

# Sources of Variation in Oat Kernel Size

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## ABSTRACT

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Oat kernel size uniformity is important to the oat milling industry because of the size fractionations that occur in the milling process. We measured frequency of single, double, and triple kernel spikelets and kernel mass of primary, secondary, and tertiary kernels from each spikelet type (for a total of six kernel types) to determine relative influence of kernel type, panicle position, genotype, and environment on oat kernel size for 10 oat cultivars grown at four locations. Kernel type was the most important factor affecting kernel size. Primary kernels from triple kernel spikelets were larger than primary kernels from double kernel

spikelets. Tertiary kernels were the smallest. Environments that produced larger kernels also produced higher frequencies of triple kernel spikelets. Some genotypes produced no triple kernel spikelets in any environment, whereas others produced varying proportions, depending on the environment. Kernels closer to the top of the panicle were larger than those near the base. The presence of tertiary kernels was neither associated with lower groat percentages nor with increased proportions of undersized kernels. Most undersized kernels were kernel types other than tertiary.

Oat kernel size is inherently nonuniform because of the multifloret habit of the oat spikelet. Oat spikelets may contain one, two, three, or more kernels. The primary kernels are larger in size than secondary kernels, which are larger than tertiary kernels, if present. As a result, distributions of kernel size in oats frequently represent multimodal populations (Symons and Fulcher 1988). Uniformity of oat kernel size is perhaps even more difficult to describe because of inconsistencies in the interpretation of the concept. A statistical definition would suggest that uniformity would mean less variation around a mean size, which could be quantified with a standard deviation or a variance of kernel size. However, because oat mills usually separate oats by size into separate streams, the ideal uniformity for their oats would be lots that would separate easily into two or three distinct size classes of equal proportions. To address the issue of improving oat size uniformity, this study sought to describe the sources of variation in oat kernel size and to describe how these affect other oat quality characteristics.

Early efforts to evaluate oat kernel size uniformity concentrated on differences in size between primary and secondary kernels (Zade 1912; Mader 1927; Milatz 1933) and on mass distributions of grain separated by sequential sieving with different widths of slotted sieves (Sword 1949; Hubner 1951; Bruchner et al 1956; Ganssmann 1964). Later studies introduced digital image analysis to oat kernel size analysis (Symons and Fulcher 1988; Pietrzak and Fulcher 1995; Doehlert et al 1999).

Many studies have indicated the influence of kernel order on kernel size, which consistently indicate that the primary, most basal kernel is the largest, followed in size by secondary and tertiary kernels (Schneider 1912; Zade 1912; Berry 1920; Mader 1927; Milatz 1933; Villers 1935; Hutchenson et al 1952; Youngs and Shands 1974). Other studies have indicated genotypic and environmental effects on oat kernel size as determined by digital image analysis (Pietrzak and Fulcher 1995; Doehlert et al 1999). Youngs and Shands (1974) demonstrated that the position of the spikelet on the

panicle affected the kernel size, where kernels near the top of the panicle are larger than those at the base. However, to the knowledge of the authors, no study has attempted to determine the relative influences of all of these factors on oat kernel size.

In this study, we have attempted to evaluate sources of variation in oat kernel size by dissecting panicles from 10 different genotypes grown at four different environments. We separated spikelets according to whorl into the three different classes, single kernel spikelets, double kernel spikelets, and triple kernel spikelets. We then divided the kernels into the respective six types: primary kernels from single kernel spikelets; primary and secondary kernels from double kernel spikelets; and primary, secondary, and tertiary kernels from triple kernel spikelets. We then determined the mass of these according to their position on the panicle. We also hand-dehulled these kernels to determine the relationship of kernel type to groat percentage. We analyzed oat samples from plots where these panicles were collected to compare quality characteristics with spikelet class frequencies and kernel characteristics, and we separated samples into size classes by sequential sieving to compare oat size uniformity with spikelet class frequencies and characteristics. Our objectives were to define the sources of oat kernel size variation and to relate this information to other oat quality characteristics.

## MATERIALS AND METHODS

Ten cultivars of oat (*Avena sativa* L., cvs AC Assiniboia, AC Medallion, Belle, CDC Boyer, Derby, Hytest, Jerry, Otana, Triple Crown, and Youngs) were grown at four locations (Carrington, Edgeley, Fargo, and Williston) in North Dakota in the 2000 growing season.

Field plots were planted and maintained as described in Doehlert et al (2001). Sound grain was stored in paper bags under refrigeration until analysis. Intact panicles were collected from plots at maturity, just before cutting or combining from rows not being used for yield calculation. Crown rust infection was evaluated by visual inspection of plots for signs of infection. Infection severity was rated 0–5, where 0 represented the absence of infection, and 5 represented a very heavy infection.

