Aggregate Size Distribution in the Row Zone of Tillage Experiments[1]

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ABSTRACT

A sampling procedure was developed to measure the distribution of soil aggregate diameters in the row zone of row-cropped corn. At each of 31 locations, 4 preplant tillage treatments were used to obtain different soil conditions in the row zone. Undisturbed soil cores were taken from the 0- to 3- and 3- to 6-inch layer. Dry aggregate-diameter distribution and dry bulk density (D_B) were measured for the 0- to 3-inch layer (D_B only in the 3- to 6-inch layer). Within 6 weeks after planting D_B increased, but the logarithm of geometric mean diameter (log GMD) and the dispersion of aggregate diameters ($\sigma_{\log d}$) changed differently depending on tillage treatment and year of study. D_B in the 3- to 6-inch layer did not change. Large differences in these measurements were observed among tillage treatments, but within a year of field trials no treatment $\times$ location interaction occurred. Some comparisons of measurements were consistent between years and others were not.

D_B of the 0- to 3-inch layer increased among tillage treatments as $\sigma_{\log d}$ increased, but decreased less as the log GMD increased. A similar relation was shown in the laboratory using mixtures of aggregate-diameter separates. These changes in D_B were mainly due to modification of the interaggregate void space. In the laboratory an increase in weight fraction of water was observed from increasing $\sigma_{\log d}$. Hence, both log GMD and $\sigma_{\log d}$ are measurable parameters of soil conditions in beds of aggregates, and may help to explain soil water retention and movement, evaporation losses, seed-soil contact, and root-soil contact.

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THE OBJECTIVES to be achieved by tillage practices in a row crop are different in the inter-row than in the row zone (8). The soil physical conditions created by tillage in each of these two zones, along with other environmental factors, determine the adequacy with which a particular soil management objective can be achieved. Measurements of soil conditions in the row zone may differ from those of the inter-row zone because of differences in the management objective and the soil conditions. Hence, the limits set on a soil-condition measurement in the row may be considered in terms of what limits will optimize soil conditions for early growth of plants. This may be done independently of the soil-condition measurements in the inter-row zone.

In a seedbed of aggregated soil, the average aggregate-diameter and the proportion having certain diameter limits may be modified somewhat by choice of tillage operation. The desired modification depends on the causal relations between aggregate-diameter distribution (and geometrical arrangement) and processes such as movement and retention of water, evaporation losses, seed-soil contact, and root-soil contact. Many of these processes have been studied in isolated experiments, usually under laboratory conditions involving beds of "uniform" sized aggregates or beds having arbitrary limits on aggregate diameter. Larson (8) has discussed some of these studies. Application of these studies for interpretation of field results involving beds of aggregates is hazardous unless more is learned about the aggregate-diameter distributions attained in the field.

This manuscript describes a procedure used to measure aggregate-diameter distributions in the row zone of tillage experiments. The measurements are evaluated in terms of their time-reproducibility, the differences among tillage treatments, and the interrelation of the different measurements. The procedure was tested during 2 years (1963 and 1964) of tillage experiments in the field.

METHODS AND MATERIALS

Sampling of Secondary Aggregates

Cores of undisturbed soil (0- to 3- and 3- to 6-inch layers) were taken from the center of the row zone with a 6-inch long cylinder made from cold rolled steel tubing having a 4-inch outside diameter and 1/16-inch wall thickness. One end of the cylinder was sharpened to a knife edge, and midway along its long axis a slot was cut perpendicular to the long axis to accommodate a cutting knife 1/16 inch thick. The cylinder was forced into the soil (by pounding on a piece of wood placed over the cylinder when the cylinder could no longer be manually forced into the soil) until the top edge of the cylinder was level with the adjacent ground surface at the center of the row. Usually, the soil material within the core settled about 0.5 inch below its original elevation; this was likely due to geometrical reorientation of the aggregates in the upper layer. The core then was removed with a tiling spade, the cutting knife inserted, excess soil trimmed off the bottom edge, and the 0- to 3- and 3- to 6-inch cores gently placed into separate containers.

