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Effects of Genotype and Seed Size on Speed of Emergence and Seedling Vigor in Nine Spring Wheat Cultivars[1]

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ABSTRACT

Rapid seedling establishment is an important attribute for successful crop production in short-season areas. A study was done to determine the role of seed size, speed of emergence and rate of plant development in seedling vigor of nine spring wheat, *Triticum aestivum* L., cultivars. Six field studies, comprised of three seeding dates in each of 2 years, were conducted. Each study included nine spring wheat cultivars divided into two seed sizes arranged in a randomized complete block design with four replications. Logistic curves were fitted to emergence data expressed as percentage of final number of seeds emerged in a 46 cm row length. Each curve was characterized by median emergence time, the most useful measurement for speed of emergence, and maximum rate of emergence. Cultivar differences were observed in both years for speed of emergence, Haun stage, and seedling shoot dry weight. The average number of growing degree-days (GDD) required for emergence in 1982 and 1983 were 109 and 103, respectively. With respect to Haun stage, approximately 68 GDD were required per phyllochron (interval between the appearance of successive leaves). 'Potam', 'Siete Cerros', and 'Glenlea' were found to require significantly fewer GDD per phyllochron interval on the third seeding date of 1983. The relative performance of cultivars was similar for speed of emergence, Haun stage and seedling shoot dry weight. Plants grown from small seeds emerged faster but accumulated less shoot dry weight than plants grown from large seeds. There was no cultivar by seed size interaction observed for speed of emergence and seedling shoot dry weight. Seed size, speed of emergence, and Haun stage all contributed to differences between cultivars in seedling vigor. Seed size accounted for approximately 50% of the variation in seedling shoot dry weight. It was concluded that selecting for seedling vigor could be done by selecting for seed size, speed of emergence and/or rate of plant development.

***Additional index words:* *Triticum aestivum* L., Haun stage, Growing degree-days, Logistic function, Phyllochron.**

EARLY seedling establishment is required for successful cereal production in short-season areas. Although many studies have considered the relationships between speed of emergence and seedling vigor, few have investigated the effects of genotype on seedling establishment.

Seedling vigor of individual genotypes of spring wheat, *Triticum aestivum* L., has been discussed in several papers. Seedlings grown from large seeds accumulate more dry matter than seedlings grown from small seeds (Brenchley, 1923; Kiesselbach, 1924; Waldron, 1941; Evans and Bhatt, 1977). Seedlings grown from seeds containing higher amounts of protein accumulate more dry matter than seedlings grown from seeds with lower amounts of protein (Schweizer and Ries, 1969; Lowe and Ries, 1972; Bulisiani and Warner, 1980). However, Bulisiani and Warner (1980) have shown that, if exogeneous N is supplied with the seed at time of planting, the differences in seedling shoot dry weight between seeds of high and low protein content disappear. The source of the seed also affects seedling shoot dry weight (Quinby et al., 1962; DasGupta and Austenson, 1973a,b). The factors responsible for source effects are in part due to seed size and seed protein content effects, as well as germination resistance, a measure of the relative rate of germination (Gordon, 1971).

Besides using shoot dry weight as a measure of seedling vigor, seedling vigor may also be measured by quantifying the stage of seedling development. Systems for describing development of adult cereal plants, such as the system of Feekes (Large, 1954), have little ability to resolve important differences in the seedling stage. Haun (1973) proposed a system for quantifying plant development using a numerical expression based on the regular appearance of leaves at the growing point on the main stem. Each new leaf represents a

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Table 1. Date of planting, soil moisture content at planting, precipitation, and accumulated growing degree-days for three seeding dates in each of 2 years.