Panicles were dissected by hand. Initially, spikelets from each whorl were removed whorl by whorl, where whorl #1 was the lowest whorl on the panicle and numbered upwards sequentially. Spikelets from each whorl were then separated into single kernel spikelets, double kernel spikelets, and triple kernel spikelets. Individual kernel types were then separated. A total of six kernel types were identified: the primary kernel from single kernel spikelets (S1), primary kernels from double kernel spikelets (D1), secondary kernels from double kernel spikelets (D2), primary kernels from triple kernel spikelets (T1), secondary kernels from triple kernel spikelets (T2), and tertiary kernels from triple kernel spikelets (T3). For each whorl

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of each panicle analyzed, the number of each spikelet type per whorl was recorded and the mass and number of each kernel type was recorded. At least 10 panicles were analyzed from each experimental plot.

### Calculations

For each experimental plot, the number of whorls per panicle was recorded for each panicle analyzed and a mean value of whorls per panicle was calculated. For each whorl, the mean number of each spikelet type per whorl was calculated. The mean kernel type mass was calculated from the summation of kernel type mass for a particular whorl for all panicles from that plot analyzed, and divided by the total number of those kernels of that type from that whorl. As data were compiled for each experimental plot and whorl, the number of each spikelet type per whorl, the number of kernels per whorl, the total kernel mass per whorl, the mean kernel mass, the percentage of single floret spikelets per whorl, the percentage of double floret spikelets per whorl, and the percentage of triple floret spikelets were calculated and recorded.

To calculate panicle means for spikelet class frequencies and kernel type mass, the per whorl values had to be multiplied by the whorl frequency among the panicles analyzed. For each experimental plot, a whorl frequency for each whorl was calculated. For example, all panicles would have had a whorl #1, so whorl #1 would have had a whorl frequency of 1.0. However, perhaps four out of the 10 panicles analyzed would have a whorl #5, so whorl #5 would have had a frequency of 0.4. Mean kernel type numbers per panicle were calculated from the summation across whorls of the kernel type numbers per whorl multiplied by the whorl frequency. Similarly, spikelets per panicle, kernels per panicle, and kernel mass per panicle were calculated from the summation across whorls of the specified value per whorl multiplied by the whorl frequency.

Mean kernel mass per panicle was calculated from the total kernel mass per panicle divided by the total kernel number per panicle. Percentages of spikelet types per panicle were calculated from the number of a particular spikelet type per panicle divided by the number of spikelets per panicle (multiplied by 100).

To calculate mean kernel type mass per panicle, a total kernel type mass per whorl was first calculated. This value was the mean kernel type mass per whorl multiplied by the kernel type number per whorl. The mean kernel type mass per panicle was calculated from the summation across whorls of total kernel type mass per whorl

divided by the summation (across whorls) of the kernel type number per whorl.

Mass proportions of each kernel type within a sample from an experimental plot were calculated from mean kernel type mass and kernel type frequency. The proportion of mass represented by a particular kernel type was calculated as the frequency of a particular kernel type multiplied by the mean mass of that kernel type, quantity divided by the summation of all kernel type frequencies multiplied by their respective mean kernel mass. The proportion was multiplied by 100 to obtain the value as a percentage. Proportions of number of a particular type of kernel could be obtained by substituting kernel type number for kernel type mass in this calculation.

### Sieving

Oat kernel size distributions within grain samples harvested from experimental plots were analyzed by sieving with slotted sieves. Grain samples of 150 g were sieved sequentially on slotted sieves of 3.18, 2.58, 2.38, and 1.98 mm. Grains held back by these sieves were labeled as oversized, large, medium, and small, respectively. Grain that passed through the 1.98-mm sieve were labeled as undersized. Sieve sizes used for separations were designed to mimic commercial systems as described by Deane and Commers (1986). The uniformity product (Doehlert and McMullen 2000b) was calculated as the product of the percent large kernels times the percent medium kernels times the percent small kernels.

From sieving data, percentage distribution of size classes were calculated for each size class, oversized, large, medium, small, and undersized, by multiplying the proportion of each size class relative to the original sample  $\times$  100.

### Dehulling

Groat percentage of kernel types was determined by hand-dehulling. For each experimental plot, samples of like kernel types from all whorls were pooled. A 2-g sample was taken and the total mass recorded. Hulls of the sample were removed by hand and the mass of groats measured. The groat mass divided by the oat mass (and the quotient multiplied by 100) was the groat percentage. If the pooled kernel type mass was  $<2$  g, then the entire sample would be dehulled.

Groat percentage of samples from experimental plots were determined by compressed air dehulling with a Codema laboratory oat huller (Doehlert et al 1999)

TABLE I  
Genotypic Mean Values of Grain Yield, Crown Rust Infection, and Some Quality Characteristics of Oats

Genotype	Grain Yield (Tons/ha)	Test Weight (kg/m <sup>3</sup> )	Groat Percentage (%)	Broken Groats (%)	Crown Rust Infection Score
AC Assiniboia	4.83	486	73.3	9.0	0.00
Belle	4.01	466	74.5	8.2	0.67
CDC Boyer	3.48	429	69.4	10.0	2.08
Derby	3.26	403	61.2	14.7	2.83
Hyttest	3.23	507	71.8	10.8	3.00
Jerry	3.62	475	70.3	9.5	3.00
AC Medallion	3.91	459	69.0	9.4	0.25
Otana	2.69	372	58.4	10.9	3.58
Triple Crown	4.12	443	70.2	3.7	0.83
Youngs	3.98	441	68.3	8.5	1.67
LSD <sup>a</sup>	0.93	50	5.3	ns	1.33

<sup>a</sup> Least significant difference ( $P < 0.05$ ); ns = not significant.