The amount of oven-dry aggregates in each of 7 (8 in 1964) sieve size groups was determined by sieving the air-dried soil in a rotary sieve (3) modified to use the following screen openings: 9.52, 5.16, 3.18, 1.98, 1.02, and 0.51 mm. In 1964, the material > 12 mm was separated from the sample prior to rotary sieving. Hence, the 1963 separations measured the > 10 mm as one fraction, and in 1964 the > 12-mm and the 10- to 12-mm fractions were measured. The sampling in the field, preparation before sieving, and sieving collectively define the "secondary aggregate." It is similar to the definition given by Chepil (2) except that his treatment of the aggregates during sampling in the field may have been more gentle. For purposes of this manuscript, the term "aggregate" will mean secondary aggregate as defined here.

In 1963, a sample was a composite of 4 cores each randomly selected in the center of the row zone of a tillage treatment. In 1964, six (in some cases eight) cores were composited into one sample. The dry bulk density, D_B, was determined on the same sample used to obtain the aggregate samples.

The moisture content of the 0- to 3-inch layer at the time of sampling was usually from 2 to 10 units of per cent water below the lower plastic limit. The moisture content of the 3- to 6-inch layer was higher but rarely exceeded the lower plastic limit. The lower plastic limit was determined by rolling the soil into a ribbon (1).

Estimation of Mean Aggregate Diameter and Aggregate-Diameter Dispersion

From the oven-dry weights of the sieve fractions of a sample from the 0- to 3-inch layer, two parameters were estimated: *(a)* the logarithm_{10} of the geometric mean diameter (log GMD), and *(b)* an index of the dispersion[4] of the aggregate diameters ($\sigma_{\log d}$). Estimation of these parameters requires that the proportion of soil aggregates by weight in the sample be distributed approximately normally as the logarithm of the diameter. The two parameters were computed mathematically, but the computation conformed to the graphical estimation illustrated in Fig. 1. Using the logarithm of the diameter of the upper limit for the sieve classes shown in Table 1 and the proportions by weight in the sieve classes, an array of fraction-undersize versus logarithm-of-aggregate-diameter was calculated. The fraction undersize was then transformed to the standard normal for the binomially distributed variate (see 4, p. 124). Under the assumption of a log-normally distributed aggregate diameter, a linear relation was expected between the standard normal of the weight fraction undersize and the logarithm of the aggregate-diameter. It is from this relation that log GMD and $\sigma_{\log d}$ were estimated.

The estimated GMD of sample 1 (Fig. 1) was 4.6 mm, and

[4] The meaning of the word dispersion is analogous to the variance in statistical concepts. Their meaning is not the same, because variance deals with precision as a component of error and dispersion as used in this manuscript deals with diameter heterogeneity in a mixture of aggregate-diameter separates. Furthermore, dispersion as used here should not be associated with sample preparation for mechanical analysis or vertical segregation of aggregate diameters in the seedbed.

Table 1—Comparison of observed and estimated weight fraction of aggregates for selected samples 1 and 2, and the average comparison of observed and estimated weight fraction in 1963 and 1964

Diameter of aggregates in mm*	Weight fraction in sample 1†		Weight fraction in sample 2†		Average estimated-minus-observed weight fraction‡	
	Observed	Estimated§	Observed	Estimated§	1963	1964
> 12	0.352	0.374	0.439	0.494	0.007	0.062
10 - 12			0.111	0.034		−0.066
5 - 10	0.131	0.106	0.126	0.091	−0.029	−0.032
3 - 5	0.090	0.083	0.063	0.072	−0.002	0.004
2 - 3	0.092	0.081	0.057	0.070	−0.001	0.002
1 - 2	0.114	0.115	0.067	0.099	0.015	0.019
0.5 - 1	0.110	0.120	0.064	0.103	0.026	0.025
< 0.5	0.111	0.120	0.073	0.037	−0.003	−0.006

