 1993) to evaluate their viability. The treated seeds were counted after 3 days at 20°C. In order to evaluate seed dormancy, the final percentage germination was divided into the number of seeds germinated prior to GA_3 treatment. A seed was considered germinated when the radicle pierced the coloeorhiza and was between 3 and 4 mm in length.

Screening Tetraploid Wheat Germplasm for Seed Dormancy

Plant Materials: A total of 78 tetraploid wheat accessions from four species (*Triticum turgidum, T. turanicum, T. carthlicum and T. polonicum*) from the USDA germplasm collection, five commercial durum cultivars, and three common wheat cultivars were used. This experiment was conducted in 1995 and 1996 at one location, University of Saskatchewan's Seed Farm. A RCBD with four replications was used. Each plot consisted of a single 2.4 m long row with a row spacing of 30cm. The sowing dates were 5 and 15 May in 1995 and 1996, respectively. Fifty spikes per plot were harvested at ZGS 92.

Laboratory Experiments: At least 15 intact spikes per plot were threshed by hand. Germination tests were carried out on the hand-threshed seeds. A RCBD with four replications was used. The experimental method was the same as in Experiment 1.

Length of Seed Dormancy in Selected Tetraploid Accessions

In this experiment, 10 accessions (six tetraploid and four hexaploid) with the highest level of seed dormancy, Kyle and Sceptre, durum controls, and RL4137 and AUS1408 (dormant common wheat controls) were evaluated for the length of seed dormancy. Germination tests were conducted using a RCBD with three replications of 25 and 50 seeds in 1995 and 1996, respectively. The experimental method was the same as in Experiment 1.

Evaluation of Seed Dormancy in Wheat Genotypes at Five Temperatures

Plant Materials: Nine accessions with a high level of seed dormancy along with the durum cultivars, Kyle and Sceptre, and common wheat cultivars, RL4137, AUS1408 and AUS1293 were tested for temperature sensitivity. Plants grown in 1996 and 1997 were used as the seed source for this experiment.

Laboratory Experiments: Fifty hand-threshed seeds stored at -20°C were placed on two filter papers (Whatman No.1) per Petri plate (9 cm diameter) containing $5mL^{-1}$ distilled water and incubated for seven days at 5, 10, 15, 20, or 25°C in the dark. A split plot design with three replications was used. The temperatures and genotypes were considered as the main and subplots, respectively. The germinated seeds were counted after seven days, and ungerminated seeds were treated with gibberellic acid (1 mM) to test their viability.

A dormancy index (DI) (Strand, 1989) was calculated from the germination test data at 10°C and at 20°C. The formula is as follows:

$$DI = \frac{\%\ \text{dormant seed at } 10\,^{\circ}\text{C} \times 2 + \%\ \text{dormant seed at } 20^{\circ}\text{C}}{3}$$

Analysis of variance was conducted for dormancy index. Genotypes were compared with respect to their dormancy indices.

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Data Analysis

Analysis of variance (ANOVA) was performed for individual experiments separately. Subsequently, combined analyses were used over the years and locations. For all experiments, years, locations and replications were considered random. To test the homogeneity of variances, the Bartlett's test was used.

In germination experiments (percentage based), a wide range of germination data (0% to 100%) results in smaller variances of means near 0% and 100% than the variances of means near the middle range (30% to 70%) (Fernandez, 1992). In the present study, since the percentages of germination ranged from 0% to 100%, an arcsin ($\sqrt{\%}$) or angular transformation is appropriate.

Least significant differences (LSD) were calculated to measure the differences between cultivars, temperatures, and dormancy indices. In a mixed model, for comparing two genotype means (averaged over all levels of other factors in the experiment), a special procedure for synthesizing F- tests, approximating degrees of freedom, and calculating appropriate LSDs is required. The procedures of Carmer *et al*. (1989) were followed with some modification to allow for environmental variation to be subdivided into year, location, and year × location interaction (R.J. Baker, personal communication).

Estimated variance of a mean and its degrees of freedom are used to calculate an LSD in the usual way, i.e., LSD $(\alpha)=t_{\alpha/2,df}\sqrt{[2 \times \text{estimated variance of a mean}]}$.