TABLE II  
Location Mean Values of Grain Yield, Crown Rust Infection, and Some Quality Characteristics of Oats

Location	Grain Yield (Tons/ha)	Test Weight (kg/m <sup>3</sup> )	Groat Percentage (%)	Broken Groats (%)	Crown Rust Infection Score
Carrington	3.37	454	64.2	29.2	2.03
Edgeley	3.83	434	68.1	2.1	2.13
Fargo	3.91	436	69.8	1.2	3.00
Williston	3.76	468	72.6	5.4	0.00
LSD <sup>a</sup>	0.32	12	3.3	1.2	0.50

<sup>a</sup> Least significant difference ( $P < 0.05$ ).

## Statistical Analysis

Experimental plots were established in a randomized complete block design with three replicates. Genotypic and location means presented were analyzed by a two-way analysis of variance using the Statistix (Analytical Software, Tallahassee, FL) computer package, where location was considered random and genotype was considered fixed. Significance of location effects were tested with the location  $\times$  replicate interaction term as the error term, and genotype effects were tested with the genotype  $\times$  location interaction as the error term. The genotype  $\times$  location interaction was tested with the residual mean square error as the error term. Differences among means were determined with the least significant difference (LSD) which were calculated using the same error terms described above. Differences among whorls were calculated with a three-way ANOVA with location, genotype, and whorl, but only the significance of whorl, whorl  $\times$  genotype, whorl  $\times$  location, and whorl  $\times$  genotype  $\times$  location were tested. The residual mean square error was used for the error term for all of these tests. To test the relative effect of kernel type, data were rearranged so that kernel type as well as location, genotype, and whorl were variables, and a four-way ANOVA calculated, again where location was considered random and genotype, whorl and kernel type were considered fixed. Error terms were as above, except kernel type was tested with the residual mean square as the error term. Three- and four-way ANOVA were calculated with SAS Proc GLM (SAS Institute, Cary, NC).

## RESULTS

### Yield and Quality Characteristics

Weather conditions differed widely among the locations studied (data not shown). Carrington had cooler temperatures and was drier in the spring. The month of June in Fargo was notable because of a heavy rain that flooded the plots for nearly 24 hr. Heavy rains in August delayed threshing in Carrington. Williston had the highest mean solar radiation.

Genotypic means for grain yield (Table I) indicated a wide range. Lower yielding cultivars were those less resistant to crown rust such as Derby, Hytest, and Otana. Cultivars with greater resistance to crown rust such as AC Assiniboia, Belle, AC Medallion, Triple Crown, and Youngs had higher yields, although Jerry yielded well in spite of a relatively high susceptibility to crown rust. Two cultivars susceptible to crown rust, Otana and Derby, also had lower test

weights and groat percentage. Significant genotype  $\times$  location interactions (not shown) were attributed to differential crown rust resistance. Lines that were particularly susceptible to crown rust, such as Derby and Otana, yielded poorly at Carrington, Edgeley and Fargo, where crown rust infection pressure was high. But these lines performed well at Williston, where crown rust was essentially absent. Similarly, lines with excellent crown rust resistance such as AC Assiniboia and AC Medallion performed poorly at Williston, which was drier than the other locations. Hytest had the highest mean test weight, whereas Otana had the lowest test weights. Groat percentage followed a similar pattern. Significant genotype  $\times$  location interactions in test weight and groat percentage are also attributed to differential crown rust resistance. Whereas Derby and Otana had lower test weights and groat percentages at Carrington, Edgeley and Fargo, they had much higher test weights at Williston. Genotype did not significantly affect the percentage of broken groats in this study.

Location means for yield and grain quality characteristics indicated that Carrington had the lowest grain yields, whereas the other locations did not significantly differ from each other (Table II). Grain from Williston had the highest test weights, followed by grain from Carrington. Grain from Edgeley and Fargo had lower test weights and did not differ significantly from each other. Lower groat percentages in oats from Carrington corresponded with particularly high rates of groat breakage (after dehulling) at that location. Although Williston samples had the highest groat percentage, they also had higher rates of groat breakage than at Edgeley and Fargo.

