TILLAGE-INDUCED SOIL AGGREGATE STATUS AS INFLUENCED BY WATER CONTENT

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ABSTRACT

An experiment was conducted on Kimo silty clay loam and Eudora silt loam soils to determine water content effects on aggregate size distribution. Five water contents were investigated. Both soils were packed, irrigated, and chiselled at initial high water contents to create a uniform initial condition with large aggregates, and disk tillage performed at selected soil water contents as the plots dried naturally. Maximum aggregate breakdown and the resulting minimum tillage-induced aggregate size distribution occurred near the optimum water content for compaction of both soils. Soil water content at the time of disk tillage had a significant effect on tillage-induced soil aggregate size distribution for the silty clay loam soil. The same relationship was evident for the silty loam soil but was not statistically significant.

KEYWORDS. Aggregate size distribution, Soil water content, Soil-tillage interactions, Proctor density curve.

INTRODUCTION

Rough surfaces have provided the best wind erosion control on lands without organic residues (Chepil, 1953; Lyles and Woodruff, 1962). Modification of a soil's relative aggregate size status through tillage is one method of managing surface roughness. Tillage can significantly alter a soil's aggregate size distribution (ASD). Variations in ASD resulting from different implements were studied by Woodruff and Chepil (1958), Siddoway (1956), and Woodruff (1964), but soil water content was not considered as an influencing factor in those investigations. Russell (1938) credits Soviet scientists (Vassilenko and Setzinksy, 1933; Vilensky and Germanova, 1934) with the first attempts to study the effects of soil water content on aggregate size distribution following tillage.

Although available literature indicates that ASD resulting from a tillage operation depends on the soil water content at the time of tillage (Chepil, 1950; Gupta and Larson, 1982), there is little experimental data to support it. The works of Lyles and Woodruff (1962, 1963) and the Canadian Soil Research Laboratory (1949) provide insufficient experimental data to develop relationships between soil water content and tillage-induced soil ASD for a variety of implements and soils. However, Lyles and Woodruff (1963) concluded that soil water content alone was not enough to predict the ASD obtained under emergency wind erosion tillage practices, but that pre-tillage soil bulk density was also a factor.

Lyles and Woodruff (1962) found that a greater percentage of large aggregates (> 38 mm) was produced when a silty clay loam soil was tilled at 0.08 and 0.25 g/g water contents. More erodible aggregates (< 0.84 mm) and fewer large aggregates were formed at the intermediate water contents. Implement type affected the size and quantity of non-erodible aggregates obtained after tillage, but showed the same trend of greater nonerodible aggregates at the extreme high and low soil water contents studied. Tangie et al. (1990) performed preliminary field experiments on one of the soils in this study. The results showed that soil water content at the time of tillage significantly affected the resulting ASD; maximum aggregate breakdown occurred when the soil was tilled at a water content near the optimum water content for compaction as determined by a standard Proctor test of that soil.

Except for these two studies, research about soil water content effects on tillage-induced ASD has pertained to the preparation and quality of seedbeds. Braunack and Dexter (1989) reviewed the subject and mentioned several works related to tillage-induced soil ASD by Cole (1939), Bhushan and Ghildyal (1972), Adem et al. (1984), Adem and Tisdall (1984), and Tisdall and Adem (1986, 1988). These works concluded that larger aggregates are formed at both high and low soil water contents. Similar results were reported by Adam and Erbach (1990) on a loamy soil.

The objective of this research was to determine the effect of soil water content at the time of tillage on tillage-induced aggregate size distribution for the two soils in this study.

MATERIALS AND METHODS

The experiment was conducted on two soils (Table 1): Kimo silty clay loam (clayey over loamy, montmorillonitic, mesic Aquic Hapludolls) and Eudora silt loam (coarse-silty, mixed, mesic Fluventic Hapludolls) at the Kansas River Valley Experiment Field near Topeka, Kansas, from July through September of 1990. Soil water content effects on post-tillage aggregate size distribution (ASD) were investigated. The experiment was a split-plot,

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TABLE 1. Selected soil properties