Year	Seeding date	Soil moisture content†	Precipitation‡	Planting to Emergence	Planting to 28 Days
		kg kg⁻¹	mm	GDD§	
1982	6 May	0.276	75	111	279
	25 May	0.285	60	120	348
	8 June	0.292	82	98	448
1983	4 May	0.236	54	95	277
	20 May	0.231	19	113	397
	2 June	0.178	116	107	454

† Moisture retention curves for this soil shows that at −0.03 MPa, moisture content is 0.266 and at −1.5 MPa, moisture is 0.178.
‡ Precipitation from planting to 28 days was obtained from the Saskatchewan Research Council.
§ Growing degree-days (GDD) was calculated using a base temperature of 0°C. Growing degree-days for emergence was based on the mean of the median emergence time over the nine cultivars for each seeding date and year of testing.

unit of development and the growth units are subdivided into decimal fractions beginning with the appearance of the next leaf. Klepper et al. (1982) have adopted this method to quantify vegetative development in small cereal grains. They refer to each unit as a Haun stage. More recently, Klepper and Skirvin (1984) have shown that Haun stage is linear with growing degree-days within a given genotype. Bauer et al. (1984) claim that Haun stage tends to be more definitive and more sensitive to changes in plant morphology than other physiological indices.

The purpose of this investigation was to study the relationships among seed size, speed of emergence, plant development as measured by Haun stage, and seedling shoot dry weight in nine spring wheat cultivars.

MATERIALS AND METHODS

Field studies were carried out for 2 years at the University of Saskatchewan in Saskatoon (52° N Lat, 104 W Long). The soil is a Typic Haploboroll clay loam with a pH of 7.4. In both years, there were three seeding dates (Table 1). Gravimetric soil moisture (0 to 15 cm) was recorded at seeding and amount of precipitation and daily minimum and maximum temperatures were recorded for the duration of the experiment. In 1982, plots consisted of four rows, 3.7 m long and spaced 30 cm apart. In 1983, only two rows were used. Seeding rate was approximately 270 seeds m^{-2}. Fertilizer N/P/K (11-51-0) was applied at a rate of 50 kg/ha with the seed. At each planting date, plots were arranged in randomized complete blocks with four replications.

Two different seed sizes from each of nine spring wheat cultivars were used for all field studies. A list of the kernel characteristics and country of origin of each cultivar is given in Table 2. The seeds were sized using sieves of decreasing mesh size. Seeds were considered large or small if they remained on sieves with hole diameters of 3.57 and 2.78 mm respectively. In both years, only seeds from a common seed source were used.

Immediately after sowing, two wooden stakes were placed 46 cm apart in the middle of the third row of each plot in 1982 and in the middle of the second row in 1983. These marked the site for measuring emergence. The number of seedlings appearing above the soil surface between the two stakes was recorded three times a day (0700, 1400, and 2000 h) during the phase of rapid emergence and twice a day thereafter.

Table 2. Origin and kernel characteristics of nine spring wheat cultivars.

Cultivar	Origin	Hardness	Color	Kernel weight 1982 Large	1982 Small	1983 Large	1983 Small
				mg			
Manitou	Canada	Hard	Red	35.8	26.3	39.3	32.9
Neepawa	Canada	Hard	Red	37.1	27.1	43.1	27.2
Columbus	Canada	Hard	Red	40.5	28.1	43.6	27.3
Sinton	Canada	Hard	Red	43.6	27.1	42.7	25.9
Glenlea	Canada	Extra-Hard	Red	45.7	32.2	49.8	45.3
NB402	Canada	Medium-Hard	White	44.8	31.0	44.1	36.9
Pitic 62	Mexico	Soft	Light-Red	40.4	33.1	44.4	37.3
Potam	Mexico	Soft	Light-Red	45.6	29.5	47.1	38.6
Siete Cerros	Mexico	Hard	Light-Red	44.2	29.6	44.4	35.6

After 28 days from planting in 1982, plants from two 30-cm row lengths were dug up from each plot and the number of plants recorded. Shoot dry weights were determined after drying for 24 h at 90°C. In 1983, shoot dry weight and stage of plant development (Haun stage) were recorded on ten individual plants taken from the marked segment used for recording emergence.