### Spikelet and Panicle Characteristics

Spikelets on an oat panicle are arranged on branches that extend from whorls on the main stem. The number of whorls per panicle varied among the genotypes tested (Table III). AC Assiniboia, Belle and Hytest had the least number of whorls per panicle, whereas Derby and Triple Crown had the most. Those genotypes with the most whorls also had the most spikelets per panicle and the most kernels per panicle. Although Triple Crown had the highest kernel mass per panicle, AC Medallion, AC Assiniboia, and Youngs had more kernel mass per panicle than other genotypes with greater numbers of kernels per panicle because of their larger mean kernel size. However, Hytest and Jerry had a lower number of whorls per panicle, lower numbers of spikelets per panicle, and lower number of kernels per panicle than other cultivars. Hytest had the lowest grain mass per panicle, but Otana, which had more kernels per

TABLE III  
Genotypic Mean Values of Some Panicle Characteristics

Genotype	Whorls/Panicle	Spikelets/Panicle	Kernels/Panicle	Mass/Panicle (g)	Mass/Kernel (mg)
AC Assiniboia	4.3	25.6	48.3	1.75	36.5
Belle	4.2	30.2	58.0	1.70	29.2
CDC Boyer	4.8	32.0	56.1	1.69	30.7
Derby	5.0	37.4	63.4	1.74	27.5
Hytest	4.3	18.2	33.8	1.07	31.7
Jerry	4.7	26.9	48.9	1.45	29.6
AC Medallion	4.5	33.0	58.6	1.97	33.4
Otana	4.5	31.6	54.4	1.32	23.6
Triple Crown	5.4	46.8	78.8	2.30	29.5
Youngs	4.7	26.0	49.3	1.72	35.2
LSD <sup>a</sup>	0.5	5.4	10.9	0.42	3.8

<sup>a</sup> Least significant difference ( $P < 0.05$ ).

TABLE IV  
Location Mean Values of Some Panicle Characteristics

Location	Whorls/Panicle	Spikelets/Panicle	Kernels/Panicle	Mass/Panicle (g)	Mass/Kernel (mg)
Carrington	4.1	23.8	43.3	1.34	31.1
Edgeley	5.1	33.3	58.8	1.70	29.1
Fargo	5.0	34.7	60.4	1.72	28.4
Williston	4.4	31.2	57.3	1.93	34.2
LSD <sup>a</sup>	0.5	2.5	4.8	0.19	2.7

<sup>a</sup> Least significant difference ( $P < 0.05$ ).

panicle than either Jerry or AC Assiniboia, had less mass per panicle than either of these cultivars, because it had smaller mean kernel mass.

Location means of panicle characteristics indicated that panicles from Carrington and Williston had fewer whorls per panicle than panicles from Edgeley or Fargo (Table IV). Panicles from Carrington had fewer spikelets per panicle and fewer kernels per panicle than the other locations. Williston had the highest kernel mass per panicle and mean kernel mass. Although mean kernel mass did not differ significantly among Carrington, Edgeley and Fargo, Carrington had the least kernel mass per panicle.

Analysis of different types of spikelets indicated that the frequency of single kernel spikelets was highly variable among genotypes (Table V), ranging from 15 to 32%. Genotypes with higher numbers of spikelets per panicle such as Triple Crown and Derby (Table III) tended to have higher frequencies of single kernel spikelets. Similarly, cultivars with lower frequencies of single kernel spikelets, such as Hytest and AC Assiniboia, tended to have lesser numbers of spikelets per panicle and higher test weights (Table I). There were no significant differences among genotypes in the frequency of double kernel spikelets (Table V), and this type of spikelet was the most common of the three types. Triple kernel spikelet frequency differed greatly among genotypes. No triple kernel spikelets were found in any panicles from CDC Boyer and Derby at any of the locations examined. In contrast, Belle and Youngs averaged over 9% triple kernel spikelets over the four locations.

Frequencies of single and double kernel spikelets did not significantly vary among the locations studied here (Table VI). However, the frequency of triple kernel spikelets varied significantly. Williston and Carrington had higher frequencies of triple kernel spikelets than did Edgeley and Fargo.

### Kernel Characteristics

Analyses of grand means of kernel mass of the six kernel types (S1, D1, D2, T1, T2, and T3), indicated that most kernel types differed significantly from each other in mass (Table VII). The T1 kernels were the largest followed by the D1 kernels. The T2 kernels did not differ significantly in mass from the S1 kernel mass, and the D2 and T3 kernels were the smallest.

Genotypic and location analyses indicated no significant differences in size of kernels from triple kernel spikelets (data not shown).

**TABLE V**  
Genotypic Mean Values of Spikelet Type Frequencies (%)  
Among 10 Genotypes and Four Locations

Genotype	Single	Double	Triple
AC Assiniboia	15.0	81.0	4.0
Belle	15.4	75.1	9.5
CDC Boyer	24.3	75.7	0.0
Derby	29.9	70.1	0.0
Hytest	16.7	80.6	2.7
Jerry	21.6	75.9	2.5
AC Medallion	23.7	75.5	0.8
Otana	29.5	67.7	2.8
Triple Crown	32.5	66.0	1.4
Youngs	20.3	70.5	9.2
LSD <sup>a</sup>	10.5	ns	6.4

<sup>a</sup> Least significant difference ( $P < 0.05$ ); ns = not significant.