RESULTS

Length of Seed Dormancy in Durum Cultivars

The cultivars exhibited a gradual loss of dormancy with after-ripening (Table 1). Among the durum cultivars, Kyle had the highest level of seed dormancy, with germination angles of 57 and 37 at week zero in 1995 and 1996, respectively (data not shown).

Combined analyses indicated that differences among cultivars and among lengths of after-ripening were statistically significant (data not shown). The interaction between cultivar and after-ripening period was highly significant, suggesting that cultivars differed in patterns of dormancy loss.

A seven-week after-ripening period resulted in a reduction in seed dormancy as demonstrated by higher germination (>80%, i.e, >63°) in all cultivars except RL4137. With the exception of RL4137 and the durum cultivar, Kyle, four weeks of after-ripening resulted in higher germination (90%, i.e., 73°) in the remaining cultivars (Table 1).

In the absence of after-ripening, three groups of cultivars can be identified (Table 1). In the first group, 11 cultivars (Arcola, Coulter, Hercules, Macoun, Medora, Ramsey, Plenty, Sceptre, Ward, Katepwa, and Fielder) showed no signs of seed dormancy at ZGS 92 as characterized by high germination (80%, i.e,>63°). Germination of this first group following seven weeks of after-ripening was similar in 1995 and 1996.

In the second group, a number of cultivars with various germination responses including Kyle (47°=53%), Wascana (52°=62%), Mindum (55°=67%), Pelissier (56°=69%), Lakota (58°=72%), and Stewart (59°=73%), exhibited intermediate levels of seed dormancy at week zero (Table 1) and a higher germination angle following after-ripening. The calculated LSD indicated that, among durum cultivars, Kyle exhibited a significantly higher level of seed dormancy at all after-ripening intervals than the non-dormant cultivars in the first group.

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Table 1. Germination angle ($\sin^{-1}\sqrt{}$ transformation) of wheat cultivars with up to seven weeks of after-ripening at room temperature averaged over years and locations.

	Length of after-ripening (weeks)								
Genotype	0	1	2	3	4	5	6	7	Average
Durum									
Arcola	81	80	85	86	89	87	88	88	86
Coulter	78	82	84	85	86	86	85	89	84
Hercules	76	80	82	82	85	83	87	86	83
Kyle	47	54	61	63	72	75	77	81	66
Lakota	58	65	67	72	75	78	80	83	72
Macoun	71	75	80	82	84	86	85	88	81
Medora	72	78	82	87	86	88	89	89	84
Mindum	55	65	70	72	77	78	85	86	73
Pelissier	56	64	71	74	78	82	80	86	74
Plenty	68	71	74	80	83	85	83	87	79
Ramsey	73	79	84	87	87	87	88	89	84
Sceptre	77	81	82	84	84	83	84	89	83
Stewart	59	73	77	83	86	86	89	90	80
Stewart 63	62	68	75	81	83	85	86	88	79
Wakooma	63	67	71	76	77	80	83	84	75
Ward	69	77	81	83	84	86	86	88	82
Wascana	52	59	65	73	74	83	81	83	71
Common wheat									
Katepwa	79	88	89	87	89	89	89	88	87
RL4137	11	13	18	30	37	45	53	59	33
Fielder	82	84	87	88	89	90	88	89	87
LSD (0.05) between two genotypes at one level of after-ripening=7[a]									

[a]synthetic error term=$\sqrt{[1/128 \times (629.8+288.2-523.7+7(39.9)+7(60.8)-7(46.9))]}$.
Satterthwaite's df=5.

The common wheat control cultivar, RL4137, was the only one with a very high level of seed dormancy at week zero. A long period of after-ripening was required for RL4137 to increase caryopsis germination. Seven weeks of storage at room temperature resulted in a large reduction in dormancy (germination angle of 59°=73%) for this cultivar.