* These diameter limits have been ronnded to the nearest 0.5 mm. In all calculations, sieve openings of 12.00, 9.52, 5.16, 3.18, 1.98, 1.02 and 0.51 mm were used.
† Sample 1 was taken in the 0- to 3-inch layer of the "wheel-track modified" treatment on a Webster soil on May 15, 1963 (at planting time). Sample 2 was taken from the 0- to 3-inch layer of the wheel-track treatment on a Kranzburg soil on May 20, 1964 (at planting time).
‡ The valnes shown are an average for 144 and 104 aggregate samples, respectively, in 1963 and 1964.
§ Calculated from the least squares estimate of the linear relation between standard normal of fraction undersize and logarithm of diameter shown each for samples 1 and 2 in figure 1.

the estimate of $\sigma_{\log d} = 0.86$ specified that 67% of the sample contained aggregates having a diameter within the range 0.6 to 33.2 mm, i.e., antilog (0.66 ± 0.86). Occasionally, the upper limit of this range was predicted to be greater than the 4-inch diameter sampling cylinder (c.f. Tables 4 and 6). This results from assuming a nontruncated log-normal distribution when in practice it was truncated by the size limit of the sampling cylinder. This is not a serious problem because some fraction of $\sigma_{\log d}$ will also describe the diameter dispersion. For instance, if 0.67 $\sigma_{\log d}$ were used as an index of diameter dispersion, 50% of sample 1 (Fig. 1) would fall in the range 1.2 to 17.1 mm.

Changes in log GMD and $\sigma_{\log d}$ due to the sieving were estimated by resieving several randomly selected samples. The changes upon sieving the second time were about 10 and 1% decreases, respectively, for log GMD and $\sigma_{\log d}$.

The validity of the assumed log-normal distribution of aggregate diameters was judged qualitatively from comparison of observed and estimated weight fractions. There appears to be no rigorous and yet facile manner to check the assumption when there is a small number of sieve sizes, and when weights are observed rather than numbers of particles. Sample 1 (Fig. 1 and Table 1) represents one of the best and sample 2 one of the poorest fits of a linear relation between standard normal of the weight fraction undersize and the logarithm of the diameter. The log-normal assumption overestimated the amount of aggregates in the 0.5- to 2-mm diameter range and underestimated in the 5- to 12-mm range (Table 1). These discrepancies were consistent among

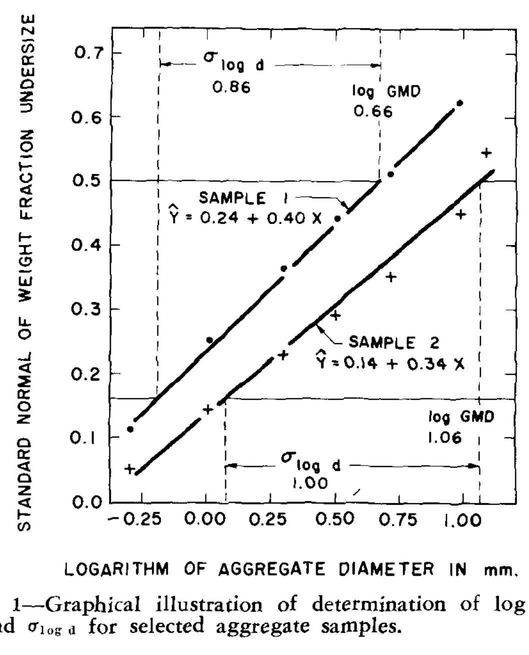

Fig. 1—Graphical illustration of determination of log GMD and $\sigma_{\log d}$ for selected aggregate samples.

Table 2—Four tillage treatments from which aggregate samples of the row zone were observed

Row treatment identification	Preplant and plant tillage operations in the row in time sequence from left to right*			
	Common moldboard plow	Tractor wheel	Other	Planter
Conventional	X	-	disc and harrow	X
Wheel track	X	X	-	X
Wheel-track modified	X	X	rotary tiller	X
Plow and plant	X	-	-	X

* The symbol X signifies the performance of the indicated tillage operation, and - signifies the absence of the indicated tillage operation.

tillage treatments, times of sampling, and locations within a soil association; but changed some among soil associations.