**TABLE VI**  
Location Mean Values of Spikelet Type Frequencies (%)  
Among 10 Genotypes and Four Locations

Location	Single	Double	Triple
Carrington	21.4	74.2	4.3
Edgeley	22.9	76.4	0.8
Fargo	25.0	74.6	0.5
Williston	22.3	70.1	7.6
LSD <sup>a</sup>	ns	ns	2.9

<sup>a</sup> Least significant difference ( $P < 0.05$ ); ns = not significant.

Significant genotypic and location effects on single and double spikelet kernel sizes were consistent with differences observed in the mean kernel masses (Tables III and IV).

Hand-dehulling results suggested that larger kernel types had lower groat percentages (Table VII). Although S1 kernels had the lowest groat percentages, the T1 and D1 kernels were not significantly higher. The T2, T3, and D2 kernels had the highest groat percentages.

Location means of groat percentages of different kernel types as determined by hand (data not shown) were interesting because of their difference with the groat percentages as determined by the compressed air dehuller (Table II). Carrington samples had much higher groat percentage as determined by hand-dehulling than by compressed air dehulling. However, there were no location differences in any groat percentages of kernel types. Genotypic means of hand groat percentages indicated that AC Assiniboia, Belle, and Hytest tended to have higher groat percentages in the various types of kernel than other cultivars and Otana tended to have lower groat percentages, which is consistent with that presented from mechanically dehulled groat percentages.

### Variations Among Whorls

Analyses of panicle structure quantified the pyramidal (or conical) structure of the oat panicle (Table VIII). The highest number of spikelets per whorl occurred in the bottom whorl (#1) and spikelet number per whorl, kernel number, and kernel mass per whorl all decreased with increasing whorl number. Analysis of genotype by whorl interaction indicated some variation in this pattern (data not shown). Triple Crown frequently had more kernels in its second whorl than in its first whorl. Hytest had a more columnar shape than other cultivars, where there was less of a change in spikelet number and kernel number per whorl with increasing whorl number.

The frequency of single floret spikelets was highest in the lowest whorls and decreased as whorl number ascended (Table VIII). The inverse pattern was seen with double floret spikelets, where the lowest frequency was found in the lowest whorls and the highest frequency was found in the highest whorls. Frequency of triple floret spikelets was higher in the middle whorls. Mean kernel mass tended to increase with increasing whorl number, although the mean mass of kernels in the top whorl was usually less than that of the second to the top whorl. The decrease in mass in the upper whorls was particularly distinct in primary kernels from single floret spikelets (data not shown). Whorl number was not a significant factor affecting kernel size from triple floret spikelets, although it was a significant factor affecting size of double floret kernels (data not shown).

### Four-Way ANOVA

Data were rearranged so that location, genotype, kernel type, and panicle position could all be analyzed as independent variables affecting kernel mass. All of these factors were significant, although kernel type accounted for the most variation, followed by genotype, location, and whorl number (data not shown).

**TABLE VII**  
Mean Groat Percentage and Kernel Mass of Different Kernel Types

Kernel Type <sup>a</sup>	Groats (%)	Kernel Mass (mg)
S1	70.6	30.8
D1	72.5	37.7
D2	77.7	23.0
T1	72.4	43.0
T2	76.2	31.7
T3	78.6	12.9
LSD <sup>b</sup>	5.4	4.5

<sup>a</sup> Mean values of 10 genotypes from four locations. S1, primary kernel from single kernel spikelet; D1, primary kernel from double kernel spikelet; D2, secondary kernel from double kernel spikelet; T1, primary kernel from triple kernel spikelet; T2, secondary kernel from triple kernel spikelet; T3, tertiary kernel from triple kernel spikelet.

<sup>b</sup> Least significant difference ( $P < 0.05$ ).

### Kernel Size Uniformity Analyses

Kernel size uniformity was evaluated by sequential sieving. Genotypic means indicated that less than 1% of kernels (by mass) of any genotype were oversized (Table IX). In contrast, genotypic means indicated that undersized kernels ranged from low values of 3.3 to 5.8% with AC Assiniboia and CDC Boyer, to 17.8 and 18.4% with Belle and Otana. Cultivars with larger proportions of large kernels tended to have less undersized kernels and larger uniformity products. Location means indicated that Edgeley and Fargo had the highest proportions of undersized kernels, and Carrington and Williston had the highest uniformity products (Table X).

Possible relationships between kernel size distributions and a frequency of kernel types was evaluated by calculating the mass proportion of grain samples for each kernel type. Of interest is a comparison of the percentage of undersized kernels with the mass percentage of tertiary kernels in samples. Genotypic means indicate that the percentages of undersized kernels are larger than the mass proportion of tertiary kernels, indicating that undersized kernels must be composed of other kernel types than just tertiary kernels (Table XI). It is also interesting to note that the locations with the highest proportions undersized kernels (Fargo and Edgeley) were also the locations with the lowest proportions of tertiary kernels (Table XII).