The emergence data were analysed using the logistic curve (Schimpf et al., 1977). The logistic curve used in this study is described by the equation $P_t = 1/[1+e^{-a-b\ln(t)}]$, where $P_t = n_t/N$ is equal to the number of seeds emerged by time $t(n_t)$ divided by the final number of seeds emerged (N), ln(t) is the natural logarithm of time in hours from the initiation of the experiment, and a and b are constants estimated for each emergence-time curve. Time was transformed to natural logarithms to remove skewness in the data.

In order to determine the values of the constants a and b, all the values P_t were transformed to logits using the relationship $\text{logit}(P_t) = \ln[P_t/(1\text{-}P_t)]$ (Berkson, 1944). This transformation linearized the logistic function to the form $\ln[P_t/(1\text{-}P_t)] = a+b[\ln(t)]$. The transformed data were then fitted using iterative weighted linear regression (Berkson, 1944, p. 363). Initial weights, W_t, were set equal to $W_t = N(P_t)(1\text{-}P_t)$, provided $W_t > 1$, and 0 otherwise. Weighted regression was used to estimate $\hat{a}$ and $\hat{b}$. Then, for each iterative cycle, fitted weights $\hat{W}_t = N(\hat{P}_t)(1\text{-}\hat{P}_t)$, where $\hat{P}_t = 1/[1+e\text{-}\hat{a}\text{-}\hat{b}\ln(t)]$, were estimated and the calculations were repeated. The iterative procedure was terminated when the coefficient of determination, based on the unweighted correlation between observed (P_t) and fitted values ($\hat{P}_t$), ceased to change by more than 0.02.

The estimated values, $\hat{a}$ and $\hat{b}$, were used to determine the median emergence time ($e^{-\hat{a}/\hat{b}}$) and maximum emergence rate ($b/4e^{-\hat{a}/\hat{b}}$). The values for median emergence time at each seeding date were then transformed to logarithms to remove the heterogeneity of variance and analysed using a combined analysis of variance over seeding dates within each year. The estimated value of maximum emergence rate showed very little variation between cultivars and will not be considered further. Median emergence time provided a good estimate of speed of emergence.

The values for shoot dry weight were transformed to logarithms and used to compute the analysis of variance combined over seeding dates in each year. Analysis of variance was computed using the mean of the two subsamples in 1982 and the mean of the 10 plants in 1983.

RESULTS AND DISCUSSION

An analysis of variance, combined over seeding dates, was done for median emergence time in each year. Transformation removed the heterogeneity of er-

Table 3. Analyses of variance of median emergence time (logarithmic scale) for 1982 and 1983.

Source	df	Mean square 1982	Mean square 1983
Seeding date (D)	2	10.9100**	14.1500**
Replications in dates	9	0.0050	0.0037
Cultivar (C)	8	0.0225**	0.0085**
Seed size (S)	1	0.1448**	0.0009
C × S	8	0.0005**	0.0015
D × C	16	0.0069*	0.0016
Non-additivity	1	0.0250**	–
Residual	15	0.0059 NS	–
D × S	2	0.0213**	0.0078**
D × C × S	16	0.0027	0.0010
Pooled error	153	0.0034	0.0014

*,** Mean squares are significant at the 5 or 1% level of probability, respectively.

Table 4. Median emergence time for nine cultivars tested at three seeding dates in each of 2 years.

Cultivar	Date I	Date II	Date III
	h		
	1982		
Pitic 62	301†	242	136
Potam	292	248	149
NB402	308	249	136
Siete Cerros	311	258	160
Glenlea	319	257	148
Columbus	309	261	147
Sinton	312	261	151
Neepawa	316	265	144
Manitou	320	261	152
BLSD (k = 100)‡	17	7	14
	1983		
Pitic 62	375	187	164
Potam	364	192	162
NB402	383	194	167
Siete Cerros	382	195	170
Glenlea	379	198	164
Columbus	394	202	170
Sinton	392	196	167
Neepawa	389	193	167
Manitou	393	200	166
BLSD (k = 100)†	10	11	6

† Each value represents the mean of eight observations.
‡ The values for Waller-Duncan's Bayesian K-ratio least significant difference (Waller and Duncan, 1969) were based on the separate analyses of variance for each seeding date within each year.

ror variances between seeding dates. The main effects (seeding date, cultivar, seed size) were all highly significant in 1982 and 1983 except for seed size in 1983. A significant seeding date by seed size interaction was observed in each year. A significant seeding date by cultivar interaction was observed in 1982 but not 1983. The cultivar by seed size interaction was not significant in either year (Table 3).