Screening Tetraploid Wheat Germplasm for Seed Dormancy

A combined analysis indicated significant differences among wheat genotypes for germination at 20°C. The interaction between year and wheat genotypes was also statistically significant (data not shown). The wheat genotypes exhibited a wide range of germination at 20°C (Table 2). The calculated LSD indicated significant variation among tetraploid accessions. The wheat genotypes ranged from 14% (22°) for accession 93-282 to 100% (90°) in germination for accessions 93-22 and 93-37.

T. polonicum and *T. turgidum* contained dormant genotypes. Based on the calculated LSD value (Table 2), a number of wheat accessions had significantly higher levels of seed dormancy than the best durum control cultivar, Kyle. Accessions 93-282 and 93-951 with 14% (22°) and 21% (26°) germination, respectively, were in that group. Accessions from *T. carthlicum* were all non-dormant.

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Table 2. Seed dormancy at ZGS 92 as characterized by the germination angle ($\sin^{-1}\sqrt{}$ transformation) and germination (%) after 7 days at 20°C (averaged over years).

Genotype	Germination angle	Germination (%)	Genotype	Germination angle	Germination (%)
93-21 (tg)	69	87	93-152	77	95
93-22	90	100	93-176	50	58
93-33	65	82	93-177	39	39
93-37	90	100	93-190A	44	48
93-40	76	94	93-190B	41	43
93-44	71	89	93-192	42	45
93-100	46	51	93-268B	57	70
93-153	77	95	93-269	40	41
93-159	61	76	93-271A	48	55
93-161	74	92	93-342	77	95
93-164	68	86	93-381	84	99
93-165A	66	84	93-416	39	40
93-173	82	98	93-460	46	52
93-183	63	80	93-461	52	62
93-197	66	84	93-474	40	42
93-209	47	53	93-822	68	86
93-214	55	67	93-976	48	55
93-218	70	88	93-363 (ca)	69	87
93-220	66	84	93-419	74	92
93-222	80	97	93-501	84	99
93-265	42	45	93-837	84	99
93-274	66	84	93-369 (po)	31	27
93-282	22	14	93-933	60	75
93-374	77	95	93-935	54	65
93-440	70	88	93-943	54	66
93-443	32	28	93-951	26	21
93-468	61	77	93-955	44	48
93-522	47	54	93-956A	66	84
93-542	76	94	93-960	36	35
93-576A	42	45	93-965	82	98
93-574	46	52	93-967	84	99
93-577	51	60	Kyle (du)	44	49
93-580	36	34	Plenty	71	89
93-583	49	57	Medora	75	93
93-823	45	50	Sceptre	76	94
93-824	47	54	Arcola	82	98
93-826	49	57	RL4137 (as)	6	1
93-827B	71	89	Aus1293	32	28
93-909	84	99	Aus1408	25	18
93-921	60	75	93-480	8	2
93-922	66	83	93-581	20	12
93-62 (ta)	37	36	93-619	30	25
93-143	78	96	93-634	16	8
LSD (0.05)=	18[a]			18	

tg=*T.turgidum*, ta=*T. turanicum*, ca=*T.carthlicum*, po=*T. polonicum*, du=*T.durum*, as=*T.aestivum.*
[a]LSD=1.99 × √[2 × 312.9/8].

On average, a higher germination was detected in 1995 than in 1996. However, a number of accessions including 93-159, 93-220, 93-369, and 93-634 did not show such a pattern with their germination being higher in 1996.

The back-transformed data in this experiment was used to group genotypes into a subjective dormancy grouping (based on average germination percentage) namely,

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non-dormant (>80%), moderately dormant (50%-80%), dormant (20%-49%), and highly dormant (<20%). *Triticum turgidum* accession 93-282 with 14% (22°) germination was the only tetraploid genotype with a high level of seed dormancy. Likewise, a number of hexaploid genotypes including RL4137, 93-634, and 93-480 with 1% (6°), 8% (16°), and 2% (8°) germination, respectively, were typical of this group.

Triticum turanicum contained a number of dormant genotypes. Accessions 93-62 and 93-177 with 36% (37°) and 39% (39°) germination, respectively, were typical of this group. The results of this study indicated that a large number of genotypes showed little or no dormancy. Accessions 93-22 and 93-37 with 100% (90°) germination were typical of the non-dormant group. Of the durum control cultivars, Kyle with 49% (44°) germination was the only one that showed an intermediate level of seed dormancy.