### DISCUSSION

Oat kernel size was significantly affected by the kernel type, genotype, environment, and position on the panicle, in that order of importance. The influences of each of these factors will be discussed individually after an initial discussion of environmental effects on grain yield and overall quality.

Environmental factors had relatively little effect on grain yield (Table II). An earlier study (Doehlert et al 2001) examined in detail environmental effects on oat grain yield and quality. The conclusions of that study would have suggested that the drier spring conditions at Carrington may have limited the grain yield at that location. These conditions may have limited the development of spikelet primordia, which may have been responsible for the smaller number of spikelets per panicle observed at this location. Lower mean test weights at Edgeley and Fargo may have been due to the crown rust infections at those sites, although Carrington was also infected. The lower groat percentage values obtained at Carrington were attributed to the high groat breakage rates that occurred during the dehulling of grain from that location. The study of Doehlert et al (2001) suggested that high groat breakage rate might be due to crown rust infection. However, both Fargo and Edgeley incurred more intense crown rust infections than Carrington (Table II), and they suffered little groat breakage. We have come to realize that this location and the location that suffered high groat breakage in the Doehlert et al (2001) study suffered sprout damage from delays between cutting and threshing. We have discovered that high groat breakage during dehulling is a characteristic of sprout damaged oat grain and we are in the process of characterizing this phenomenon, which has not yet been described in oats.

Crown rust infections at Carrington, Edgeley and Fargo appeared to be associated with lower test weight, groat percentage, kernel mass and lower mass per panicle. Also the percent undersized kernels was higher in cultivars infected with crown rust when compared to the same cultivar not infected with crown rust (data not shown).

Environmental effects on oat kernel size were complex. Environments that favored the generation of triple floret spikelets also gen-

TABLE VIII  
Panicle Characteristics by Whorl

Whorl <sup>a</sup>	Single	Double	Triple	Spikelets/Whorl	Kernels/Whorl	Mean Kernel Mass (mg)	Mass/Whorl (mg)
1	26.7	71.7	1.6	10.8	18.8	29.1	549
2	22.9	74.0	3.3	8.9	15.9	30.6	480
3	19.7	75.7	4.8	5.5	10.1	32.0	311
4	18.1	75.4	6.7	3.6	6.7	33.1	219
5	18.0	74.6	8.0	2.3	4.3	32.8	140
6	16.7	82.3	1.1	1.1	2.0	32.0	63
7	19.0	80.9	0.0	0.3	0.5	29.9	14
LSD <sup>b</sup>	4.5	4.8	2.4	0.3	0.6	1.4	19

<sup>a</sup> Whorl number 1 is the lowest on the panicle.

<sup>b</sup> Least significant difference ( $P < 0.05$ ).

TABLE IX  
Genotypic Mean Values of Size Distributions (% kernels) of Oat Samples by Sequential Sieving with Width-Incremented Slotted Sieves

Genotype	Oversized	Large	Medium	Small	Undersized	Uniformity Product
AC Assiniboia	0.30	28.9	34.4	33.0	3.3	30,947
Belle	0.04	2.9	16.3	62.7	17.8	3,222
CDC Boyer	0.33	30.1	30.1	36.3	5.8	27,634
Derby	0.23	12.6	26.7	48.9	11.4	16,139
Hyttest	0.12	8.4	27.4	56.1	7.8	12,835
Jerry	0.22	5.6	18.8	64.7	10.5	7,451
AC Medallion	0.27	25.3	24.8	43.2	8.1	25,297
Otana	0.20	9.7	18.2	53.2	18.4	8,651
Triple Crown	0.83	10.8	27.3	53.3	7.6	15,595
Youngs	0.89	10.8	33.6	48.0	6.6	16,763
LSD <sup>a</sup>	0.37	8.9	10.8	12.7	4.2	8,144

<sup>a</sup> Least significant difference ( $P < 0.05$ ).

TABLE X  
Location Mean Values of Size Distributions (% kernels) of Oat Samples by Sequential Sieving with Width-Incremented Slotted Sieves

Location	Oversized	Large	Medium	Small	Undersized	Uniformity Product
Carrington	0.57	20.1	28.7	43.0	7.3	19,575
Edgeley	0.41	12.9	25.6	50.5	10.4	15,472
Fargo	0.24	9.0	20.8	56.9	14.6	10,716
Williston	0.14	13.0	27.8	49.3	6.7	20,010
LSD <sup>a</sup>	0.20	2.3	2.8	3.1	1.5	2,210

<sup>a</sup> Least significant difference ( $P < 0.05$ ).