Tukey's test for non-additivity of the seeding date by cultivar interaction in 1982 was significant with the residual effects not significant (Table 3). The logarithmic transformation removed the heterogeneity of error variance among seeding dates, but did not remove the non-additive effects. The nature of the interaction is due in part to the greater range of median emergence times at the first seeding date than at the others. The difference between the fastest and slowest emerging cultivar was 28, 22, and 24 h for the first, second, and third seeding dates (Table 4), respectively. The interaction is due also, to ranking changes of the cultivars on the third seeding date, when compared to the first two seeding dates.

Table 5. Analysis of variance of plant development (Haun stage) combined over three seeding dates.

Source	df	Mean square
Seeding Date (D)	2	97.710**
Error (a)	9	0.116
Cultivar (C)	8	0.579**
Seed Size (S)	1	0.169**
C × S	8	0.079**
D × C	16	0.075**
D × S	2	0.038
D × C × S	16	0.054**
Error (b)	153	0.024

** Mean squares are significant at the 1% level of probability.

Table 6. Average Haun stage at 28 days from sowing for nine cultivars tested at three seeding dates in 1983.

Cultivar	Date I	Date II	Date III
Pitic 62	2.93†	4.42	5.14
Potam	2.93	4.37	5.41
NB402	2.88	4.20	5.04
Siete Cerros	2.60	3.84	5.11
Glenlea	2.76	4.03	5.24
Columbus	2.66	3.90	4.92
Sinton	2.66	3.91	4.96
Neepawa	2.68	4.05	5.00
Manitou	2.70	3.87	4.89
BLSD (k = 100)‡	0.16	0.14	0.14

† Each value represents the mean of 80 observations.
‡ The values for Waller-Duncan's Bayesian K-ratio least significant difference (Waller and Duncan, 1969) were based on the separate analyses of variance for each seeding date.

In this study, delayed seeding, from the first to the last seeding date, resulted in higher soil temperatures at planting and, therefore, shorter times to emergence in both years. The average number of growing degree-days (0°C base) required for spring wheat to emerge was 109 for 1982 (range 98 to 120) and 105 for 1983 (range 95 to 113). Bauer et al. (1984) reported 106 as the average number of degree-days required for emergence of 18 cultivars which included 'Sinton' and 'Columbus'. In the present study, significant cultivar differences were observed for median emergence time at all seeding dates and in both years. This contrasts with the results of Bauer et al. (1984) who reported no cultivar differences for emergence. 'Pitic 62', Potam, and 'NB402' tended to emerge more quickly than the other cultivars regardless of seeding date and year. Similar results were observed for rate of germination (Lafond and Baker, submitted for publication, 1986).

The experimental error variances for growth stage were homogeneous over the three seeding dates in 1983. A combined analysis of variance indicated highly significant effects of seeding date, cultivar and seed size as well as highly significant interactions between seeding date, cultivar and seed size (Table 5). All interactions were related to the third seeding date. The delayed seeding resulted in greater heat unit accumulation between planting and harvest (28 days after planting). As a result, greater morphological changes occurred in the plants. Close examination of average growth stages (Table 6) revealed that three cultivars in particular had values that were greater on the third seeding date than would be expected from the values of the two first seeding dates. Glenlea, Siete Cerros, and Potam showed substantial increases in Haun stage. The time required between phyllochrons either changed or became more apparent on the third seeding date.