Tillage Treatments

Aggregate samples were taken in the row zone of each of 4 tillage treatments (Table 2) conducted at 31 locations in eastern South Dakota and western Minnesota in 1963 and 1964 (18 locations in 1963). Samples were taken at planting and 4 to 6 weeks after planting. Each tillage treatment at a location consisted of at least four 40-inch rows of corn *(Zea mays* L.) and the plot length was at least 60 but less than 100 feet. At 4 locations, plots were plowed in the fall and at 27 locations in the spring. No other tillage was performed until the following spring on fall plowed plots. The plowing depth was 6 inches using a plow with 16-inch moldboards. The tractor-wheel treatment, in all cases was made with the standard rear tire of a 5,000-lb tractor. A tandem disc with 16-inch notched blades on the front gang and standard blades on the rear gang (followed by an attached spring-tooth harrow) was used on the conventional treatment. In nearly all cases only one tillage treatment was made with the disc and harrow. In the "wheel-track modified" treatment, a band of soil 10 inches wide, centered over the row, and less than 6 inches deep was rotary tilled. A recent model toolbar corn planter with rubber press-wheels was used in 1963, and in 1964, a pull-type corn planter with steel press-wheels was used. Both planters used double-disc furrow openers.

The tests were performed on four soil associations: Barnes-Aastad, Fargo-Hegne, Kranzburg-Poinsett, and Nicollet-Webster. The clay content of the 0- to 6-inch layer of the soils ranged from 19 to 46%, and the texture ranged from loam to clay. Previous to the initiation of the tillage treatments the plot area was cropped to corn, alfalfa-brome (*Medicago sativa* L.–*Bromus* L. spp.), oats *(Avena sativa* L.) interseeded with sweetclover *(Melilotus* Mill.), or soybeans (*Glycine max* (L.) Merr.), and was handled with no particular reference to its later use for these tests.

Laboratory Measurements on Mixtures of Aggregate-Diameter Separates

The weight fraction of water held at 0.10-bar suction, D_B, and volume loss due to mixing were measured on synthesized mixtures of aggregate-diameter separates. The composition of these mixtures was determined by the values of log GMD and $\sigma_{\log d}$ shown in Table 7. A wire ring for mixing was first inserted into a plexiglass ring. Beginning with the 10- to 12-mm separate and proceeding to the smallest separate ($<$ 0.5 mm) about one-half of the calculated amount of air-dried separate was placed into the plexiglass ring on a porous ceramic plate. The same procedure was repeated for the remaining one-half of the calculated amount of separate. The previously inserted wire ring was then lifted through the sample, which tended to lift the larger aggregates and mix the sample. A layer of silica sand (of known volume) was placed over the aggregate mixture and the height of sample and sand in the ring was measured. The sample was wetted under vacuum (10); then equilibrated at 0.10-bar suction. Triplicate measurements were made, and seven aggregate-diameter separates were used to synthesize the mixtures. The volume loss per 100 cm^3 of initial volume of aggregates, which results from mixing, was computed as:

$$V_l = [1 - (V_f / \sum_{i=1}^{7} V_i)] 100 \qquad [1]$$

where V_f is the volume after mixing the aggregate-diameter separates, and

where V_i is the bed volume of the *ith* aggregate-diameter separate before mixing and is computed as the ratio of the oven-dry weight and the dry bulk density.

RESULTS

The soil samples from the 0- to 3-inch layer of the row zone were distinctly aggregated in all cases whereas those samples from the 3- to 6-inch layer were often consolidated (especially, in those treatments where the tractor wheel passed over the row). A criterion used to make this judgment was the presence of an adhering soil mass having the approximate dimensions of the 4-inch diameter cylinder. The log GMD and $\sigma_{\log d}$ were therefore estimated only for the 0- to 3-inch layer.

Accuracy of the Sampling Technique

The accuracy of the aggregate sampling and estimation of log GMD and $\sigma_{\log d}$ was evaluated in terms of variation among cores within the row and in terms of the similar estimation of these measurements at different times of sampling.

As a measure of heterogeneity among random cores within a row, the standard deviation of the log GMD and $\sigma_{\log d}$ for a composite of 4 cores was 0.198 and 0.075, respectively, and the respective coefficients of variation were 32 and 8%. Among cores within a row, greater heterogeneity of average diameter and diameter dispersion resulted in those treatments having larger average aggregate-diameter. For the wheel track treatment (larger log GMD), the respective coefficients of variation were 38 and 10%; for the conventional treatment (smaller log GMD), they were 17 and 5%.