erated higher mean kernel mass and higher test weights. This is consistent with the observations of Barry (1920). The frequency of triple kernel spikelets did not appear to be associated with grain yield as suggested by Takeda and Frey (1980) or with lower groat percentage as suggested by Palagyi (1983). It appeared that the potential of a panicle to produce triple floret spikelets was dependent on the ability of the plant to fill existing kernels. The primary kernel of triple kernel spikelets had the greatest mass of all kernel types (Table VII). It might appear that tertiary kernel filling was initiated only when an overabundance of assimilates existed to fill primary and secondary kernels within a spikelet. The apparent negative association of crown rust infection with the frequency of triple floret spikelets is consistent with this, as crown rust would divert assimilate away from grain filling. Williston, which was essentially free of crown rust, had the highest frequency of triple kernel spikelets. Although Carrington had the lowest grain yield, it had relatively large kernels and also had a relatively high frequency of triple kernel spikelets. Carrington also had the lowest numbers of spikelets per panicle. Drier spring conditions may have inhibited spikelet primordia in the developing panicle, thus limiting yield potential. However, relatively good conditions during grain fill may have allowed the complete filling of those spikelets available, resulting in larger kernels and a higher frequency of tertiary kernels. Edgeley and Fargo both initiated large numbers of spikelets, but poorer grain filling conditions, largely brought about by crown rust infections may have been responsible for the smaller kernels and very low frequencies of triple spikelets at those locations. Our results suggest that the potential of a given genotype to produce triple spikelets is plastic and dependent on the grain-filling conditions. If assimilate supply is sufficient to fill kernels beyond a threshold mass, then tertiary kernel filling may be initiated. Similarly, the frequency of single kernel spikelets appeared to be highest in environments with the poorest potential for grain filling.

It is also evident that genotype played a major role in affecting oat kernel size, yield and other quality characteristics. Genotypic differences in crown rust resistance accounted for much of the observed variations in oat yield, test weight, and groat percentage. Otana, Derby, Hytest and Jerry all were moderately to very susceptible to prevailing races of crown rust, and had reduced grain yields at

Carrington, Edgeley, and Fargo as a result. AC Assiniboia, Belle, AC Medallion, and Youngs all had better crown rust resistance and performed better at these locations. It is interesting that the cultivars with the most environmentally stable test weights, AC Assiniboia, Jerry and Hytest, all had the smallest panicles, as far as spikelet number per panicle was concerned. Hytest in particular had the smallest panicles, but had the highest test weights in all environments, as its cultivar name commemorates, in spite of a moderate crown rust susceptibility. A smaller panicle may assure a more complete filling of existing spikelets, resulting in a higher test weight even in poorer environments.

Obvious genotypic differences in spikelet type frequencies are evident. Two cultivars, CDC Boyer and Derby, did not produce triple kernel spikelets in any of the environments tested. Others such as Belle and Youngs showed potential to produce relatively high frequencies of triple kernel spikelets in favorable environments but would produce very low frequencies in other environments. Because the ranking of cultivars for frequency of triple spikelets was very consistent across environments, genotype appeared to play a very important role in determining the potential of a cultivar to produce triple spikelets. However, the presence of tertiary kernels was not associated with any negative quality characteristics. Across environments, the frequency of triple kernel spikelets appeared to be associated with higher test weight, higher uniformity products and lower frequencies of undersized kernels. Takeda and Frey (1980) and Palagyi (1983) also documented genotypic variation in tertiary kernel frequency. However, Palagyi (1983) suggested that increased tertiary kernel frequency was associated decreased size and groat percentage of primary and secondary kernels.

Certain cultivars also produced higher frequencies of single spikelets. Triple Crown and Derby had the highest frequencies of single kernel spikelets and also had the more spikelets per panicle than other cultivars. We hypothesize that the larger number of spikelets resulted in the demand for assimilate to become more highly divided, which initiated filling of fewer secondary and tertiary kernels within individual spikelets. Otana also had a relatively high number of single kernel spikelets, but this was likely to have been caused by its extreme susceptibility to crown rust that would have limited its potential to fill primary kernels. Otana also had the smallest kernels of any cultivar

TABLE XI  
Genotypic Mean Values of Mass Proportions for Different Kernel Types<sup>a</sup>

Genotype	S1	D1	D2	T1	T2	T3
AC Assiniboia	10.4	49.1	32.7	3.9	2.9	1.0
Belle	5.8	39.1	25.8	14.2	10.2	4.0
Boyer	13.9	52.9	33.2	0.0	0.0	0.0
Derby	12.2	54.9	32.9	0.0	0.0	0.0
Hytest	11.4	52.2	32.4	1.9	1.4	0.6
Jerry	9.7	48.9	31.9	4.9	3.3	1.3
AC Medallion	10.0	53.6	32.7	1.9	1.3	0.5
Otana	9.7	49.5	30.9	4.8	3.7	1.4
Triple Crown	30.2	40.3	25.4	1.8	1.6	0.7
Youngs	10.9	33.4	20.3	17.3	13.1	5.1
LSD <sup>b</sup>	10.4	8.0	4.8	6.7	4.8	1.6

<sup>a</sup> S1, primary kernel from single kernel spikelet; D1, primary kernel from double kernel spikelet; D2, secondary kernel from double kernel spikelet; T1, primary kernel from triple kernel spikelet; T2, secondary kernel from triple kernel spikelet; T3, tertiary kernel from triple kernel spikelet.