Similar observations have been reported by Bauer et al. (1984). They found two spring wheat cultivars for which the required time (measured in GDD) for a phyllochron was less than in the other cultivars used in their study. They also stated that the GDD requirements between phyllochron intervals is the same from one interval to the next. In this study, we found that the GDD per phyllochron interval was not constant across seeding dates and decreased as seeding was delayed. However, Glenlea, Potam, and Siete Cerros still showed the greatest decrease in GDD per phyllochron interval, with the greatest decrease occurring between the second and third seeding date.

Cultivar differences for Haun stage were observed on all three seeding dates. Pitic 62, Potam, and NB402 had the highest values on the first two seeding dates while Siete Cerros and Glenlea were similar to them on the third date. When the number of GDD per phyllochron was calculated using GDD from emergence to 28 days, average values of 66, 69, and 68 were obtained for the three seeding dates. These values are similar to 73 GDD/phyllochron interval reported by Bauer et al. (1984) but less than values of 100 GDD/phyllochron interval reported by Klepper and Skirvine (1984). However, when GDD/phyllochron interval were calculated using GDD from planting to 28 days, values of 101, 98, and 90 were obtained. These values are similar to those reported by Klepper and Skirvin (1984).

The relative performance of the cultivars was similar for median emergence time and Haun stage. Haun stage could therefore be used to compare median emergence times of different genotypes; those with the higher Haun stage at 28 days had the shorter median emergence time. Speed of emergence could be estimated at any point in time (preferably before the five leaf stage) by measuring Haun stage on a random sample of plants. This approach would not be useful if rates of leaf appearance were to differ markedly among genotypes.

Data for shoot dry weight were transformed using logarithms to remove the heterogeneity of error variance. A combined analysis of variance over seeding dates was done for both years. In both years, seeding date, cultivar, and seed size were all highly significant. None of the interactions was significant in either year. In 1982, the large seed size samples produced shoot dry weights that were 24, 26, and 21% greater on average than those produced from small seed samples at the first, second, and third seeding dates, respectively. Similarly, in 1983, shoot dry weights from large seeds were 28 and 21% greater on average than those from small seeds on the two planting dates.

The lack of a cultivar by seeding date interaction is a good indication that the relative performance of the cultivars for seedling vigor did not change with seeding dates (Table 7). When a comparison is done between 1982 and 1983, Glenlea had relatively greater seedling shoot dry weight in 1983 than in 1982. For Glenlea, a larger seed fraction was used for both seed sizes in 1983 because there was insufficient seed to provide the required amount of small seed. Since seed size influences seedling shoot dry weight, it is not surprising to find that Glenlea had relatively greater shoot dry weights in 1983 than in 1982. Based on shoot dry weights, Potam and Pitic 62 produced the most vigorous seedlings in 1982 and these two cultivars along with Glenlea were most vigorous in 1983 (Table 7). This result corresponds well with the observations for speed of germination (Lafond and Baker, submitted for publication, 1986), speed of emergence (Table 4), and Haun stage (Table 6).

Table 7. Shoot dry weight per plant for nine cultivars tested at three seedling dates in each of 2 years.

	Date I	Date II	Date III
	mg		
	1982		
Pitic 62	35†	200	747
Potam	40	198	769
NB402	35	190	681
Siete Cerros	39	181	646
Glenlea	39	174	709
Columbus	33	154	579
Sinton	35	160	633
Neepawa	38	166	646
Manitou	36	154	586
BLSD (k = 100)‡	-	17	73
	1983		
Pitic 62	61	225	-§
Potam	67	201	-
NB402	58	202	-
Siete Cerros	59	172	-
Glenlea	73	205	-
Columbus	56	155	-
Sinton	57	175	-
Neepawa	58	166	-
Manitou	55	163	-
BLSD (k = 100)‡	8	27	-

† Each value represents the mean of 16 observations in 1982 and 80 observations in 1983.

‡ The values for Waller-Duncan's Bayesian K-ratio least significant difference (Waller and Duncan, 1969) were based on the separate analyses of variance for each seeding date within year; differences were not significant for Date I in 1982.

§ Values for seeding Date III in 1983 are not included due to measurement errors encountered with the balance.