The correlation coefficients (Table 3) indicate an acceptable reproducibility of the measurements for sampling at different times within 6 weeks after planting. In a plot of the value observed at planting versus the value observed at 4 to 6 weeks after planting, the scatter revealed no curvilinearity, or significant segregation of points due to tillage treatment or location. For log GMD and $\sigma_{\log d}$, the estimates of standard error due to failure of reproducibility with time (Table 3) are not significantly different from the above estimates obtained from repeated cores within a row. Correlations and standard errors are shown for D_B in Table 3 to compare the reproducibility characteristics of log GMD and $\sigma_{\log d}$ with those of a common measurement of soil condition in the row.

Differences Among Tillage Treatments

Large differences of soil condition resulted from different tillage treatment of the row zone (Table 4). The values for each tillage treatment for each measurement were averaged over locations and sampling times. The time changes (Table 5) were small relative to the differences among treatments, and the location $\times$ treatment interaction was nonsignificant as judged from the F-ratio of the location $\times$ treatment mean square and the square of the standard error of estimate shown in Table 3.

Table 3—Reproducibility of measurement of log GMD, $\sigma_{\log d}$, D_B of 0- to 3-inch layer, and D_B of 3- to 6-inch layer at planting time and 4 to 6 weeks after planting*

Measurement	Correlation between values measured at planting and 4 to 6 weeks after planting		Standard error of a 4-core sample as measured by failure of time reproducibility	
	1963	1964	1963	1964
log GMD	0.72	0.88	0.229	0.140
$\sigma_{\log d}$	0.51	0.89	0.164	0.067
D_B, 0 to 3 inches	0.76	0.82	0.056	0.054
D_B, 3 to 6 inches	0.76	0.91	0.052	0.036

* The number of values correlated were 72 and 52, respectively, in 1963 and 1964; and the number of cores per sample was 4 and 6, respectively, in 1963 and 1964.

Table 4—Measurements of soil condition in the row zone as affected by 4 tillage combinations of row treatment*

Tillage treatment	Measurements in 0- to 3-inch layer			D_B in 3- to 6-inch layer
	log GMD	$\sigma_{\log d}$	D_B	
	1963, 18 locations			
Conventional	0.862	0.938	0.86	0.97
Wheel track	1.278	1.208	0.93	1.07
Wheel-track modified	0.926	0.972	0.87	1.04
Plow and plant	0.946	0.998	0.85	0.97
95% confidence limit	±0.075	±0.053	±0.01	±0.01
	1964, 13 locations			
Conventional	0.692	0.902	0.91	0.99
Wheel track	1.014	1.046	0.97	1.09
Wheel-track modified	0.694	0.846	0.92	1.02
Plow and plant	0.752	0.853	0.92	0.98
95% confidence limit	±0.054	±0.026	±0.02	±0.01

* The 1963 values in the table are means of 2 times of sampling and 18 locations, i.e., mean of 36 four-core composites. The 1964 values in the table are means of 2 times of sampling and 13 locations, i.e., mean of 26 six-core composites. The units of GMD were mm, and D_B is given as g cm^{-3}.

Some modifications of the measured soil conditions by tillage treatment were similar within 1963 and 1964. Tractor wheel traffic over the row increased the D_B of the 3- to 6-inch layer. In the 0- to 3-inch layer, the D_B in the wheel-track treatment was significantly higher than in the other treatments even though the tractor wheel passed over the row in the "wheel-track modified" treatment. The log GMD and $\sigma_{\log d}$ in the wheel-track treatment were much larger than in the other treatments in both years.

Among treatments other than wheel track, log GMD and $\sigma_{\log d}$ were often significantly different, but the differences were not similar in both years. Comparison of the conventional and "plow and plant" treatments shows that disking and harrowing had little effect on D_B of either layer and decreased the log GMD in both years, but the change in $\sigma_{\log d}$ differed between years. It is also interesting to note the large log GMD in 1963 compared with 1964. The dissimilar effect of disking and harrowing on $\sigma_{\log d}$ as influenced by year and the overall larger log GMD in 1963 suggest systematic differences of tillage between years, susceptibility of the soil to tillage manipulation, or both.