With the exception of *T. carthlicum*, each species contained dormant and highly dormant genotypes (Table 3). *T. polonicum* and *T. turanicum* were the most dormant, having the lowest average germination level.

Table 3. Average and range of germination (%) for four tetraploid species and five durum control cultivars evaluated in 1995 and 1996.

Species	Number of accesions	Average	Range
T. carthlicum	4	94	87-99
T. polonicum	10	61	21-99
T. turgidum	41	74	14-100
T. turanicum	19	61	36-99
T. durum	5	85	49-98
Total	79		

Length of Seed Dormancy in Selected Tetraploid Accessions

Ten accessions with the highest level of seed dormancy were selected from Experiment 2 (Table 4). Two durum cultivars (Kyle and Sceptre) and two highly dormant common wheat cultivars (RL4137 and AUS1408) were considered as controls in this experiment.

Significant differences were observed among genotypes and lengths of after-ripening in both years (1995 and 1996) (data not shown). Likewise, the interaction between genotype and after-ripening was statistically significant. Tetraploid wheat genotypes expressed varying levels of seed dormancy at week zero in both years and lost dormancy following different patterns. At week zero, tetraploid genotypes 93-282 and 93-951 expressed higher levels of dormancy than Kyle in 1995 and 1996 (data not shown). Likewise, hexaploid accession 93-480 was more dormant than the control cultivar (RL4137) in 1995, 20% (24°) versus 40% (38°) germination percent, and expressed a similar level of dormancy (19%=26°) in 1996. Sceptre, with the highest level of germination, was considered as non-dormant with more than 90% germination.

A combined analysis of variance was conducted on transformed data (data not shown). Significant differences were detected among genotypes and length of after-ripening. Accessions displayed a wide range of seed dormancy at ZGS 92 (week zero) (Table 4). Among tetraploid genotypes, accessions 93-282 and 93-951 with a germination percentage of 11% (19°) and 12% (20°) were highly dormant. The LSD (Table 4) indicated that significant differences existed between all tetraploid accessions and Sceptre (non-dormant cultivar) at week zero. However, only accession 93-282 exhibited a

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Table 4. Germination angle ($\sin^{-1}\sqrt{}$ transformation) of selected tetraploid and hexaploid wheat genotypes (averaged over years) at ZGS 92 (week 0) and up to seven weeks of after-ripening at room temperature.

	Length of after-ripening (week)								
Genotype	0	1	2	3	4	5	6	7	Average
Tetraploid									
93-282	19	21	39	51	61	67	70	79	51
93-369	30	48	59	73	73	79	88	88	67
93-580	30	45	50	61	70	77	81	85	62
93-951	20	52	74	77	90	86	90	90	72
93-955	46	56	69	78	78	85	87	88	73
93-960	32	55	63	75	81	84	90	86	70
Kyle	39	44	55	66	68	71	76	77	62
Sceptre	79	81	84	88	85	86	88	90	85
Hexaploid									
93-480	5	9	17	20	23	31	34	45	23
93-581	15	27	35	42	47	54	56	62	42
93-619	18	26	42	41	53	61	69	69	47
93-634	9	14	24	25	34	41	45	47	30
RL4137	10	16	23	26	34	39	44	47	30
AUS1408	13	22	23	26	30	31	37	34	27
LSD (0.05) (between two genotypes at one level of after-ripening)= 22[a]									

[a] $2.07 \times \sqrt{[2/48 \times (2082.3+7(99.0))]}$ where synthetic error is: $[2/48 \times (2082.3+7(99.0))]$; df=23.

significantly higher level of seed dormancy than the durum control cultivar Kyle at a given level of after-ripening (first week). Among hexaploid genotypes, no significant differences were detected. All these genotypes exhibited a high level of seed dormancy at week zero. The level of dormancy in the selected hexaploid genotypes was higher than that of the selected tetraploid genotypes.