Seed size has important effects on emergence, Haun stage, and shoot dry weight. The general lack of a cultivar by seed size interaction suggests that seed size effects were the same regardless of the cultivars used. Significant seed size effects on median emergence time were observed only on the third seeding date in each year (Table 8). Small seeds emerged more quickly than large seeds. The soil moisture content was much lower in 1983 on the third seeding date (Table 1) than on the two earlier seeding dates. This may have provided for more uniform and shallower seed placement. Small seeds have been found to germinate faster than large seeds (Lafond and Baker, submitted for publication, 1986). In 1982, the soil moisture conditions were similar for all three seeding dates. However, a more uniform and shallower seed placement would have favored the faster emergence of small seeds. Seeding depth has a large effect on speed of emergence (deJong and Best, 1979; Lindstrom et al., 1976) and non-random variations in seeding depth would quickly remove the advantages of the small seeds.

Seed size had a significant effect on shoot dry weight. Plants grown from large seeds always accumulated more seedling shoot dry weight than plants grown from small seeds. In the case of Haun stage, seed size differences were also observed only on the third seeding date in 1983. Based on the shorter emergence time, small seeds should have a higher Haun stage value than large seeds. That the opposite was observed sug-

Table 8. Effects of seed size on median emergence time, Haun stage, and shoot dry weight for three seeding dates in each of 2 years.

Seed size	Median emergence time DI	DII	DIII	Haun stage DI	DII	DIII	Shoot dry weight DI	DII	DIII
	h						mg		
				1982					
Large	308†	257	151	--	--	--	41	195	729
Small	311	255	143	--	--	--	33	155	603
Difference	−3	2	8*				8**	40**	166**
				1983					
Large	383	194	169	2.79	4.07	5.12	68	203	-
Small	384	197	164	2.72	4.06	5.03	53	168	-
Difference	−1	−3	5*	0.07	0.01	0.09*	15*	36*	-

*,** Differences are significant at the 5 or 1% level of probability, respectively.
† Each value in 1982 represents the mean of 72 observations and in 1983, the mean of 360 observations.

Table 9. Coefficients of determination for regression of shoot dry weight (n = 9) on seed weight, median emergence time and/or Haun stage for three seeding dates in 1982 and two seeding dates in 1983.

Independent variables used in regression† Seed weight	Emergence	Haun stage	Coefficients of determination DI‡	DII	DIII	Combined
			%			
			1982			
+	+		12	62*	31	53*
+			12	49*	50*	52*
	+		10	62**	12	61*
			1983			
+	+	+	92**	74*	--	79**
+	+		90**	64**	-	69**
+		+	81**	66**	-	76**
	+	+	28	49*	--	53*
+			88**	37	-	52*
	+		50*	52*	-	67**
		+	18	69**	--	81*

*,** Simple or multiple correlation significantly different from zero at 5 or 1% level of probability, respectively.
† The + sign indicates that the variable was included for calculation of the regression equation.
‡ DI, DII, and DIII corresponds to seeding dates one, two, and three.

gests that large seeds grow faster than small seeds. This conclusion is supported by the earlier observation that dry matter production by plants grown from large seeds was always significantly greater than when plants were grown from small seeds. In this study, there were no cultivar-by-seed size interactions for median emergence time and seedling shoot dry weight. The cultivar-by-seed size interaction observed for Haun stage was caused by the higher temperatures of the third seeding date compared to the two earlier seeding dates.

All possible simple and multiple regressions of shoot dry weight, using averages of nine cultivars, on seed weight, median emergence time, and Haun stage indicated significant relationships for the second date and the combined data in 1982 and for most regressions in 1983 (Table 9). The higher coefficients of determination obtained from the 1983 results compared to the 1982 results reflect the fact that emergence, Haun stage, and shoot dry weight were measured on the same plants rather than on different plants as in 1982. Seed weight, speed of emergence, and Haun stage all contribute to differences among cultivars in seedling vigor. Seed weight accounted for approximately 50% of the variation between cultivars in seedling shoot dry weight. Selecting for seedling vigor could be accomplished by selecting for greater seed weight (possibly the easiest character to select for), shorter median emergence time, and faster rate of plant development measured as Haun stage.