During the 6 weeks following planting, the changes in log GMD, $\sigma_{\log d}$, and D_B in the 0- to 3-inch layer differed depending on the row treatment and the rainfall during the period (Table 5). In 1963, the precipitation was 3 or more inches, and in 1964, it was less than 0.2 inch during this period. Increases in both D_B and $\sigma_{\log d}$ were observed in 1963 and were correlated with each other. Both of these measurements should increase because of reduction of aggregate size during weathering and slaking at the surface, but the increase of D_B is more than expected from the increase of $\sigma_{\log d}$ (see a later discussion). Changes in log GMD appear unrelated to changes in D_B or $\sigma_{\log d}$, and were variable among locations. Changes of D_B in the 3- to 6-inch layer were <1% within both years. In 1964, where the aggregates merely dried during the 6-week period, both log GMD and $\sigma_{\log d}$ increased in the wheel-track treatment and decreased in the other treatments. This observation was consistent among locations, and may be related to the drying rate as affected by the interaggregate void volume (see a later discussion). As in 1963, the D_B increased, but the increase was less and the rank of treatments was opposite to that in 1963.

DISCUSSION

The increases of D_B with time in the 0- to 3-inch layer (Table 5) and the greater D_B in the 3- to 6-inch layer

Table 5—Changes in the measurements of soil condition in the 0- to 3-inch layer as affected by row treatment and rainfall during the 6-week postplant period

Tillage treatment	Percentage increase in the indicated measurement for the indicated year*					
	1963			1964		
	log GMD	$\sigma_{\log d}$	D_B	log GMD	$\sigma_{\log d}$	D_B
Conventional	5	12	12	−16	−5	6
Wheel track	−6	9	7	2	4	8
Wheel-track modified	−5	11	9	−9	−3	7
Plow and plant	1	15	14	−18	−3	4

* There was > 3 and about 0.2 inches of rain, respectively, in 1963 and 1964 during the period between planting and the second sampling for aggregate-diameter distribution and dry bulk density.

(Table 4) suggest a loose packing of aggregates in the 0- to 3-inch layer. Evidence against close-pack arrangement of aggregates cannot be ascertained rigorously because of the nonspherical shape of the aggregates. However, the following reasoning can be used to illustrate the divergence of the arrangement from close-pack. To obtain a close-pack arrangement, the interaggregate porosity in a bed of aggregates having a diameter (d_1) is filled with the next smaller diameter (d_2) aggregates and their corresponding interaggregate pore space. Where $d_1 >> d_2$, this can be accomplished without increasing the bulk volume of the aggregates having diameter (d_1). In the binary-mixture bed of aggregates the fractional volume (v_1) of interaggregate space in the bed as determined by the packing of aggregates having diameter (d_1) is: $v_1 = (D_{A_1} - D_{B_1})/D_{A_1}$, where D_A and D_B are the aggregate density and bulk density, respectively. The weight (g per cm^3 of bulk of aggregates) having diameter (d_1) is given as: $W_1 = (1 - v_1)D_{A_1}$ and for the aggregates having diameter (d_2), the weight of aggregates per cm^3 of bulk of aggregates is given as: $W_2 = v_1 (1 - v_2) D_{A_2}$. W_1 and W_2 will reduce to D_{B_1} and $D_{B_1} D_{B_2}$, respectively, but the non-reduced form will be used to facilitate understanding. For a system of seven aggregate-diameter separates the percentage, Z_i, by weight for the *ith* aggregate diameter (d_i) is given as:

$$Z_i = \frac{D_{A_i}(1-v_i)\prod_{j=0}^{i-1} v_j}{\sum_{i=1}^{7} D_{A_i}(1-v_i)\prod_{j=0}^{i-1} v_j}\,. \qquad [2]$$

In the equation, $i = 1, 2, \ldots, 7$; $v_j = 1$ for $j = 0$; π signifies taking the product; and d_1 and d_7 are, respectively, the largest and smallest aggregate-diameter separates. The above development is treated somewhat differently in Herdan (7). Values of D_A and D_B were those estimated for an Aastad soil (see Table 7). When the percentages by weight are calculated from equation [2] and are treated similar to the manner illustrated in Fig. 1, the relation between standard normal of fraction undersize and logarithm of diameter is unlike those observed in the field. The slope is nearly zero at lower logarithms of diameter and increases sharply as the logarithms of diameter increase. Hence, the field packing arrangement is not close-pack and allows considerable change in packing arrangement (total porosity) due to aggregate-diameter distribution changes.