The data suggest different patterns of dormancy loss during after-ripening among genotypes (Table 4). The first pattern, exhibited by hexaploid genotypes 93-480, 93-634, RL4137, and AUS1408, showed no apparent changes in the level of seed dormancy after four weeks of after-ripening and only a moderate change between 4 and 7 weeks. In this highly dormant group, genotypes exhibited nearly identical levels of seed dormancy at ZGS 92 (week zero). Seven weeks of after-ripening resulted in moderate increases in germination angle of the aforementioned genotypes.

In the second patten characteristic of tetraploid accessions 93-960, 93-580, 93-955, 93-369, and 93-951 and the cultivar Kyle, three weeks of after-ripening significantly reduced the level of dormancy with the germination percentage ranging from 76% (61°) to 94% (77°).

The third pattern, characteristic of 93-282, 93-581 and 93-619 showed a moderate reduction in seed dormancy after four weeks, with a further decrease between 4 and 7 weeks. Although accessions 93-581 and 93-619 exhibited a similar level of seed dormancy to the first group at week zero, in contrast to the first group, they reached 77% (62°) and 85% (69°) germination , respectively after seven weeks of after-ripening. The last pattern, exhibited by durum cultivar, Sceptre, showed no dormancy at any stage of after-ripening.

Evaluation of Seed Dormancy in Wheat Genotypes at Five Temperatures

A combined analysis of variance detected significant differences among years, replication, genotypes, and temperatures (data not

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Table 5. Germination angle (arcsin square-root transformation) of wheat genotypes at ZGS 92 conducted at five temperatures for seven days over two years (1996 and 1997).

	Temperature					
Genotype	5 °C	10 °C	15 °C	20 °C	25 °C	Average
Tetraploid						
93-282	6	78	63	30	13	38
93-369	20	79	76	35	20	46
93-580	7	65	69	42	28	42
93-951	14	76	79	30	13	43
93-955	19	78	73	39	15	45
93-960	20	79	72	33	11	42
93-443	32	85	82	43	24	53
93-62	6	53	47	28	20	31
93-177	6	57	50	23	21	31
Kyle	4	69	58	40	29	40
Sceptre	5	79	70	60	65	56
Hexaploid						
RL4137	3	67	40	11	4	25
AUS1408	7	53	33	21	7	24
AUS1293	3	71	48	27	19	34
LSD (0.05) (between two genotypes at one level of temperature)=23[a]						

[a] $2.01 \times \sqrt{[2/30 \times (744.6+4(290.90))]}$; where synthetic error is $1/30 \times (744.6+4(290.90))$; df=53.

shown).

Genotypic differences in germination occurred both at low and high temperatures (Table 5). In general, a higher percentage of seeds germinated at 10°C compared to 20°C. However, the magnitude of the change resulting from the temperature shift differed from genotype to genotype.

Among the genotypes that showed no level of dormancy at 10°C, a relatively high level of dormancy and large genotypic differences were observed at 20°C. Except for the non-dormant cultivar, Sceptre, which had a relatively high germination across temperatures (10°C to 25°C), germination of other genotypes decreased at higher temperatures (Table 5).

After seven days of incubation, all cultivars showed low germination at 5°C. While accession 93-443 exhibited the highest level of germination, the calculated LSD did not detect any significant differences between the durum cultivar Kyle and the best tetraploid accession, 93-282. At this temperature, a longer period of time is required for germination. According to Bewley and Black (1994), lack of high metabolic activity (e.g. enzyme activity for respiration) at low temperature could result in lower germination levels. However, this low temperature can condition the seeds to germinate at higher temperatures. At 10°C, the germination of all genotypes increased significantly. With the exception of 93-62 and 93-177 with germination percentages 64% (53°) and 69% (57°), respectively, the other genotypes exhibited higher levels of germination. At 10°C, these two tetraploid accessions exhibited significantly higher levels of seed dormancy than the durum control cultivar, Sceptre. At this temperature (10°C), very little seed dormancy was detected for the highly dormant hexaploid controls, RL4137 and AUS1293 (84% (67°) and 89% (71°), respectively.

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Table 6. Dormancy indices of wheat genotypes at two germination temperatures conducted in 1996 and 1997.