For the genotypes tested in this study, the maximum difference in emergence time was observed at the first seeding date in 1983 where Columbus and Potam differed by 30 h or approximately 10% (Table 4). Similarly, the maximum difference for Haun stage was observed at the third date where Manitou and Potam differed by 0.52 Haun stage units, or about 10% (Table 6). While these differences are not very large, they are believed to be closely related to observed differences on the order of 20 to 30% in shoot dry weight. In marginal growing conditions where early seedling establishment is apt to be critical to final yield performance, selection for even moderate improvement in median emergence time or early Haun stage may lead to significant progress in biomass accumulation and final yield.

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REFERENCES

Bauer, A., A.B. Frank, and A.L. Black. 1984. Estimation of spring wheat leaf growth rates and anthesis from air temperatures. Agron. J. 76:829–835.

Berkson, J. 1944. Applications of the logistic function to bioassay. J. Am. Stat. Assoc. 39:357–365.

Brenchley, W.E. 1923. Effect of seed weight upon the resulting crop. Ann. Appl. Biol. 10:223–240.

Bulisiani, E.A., and R.L. Warner. 1980. Seed protein and nitrogen effects upon seedling vigor in wheat. Agron. J. 72:657–662.

DasGupta, P.R., and H.M. Austenson. 1973a. Relation between estimates of seed vigor and field performance in wheat. Can. J. Plant Sci. 53:43–46.

----, and ----. 1973b. Analysis of interrelationships among seedling vigor, field emergence and yield in wheat. Agron. J. 65:417–422.

deJong, R., and K.F. Best. 1979. The effect of soil water potential, temperature and seeding depth on seedling emergence of wheat. Can. J. Soil Sci. 59:259–264.

Evans, L.E., and G.M. Bhatt. 1977. Influence of seed size, protein content, and cultivar on seedling vigor in wheat. Can. J. Plant Sci. 57:929–935.

Gordon, A.G. 1971. The germination resistance test—A new test for measuring germination quality of cereals. Can. J. Plant Sci. 51:181–183.

Haun J.R. 1973. Visual quantification of wheat development. Agron. J. 65:116–119.

Kiesselbach, T.A. 1924. Relation of seed size to yield of small grain crops. J. Am. Soc. Agron. 16:670–682.

Klepper, B., R.W. Rickman, and C.M. Peterson. 1982. Quantitative characteristics of vegetative development in small cereal grains. Agron. J. 74:789–792.

Klepper, B., and K.S. Skirvin. 1984. Developmental relationships in wheat seedlings. Agron. Abstr. American Society of Agronomy, Madison, WI. p. 14.

Large, E.C. 1954. Growth stages in cereals. Illustrations of the Feekes' scale. Plant Pathol. 3:128–129.

Lindstrom, M.J., R.I. Papendick, and F.E. Kochler. 1976. A model to predict winter wheat emergence as affected by soil temperature, water potential, and depth of planting. Agron. J. 68:137–141.

Lowe, L.B., and S.K. Ries. 1972. Effects of environment on the relation between seed protein and seedling vigor in wheat. Can. J. Plant Sci. 52:157–164.

Quinby, J.R., L.R. Reitz, and H.H. Laude. 1962. Effect of source of seed on productivity of hard red winter wheat. Crop Sci. 2:201–203.

Schimpf, D.J., S.D. Flint, and I.G. Palmblad. 1977. Representation of germination curves with the logistic function. Ann. Bot. 41:1357–1360.

Schweizer, C.J., and S.K. Ries. 1969. Protein content of seed: Increases improves growth and yield. Science 165:73–75.

Waldron, L.R. 1941. Analyses of yield of hard red spring wheat grown from seed of different weights and origin. J. Agric. Res. 62:445–460.

Waller, R.A., and D.B. Duncan. 1969. A Bayes rule for the symmetric multiple comparisons problem. J. Am. Stat. Assoc. 64:1484–1503.