The significance of the aggregate-diameter distribution for describing packing arrangement was evaluated from changes in D_B (also from the volume loss upon mixing diameter separates) as predicted by changes in log GMD

Table 6—Examples of aggregate-diameter distribution for several tillage treatments in each of 3 soil associations

Soil association	Proportional variation in log GMD accounted for by $\sigma_{\log d}$‡	Description of aggregate-diameter limits in indicated tillage treatment*							
		Wheel track				Conventional			
		log GMD	$\sigma_{\log d}$	Range for 67% of sample†		log GMD	$\sigma_{\log d}$	Range for 67% of sample†	
				Lower	Upper			Lower	Upper
Barnes-Aastad	0.21	0.660	1.011	0.4	47	0.440	0.934	0.3	24
		1.083	1.010	1.2	124	0.849	0.891	0.9	55
Nicollet-Webster	0.42	1.002	0.963	1.1	92	0.836	0.858	0.9	49
		1.133	1.035	1.3	147	0.859	0.961	0.8	66
Kranzburg-Poinsett	0.77	1.402	1.135	1.8	344	1.010	0.898	1.3	81
		1.600	1.254	2.2	714	1.044	0.973	1.2	104

* For each soil association and each tillage treatment, two sets of diameter distributions are given to approximate the range in observed diameter distributions.

† Range was obtained as the antilogarithm (log GMD ± 1 $\sigma_{\log d}$), and is given in mm.

‡ Based on data from all tillage treatments in both years of study on the indicated soil association.

and $\sigma_{\log d}$. In some instances log GMD and $\sigma_{\log d}$ were highly correlated, and appeared to be related to the adequacy of the log-normal assumption and to the aggregate system itself. Scatter diagrams of log GMD versus $\sigma_{\log d}$ (a scatter diagram for each year and time of sampling) revealed a segregation of points due to soil association, and the scatter about the linear relation was distinctly different for the three soil associations (Table 6). This correlation between log GMD and $\sigma_{\log d}$ was larger for those soil associations showing greater multimodal tendencies in the aggregate-diameter distributions. Some typical values of aggregate-diameter limits as predicted by log GMD and $\sigma_{\log d}$ are shown in Table 6. The lower diameter limit (columns 5 and 8, Table 6) is the maximum diameter for 16.7% of the sample. Within a soil association, only small changes in the lower diameter limit were observed among treatments, but changes in the upper limit were large. Because the proportion less than about 1 mm remained fairly constant within a soil association, larger values of $\sigma_{\log d}$ should be expected for larger values of log GMD.

A change of D_B was observed concomitantly with changes in $\sigma_{\log d}$ (Tables 4 and 5). Some change in log GMD was also observed. These relations were examined more comprehensively. For each of 4 tillage treatments at each of 29 locations (16 locations in 1963), log GMD, $\sigma_{\log d}$, and D_B were measured. For a given location, the mean of each of these measurements was taken as a reference point, and the deviations (4 for each location for each measurement) from the corresponding reference point were computed. These deviations were not affected by among-locations factors and retained the tillage treatment effect within each of the locations. The relation of interest was the linear model:

$$\Delta(D_B) = \beta_1 [\Delta(\log \text{GMD})] + \beta_2 [\Delta(\sigma_{\log d})] \qquad [3]$$

where the Δ symbolizes that the deviations were used in the model. Each of both Δ(log GMD) and $\Delta(\sigma_{\log d})$ made only a linear contribution to $\Delta(D_B)$, since there was no significant relation between the location means for D_B and log GMD (also $\sigma_{\log d}$). From a composite of all data ($n = 116$), the calculated relation for the model shown in [3] was:

$$\Delta(D_B) = -0.040 [\Delta(\log \text{GMD})] + 0.361 [\Delta(\sigma_{\log d})],$$

with an $R^2 = 0.63$. The estimate of β_1 was not significantly different from zero, while the estimate of β_2 was significantly ($p < 0.001$) different from zero.