Genotype	Dormancy index	
	1996	1997
Tetraploid		
93-282	41.3	13.6
93-369	32.4	16.7
93-580	55.1	12.4
93-951	46.7	15.1
93-955	27.3	21.3
93-960	34.7	20.9
93-443	32.4	3.8
93-62	75.3	25.3
93-177	73.1	28.0
Kyle	52.0	11.3
Sceptre	12.0	11.7
Hexaploid		
RL4137	53.1	34.2
AUS1408	74.2	28.2
AUS1293	39.8	19.7
LSD (0.05)=	14.0[a]	10.8[b]

[a] $1996=2.056\times\sqrt{[2\times70/3]}$
[b] $1997=2.056\times\sqrt{[2\times41.2/3]}$

Raising the temperature beyond 10°C reduced germination thus increasing the expression of seed dormancy. At 20°C, seeds of all genotypes had significantly lower germination than at 10°C.

Among tetraploid wheat genotypes, the non-dormant cultivar Sceptre had high levels of germination at all temperatures above 5°C. Except at a very low temperature (5°C), accessions 93-62 and 93-177 exhibited higher levels of seed dormancy than Sceptre at the other temperatures. The hexaploid control cultivars expressed a high level of dormancy and did not differ significantly from each other. On average, tetraploid accessions 93-62 and 93-177 exhibited a higher level of seed dormancy than the durum control cultivar, Kyle. Averaged over temperatures, hexaploid wheat controls, RL4137 and AUS1408, expressed the highest level of seed dormancy.

Germination at 10°C and at 20°C is considered as a strong test for seed dormancy (Strand, 1989). Transformed data were used to calculate the dormancy index. The dormancy indices (DI) of wheat genotypes were calculated from germination data at 10°C and 20°C. Analysis of variance detected significant differences among genotypes in both 1996 and 1997 (data not shown). On average, the dormancy index was 57% higher in 1996 than in 1997. Except for Sceptre, which had a similar dormancy index in both years, the dormancy indices of all genotypes decreased in 1997.

A relatively wide range of dormancy indices was detected among genotypes. Accessions 93-62 and 93-177 with dormancy indices of 75.3 and 73.1 in 1996 and 25.3 and 28.0 in 1997, respectively, had stronger dormancy levels than the tetraploid durum control, Kyle (Table 6). All hexaploid genotypes exhibited similar dormancy indices in 1997 based on the calculated LSD.

DISCUSSION

Resistance of cereal cultivars to preharvest sprouting is thought to be largely a result of seed dormancy (Fujita *et al*., 1996). In the first part of the current study, the genetic variation in dormancy level and length of after-ripening in a cross-section of Cana-

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dian and U.S. durum cultivars were investigated. In this study, dormancy loss in durum wheat was characterized by progressive changes in germination angles. None of the durum cultivars exhibited high levels of dormancy at ZGS 92. The cultivars Kyle, Wascana, Mindum, and Pelissier were the only cultivars that exhibited moderate levels of dormancy at ZGS 92 (Table 1). Different cultivar patterns of germination response were observed over the seven weeks of after-ripening. Among durum cultivars, Kyle was the only one that required a longer period (four weeks) of after-ripening to reach high germination angle. The hexaploid control cultivar RL4137 required the longest period of after-ripening.

In breeding programs, the use of tetraploid sources with high levels of seed dormancy would be genetically easier (Clarke *et al*., 1994). The accessions displayed a wide range of seed germination at 20°C (Table 2). Based on the calculated LSD (p=0.05), only one accession had a significantly lower germination than the control cultivar Kyle. With the exception of *T. carthlicum*, each tetraploid species contained dormant and moderately dormant genotypes. *T. turgidum* contained the most dormant accession with only 14% germination. Control cultivar, RL4137, with a very low germination percentage exhibited the highest level of dormancy in this study. However, based on the LSD test, there is no significant difference between the best tetraploid dormant accession (93-282) and RL4137.