<sup>b</sup> Least significant difference ( $P < 0.05$ ).

TABLE XII  
Genotypic Mean Values of Mass Proportions for Different Kernel Types<sup>a</sup>

Location	S1	D1	D2	T1	T2	T3
Carrington	12.7	49.9	31.0	3.2	2.2	0.9
Edgeley	13.7	53.9	31.4	0.5	0.4	0.1
Fargo	15.8	53.2	31.3	0.4	0.3	0.1
Williston	12.4	47.5	29.8	5.1	3.7	1.5
LSD <sup>b</sup>	ns	2.8	ns	1.7	1.2	0.7

<sup>a</sup> S1, primary kernel from single kernel spikelet; D1, primary kernel from double kernel spikelet; D2, secondary kernel from double kernel spikelet; T1, primary kernel from triple kernel spikelet; T2, secondary kernel from triple kernel spikelet; T3, tertiary kernel from triple kernel spikelet.

<sup>b</sup> Least significant difference ( $P < 0.05$ ); ns = not significant.

studied. The occurrence of single kernel spikelets appeared to be more associated with negative quality characteristics than other spikelet types. Single kernel spikelets appeared to be associated with lower yields, test weights, and higher proportions of undersized kernels.

The position of the spikelet within the panicle also had an effect on kernel mass. Kernels in lower whorls had less mass than kernels in upper whorls. Because there are less kernels in upper whorls than in lower whorls, we suggest that the upper kernels are larger because the assimilate stream is being divided among fewer kernels. Some cultivars differed in this trend and appeared to exhibit more uniformity in size between the lower and upper whorls. These cultivars included AC Assiniboia, Triple Crown, and Youngs. An earlier work by Youngs and Shands (1974) also documented this difference in kernel size between the top and bottom of the panicle. They suggested this was because the top kernels entered anthesis earlier than the bottom kernels and had a longer time to develop.

The major factor affecting oat kernel mass was the kernel type. Primary kernels of triple kernel spikelets were the largest kernels examined, and the tertiary kernels from these same spikelets were the smallest. These results are consistent with data offered by Berry (1920) and Hutchinson et al (1952) and with discussion offered by Youngs and Shands (1974). It is interesting to note that the mean kernel mass within a spikelet was about the same for all spikelet types (data not shown). That is, the mass of primary, secondary, and tertiary kernels from a triple floret spikelet averaged together was not significantly different from the mass of primary and secondary kernels averaged together from double spikelets, and these were not significantly different from the mass of kernels from single spikelets. Consistent with this is the observation that the secondary kernels from triple kernel spikelets were not significantly different in mass from the primary kernel of the single kernel spikelet.

The results presented here suggested a strong negative association within a genotype and environment of kernel size with groat percentage, as determined by hand-dehulling (Table VII). Essentially, T3, T2, and D2 kernels had the highest groat percentages and T1, D1, and S1 kernels had lower groat percentages. This trend, where higher order kernels have higher groat percentages, has been documented previously by a number of studies (Zade 1915; Berry 1920; Villers 1935; Atkins 1943; Hutchinson et al 1952; Youngs and Shands 1974; Palagyi 1983). Palagyi (1983) suggested that the presence of tertiary kernels reduced the groat percentage of the primary and secondary kernels in the triple kernel spikelet. Our results do not support this hypothesis. The groat percentage of the T1 kernels were not significantly different from the S1 kernels that had no secondary or tertiary kernel competing with it for assimilate. We suggest larger kernels may simply have thicker hulls.

Frequently, the presence of tertiary kernels are considered an antiquality factor in oats, because the smaller tertiary kernels contribute to undersized kernels (<2 mm wide), which are generally discarded from a milling stream and thus subtract from the value of the oats. We tested this hypothesis by comparing the percentage undersized kernels (Tables IX and X) with the calculated mass proportions of the different kernel types (Tables XI and XII) in the same oat samples. We found that all genotypes had more undersized kernels than tertiary kernels. Thus, kernels other than tertiary kernels must contribute to undersized kernels. Overall, no relationship between

proportions of tertiary kernels and percent of undersized kernels could be determined. Although Belle had a relatively high proportion of tertiary kernels and had the highest proportion of tertiary kernels, it appeared that >75% of the undersized kernels in Belle samples were kernel types other than tertiary. Furthermore, the cultivar Derby, which had no tertiary kernels, had a relatively high level of undersized kernels. Of the three cultivars with the lowest levels of undersized kernels, CDC Boyer had no tertiary kernels, Youngs had the highest mass proportion of tertiary kernels of any cultivar evaluated, and AC Assiniboia had a moderately low level of tertiary kernels. Thus, it appeared that, in most of the cultivars studied, kernel types other than tertiary kernels contributed more to undersized kernels, presumably D2 kernels. Although tertiary kernels do contribute to undersized kernels, triple kernel spikelets also produce two large kernels, which can offset the negative effect of the tertiary kernel. Furthermore, environments that produce the most tertiary kernels produced the least proportion of undersized kernels.

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