Table 7—Effect of log GMD and $\sigma_{\log d}$ on the volume change due to mixing, D_B, and moisture retention by beds of Aastad aggregates made up of aggregate-diameter separates

Parameters of mixture of aggregate-diameter separates		Volume loss upon mixing (cm^3/100 cm^3 initial volume)	Dry bulk density of mixture	Weight fraction of water at 0.10-bar suction
log GMD	$\sigma_{\log d}$			
0.211	1.250	24.07	1.181	0.417
	0.884	20.37	1.133	0.408
	0.685	18.55	1.106	0.405
0.611	1.250	25.96	1.164	0.401
	0.884	22.60	1.101	0.394
	0.685	18.64	1.045	0.388

* The Aastad aggregate-diameter separates were taken from the surface layer of an Aastad clay loam sampled in August 1962 near Morris, Minnesota. The measurements of D_B and D_A were as follows:

Separate diameter	D_B	D_A
mm	g cm^{-3}	g cm^{-3}
10 - 12	0.76	1.57
5 - 10	0.82	1.57
3 - 5	0.83	1.60
2 - 3	0.87	1.62
1 - 2	0.90	1.65
0.5 - 1	0.96	1.67
< 0.5	1.08	1.67

An increase in D_B was observed as the dispersion of diameters increased. From geometric consideration of total pore space in a bed of spheres, Graton and Fraser (6) predicted a decrease in total pore space with an increase in dispersion of sphere diameters. Fraser (5) also observed the same result with clastic sediments. Dry aggregate density was measured for all aggregate-diameter separates for all four treatments from several randomly selected locations. There were no differences in D_A as affected by tillage treatment even though there were differences as great as 0.16 g cm^{-3} among locations. Therefore, the observed increase in $\Delta(D_B)$ with increase in $\Delta(\sigma_{\log d})$ resulted mainly from tillage modification of the interaggregate void space.

The sign of the estimate of β_1 agrees with observations by Miller and Mazurak (9) and the laboratory results for systems of mixed aggregate-diameter separates (Table 7). At least part of this result is likely due to a decrease in aggregate density as size of the aggregate increases.

In the laboratory-synthesized mixtures of aggregate-diameter separates, the volume loss upon mixing (D_B also) decreased with decreasing $\sigma_{\log d}$ (Table 7). There was a greater decrease of volume loss (D_B also) with decreasing $\sigma_{\log d}$ at the larger log GMD. Because the volume loss measurement deals with interaggregate void space, the associated changes in D_B were brought about mainly by changes in interaggregate void space. The decrease in D_B per unit decrease of $\sigma_{\log d}$ was 0.170 g cm^{-3} compared to 0.361 predicted in the field where the changes in $\sigma_{\log d}$ were brought about by tillage operations. Inspection of Table 7 (column 3) indicates a volume loss of about 18 to 25 cm^3/100 cm^3 initial volume. Similar measurements on samples observed in the field ranged from about 5 to 15. It is therefore likely that there was more thorough mixing of aggregate-diameter separates in the laboratory, more bridging (causing a loose packing) between aggregates in the field, or both. In Table 5 the increases of D_B with time after planting also suggested bridging between aggregates.

Associated with decreases of $\sigma_{\log d}$, there were also decreases in the weight fraction of water at 0.10-bar suction (column 5, Table 7). Amemiya found differences of capillary conductivity in beds of mixtures of aggregate-diameter separates when the suction-moisture curves for these beds differed (M. Amemiya, 1965. The influence of aggregate size on soil moisture content—capillary conductivity relations. *Unpublished manuscript, Ames, Iowa.*). Hence, alterations of interaggregate void space may also affect water movement relations in beds of aggregates in the row zone.

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