Six accessions were advanced for evaluation of the after-ripening requirement. The LSD test (p=0.05) detected significant differences between the most dormant accession (93-282) and the durum control, Sceptre, at ZGS 92 and for the first four weeks of after-ripening (Table 4). The dormancy levels of three accessions (93-282, 93-369, and 93-580) declined after three weeks while those of the other three (93-951, 93-955, and 93-960) had already broken down. The selected common wheats exhibited greater lengths of dormancy compared to the tetraploid accessions. The patterns of after-ripening for two hexaploid wheat accessions (93-480, 93-634) and RL4137 seem to be greater than seven weeks.

Several studies were conducted to identify sprouting resistant durum wheat (*T.turgidum* L. var durum) (Hare *et al.*, 1988; Clarke *et al.*, 1994). However, these studies did not directly address the after-ripening requirement of tetraploid wheat germplasm. After evaluating diverse wheat germplasm, Gordon (1983) reported that the durum cultivar Stewart was dormant and exhibited the lowest level of α-amylase activity among 43 white seed coat genotypes. In the current study, Stewart was considered non-dormant. A collection of durum wheat germplasm from ICARDA and Spain was evaluated by Clarke *et al.* (1994) for sprouting resistance. In agreement with our results, Kyle (with a moderate level of seed dormancy) was considered a genotype with an intermediate level of sprouting resistance. In contrast, Stewart 63, reported to be a sprouting resistant cultivar in their study, was considered non-dormant in the present study. In a study by Mares (1987), 80 wheat accessions from eight tetraploid species were evaluated for seed dormancy. Similar to our results, two tetraploid species, *T. durum* and *T. polonicum*, contained promising accessions for sprouting resistance.

There is considerable genetic diversity in the expression of dormancy in response to germination temperature. Seeds of all genotypes expressed no seed dormancy at 10°C as indicated by high germination (Table 5). At this temperature, the LSD test (p=0.05) detected no significant difference between the non-dormant durum cultivar Sceptre and the highly dormant tetraploid accession 93-282. It has been reported that a large proportion of dormant seeds from different species can be released from seed dormancy by exposing imbibed seed to low temperatures, normally between 1° and 10°C (Corbineau *et al*., 1993).

At an intermediate temperature (15°C), a slight reduction in germination was observed for some dormant genotypes, while others still showed high levels of germination. A

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germination temperature of 20°C resulted in the expression of seed dormancy in highly dormant genotypes. However, maximum genetic variation occurred at the highest temperature (25°C).

According to Simpson (1990), mature seeds may: germinate at all temperatures (no dormancy); germinate partially at low but not at higher temperatures (thermal dormancy); or not germinate at any temperature (full dormancy). Using this classification and the results presented in Table 5, there is only one cultivar that can be categorized as non-dormant, namely, Sceptre. The remaining cultivars can be categorized in the thermal dormancy group. For these cultivars, reducing the temperature from high (20°C), in which thermal dormancy is expressed, to a low (10°C) led to normal germination in seeds. This indicated shallow dormancy for these cultivars. Apparently, there is no cultivar with full dormancy among the cultivars tested.

The arbitrary division of tetraploid accessions and common wheat genotypes into phenotypically distinct dormant and non-dormant genotypes becomes blurred when the genotypes were exposed to different germination temperatures. To overcome this problem, a dormancy index (DI) was used (Strand, 1989). Since seed dormancy is manifested more strongly at high germination temperatures, such temperatures should be applied to low dormancy material and vice versa. Therefore, germination at 10 °C versus 20 °C is considered as a strong test for seed dormancy. With respect to dormancy index values (Table 6), the LSD test (p=0.05) detected significant differences among tetraploid wheat accessions. On average, the germination indices of tetraploid accessions 93-62 and 93-177 were 37% higher than those of the durum control cultivar, Kyle. These accessions (93-62 and 93-177) showed very similar dormancy indices to the dormant common wheats RL4137 and AUS140.

In agreement with our results, Oda and Seko (1993) reported that incubation at low temperatures resulted in a higher percentage of germinated seeds compared to the high temperature (20°C). Another study by Amano and Tsuchiya (1993) showed that, at seed maturity, dormant varieties lost their dormancy at a low temperatures (10°C).

CONCLUSION

There are at least two important questions that are answered by the first and second parts of this study. First, what is the level of variation in seed dormancy among tetraploid wheat cultivars? Secondly, how reliably can after-ripening patterns be predicted on the basis of seed dormancy at maturity? In other words, will genotypes with comparable dormancy levels at maturity after-ripen similarly?

Based on these results, one can conclude, with the exception of the cultivar Kyle which has a moderate level of seed dormancy at maturity, the Canadian durum cultivars are non-dormant. The accessions with a high level of seed dormancy selected in this study can provide breeding material for the improvement of pre-harvest sprouting tolerance. Pre-harvest sprouting caused by a lack of dormancy could be reduced or eliminated by breeding for a gradual, not rapid, loss of dormancy during after-ripening.

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تنوع خواب بذر و دوره پس از رسیدگی در گندم های تتراپلوئید

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چکیده

واریته‌های گندم دوروم *(Triticum durum)* دارای سطوح پایین تا متوسطی از خواب بذر بوده و به جوانه‌زنی قبل از برداشت حساس می باشند. اهداف این مطالعه ارزیابی خواب بذر در ارقام تجاری گندم دوروم در آمریکای شمالی و همچنین شناسایی نمونه‌های (accession) گندم تتراپلوئید با سطوح بالای خواب در ژرم‌پلاسم وزارت کشاورزی آمریکا بودند. در اولین مطالعه، میزان خواب بذر و طول دوره پس از رسیدگی در ۱۷ رقم از ارقام تجاری دوروم در آمریکای شمالی مورد ارزیابی قرار گرفت. در این آزمایش، گیاهان در شرایط مزرعه در سالهای ۱۹۹۵ و ۱۹۹٦ کشت شده، سپس در مرحله رشدی زیداکس ۹۲ خوشه‌ها برداشت شده و به مدت یک هفته در درجه حرارت اتاق خشک گردیدند. جهت حفظ سطوح احتمالی خواب در بذور، خوشه‌های برداشت شده در ۲۰- درجه سانتی‌گراد ذخیره شدند. آزمون جوانه‌زنی در ۲۰ درجه سانتی‌گراد و به مدت هفت هفته برای ارزیابی خواب بذر و طول دوره آن مورد استفاده قرار گرفت. براساس نتایج این مطالعه تنها پنج رقم از ارقام تجاری دوروم سطوح متوسطی از خواب بذر را نشان داده و بقیه ارقام فاقد هرگونه خواب بذر بودند. همچنین طول دوره پس از رسیدگی در این پنج رقم بسیار کوتاه بود (حداکثر دو یا سه هفته). در دومین آزمایش تعداد ۷۸ نمونه از گندم‌های تتراپلوئید شامل *T. polonicum, T. durum, T. turgidum, T. turanicum, T. carthlicum* از ژرم پلاسم وزارت کشاورزی آمریکا در شرایط مزرعه و درسالهای ۱۹۹۵ و ۱۹۹٦ به منظور شناسایی منابع با سطوح بالای خواب بذر کشت گردیدند. نحوه ارزیابی خواب بذر مشابه آزمایش قبلی بود. نتایج این آزمایش مشخص نمود که تعداد ۱۸ نمونه دارای سطوح بالایی از خواب بودند. نمونه ۲۸۲-۹۳ در این میان بالاترین میزان خواب را نشان داد. همچنین دوره پس از رسیدگی در این نمونه‌ها بسیار طولانی‌تر از ارقام شاهد تجاری بود. در آخرین مرحله ضریب خواب بذر با استفاده از آزمون جوانه‌زنی در دو حرارت ۱۰ و ۲۰ درجه سانتی‌گراد محاسبه گردید. نمونه‌های موجود در ژرم پلاسم مانند ٦۲-۹۳ و ۱۷۷-۹۳ ضریب بالاتری از خواب را نسبت به ارقام تجاری دوروم از خود نشان دادند. شناسایی نمونه‌های فوق می‌تواند در برنامه‌های اصلاح نباتات به منظور کاهش خسارت جوانه‌زنی قبل از برداشت مورد استفاده قرار گیرد.

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