Property	Eudora Silt Loam	Kimo Silty Clay Loam
Textural Composition:		
sand (2.0–0.05 mm)	29.1%	20.0%
silt (0.05-0.002 mm)	54.5%	44.0%
clay (< 0.002mm)	16.4%	36.0%
Water Content at:		
−33 J/kg	0.165 g/g	0.249 g/g
−1 kJ/kg	0.061 g/g	0.140 g/g
Standard Proctor Test:		
Maximum Density	1.58 Mg/m^3	1.53 Mg/m^3
Optimum Water Content	0.155 g/g	0.192 g/g
Organic Matter	1.50%	2.20%
pH	6.30	6.50
Exchangeable Cations:		
K	149 ppm	350 ppm
Ca	1698 ppm	3470 ppm
Mg	208 ppm	330 ppm
Na	8 ppm	14 ppm
Al	0 ppm	0 ppm

randomized block design. For each soils three blocks are selected with each covering an area of 30 m by 22 m. Within each block there are five plots, five treatments which are soil water contents ranging from air dry to near saturation, that are randomly applied to each plot. The five water contents at tillage were selected from standard Proctor density curves (PDC) of the soils (two from each side of the curve and one from near the peak, fig. 1). Table 2 shows treatment sequence, dates, and descriptions.

Both fallow plots were disked in the fall following soybean harvest and once in late spring to eliminate vegetative growth not adequately controlled with herbicides. A uniform pre-tillage condition consisting of large aggregates* was created by mechanically packing both soils (which were near their optimum water contents based on the Proctor test) with a Marliss drill with only the press wheels, 25.4 cm spacing, contacting the soil surface. Pressure from the wheels was estimated at 127 kN/m^2. Three passes were made with one pass at a 45° and another at a 90° angle to the original pass. The soils were then sprinkle irrigated at approximately 25.4 mm/h for two hours to bring the soil water content near saturation. All plots were then chiselled (inter-tool spacing of 24 cm) to a depth of 19 cm after they had dried sufficiently to support tillage operations. Tillage to a depth of 16 cm on each treatment plot, at the desired water content†, was performed by using an offset disk at 8 km/h. The disk had a 4.45 m swath width with 45 cm dia blades at a 30 cm inter-disk spacing.

* Large initial aggregates were required for development work on a model to predict tillage-induced ASD.

† Water contents were monitored by obtaining 100-150 g of soil within the first 15 cm and drying them in a Tapan microwave oven (model 1226) for 30 min on "high".

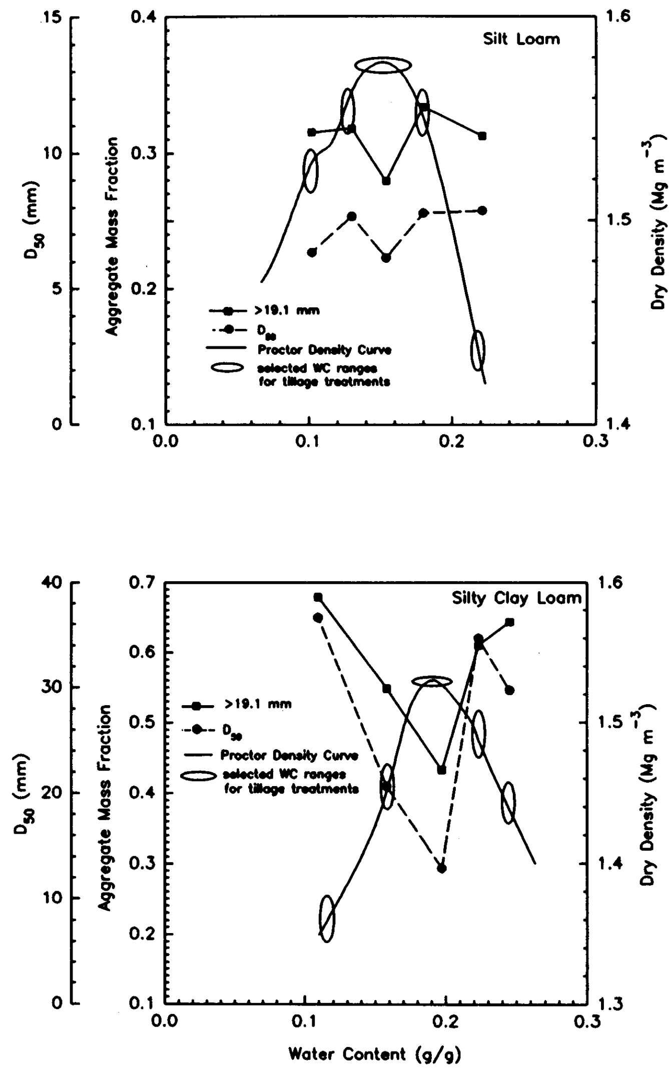

Figure 1–Aggregate size distribution vs. proctor density curve relationships.

Because of precipitation, treatments 4 and 5 of the silt loam soil were covered once and twice, respectively, with 6-mil black Visqueen plastic sheets. The sheets were anchored into the soil along the sides and furrows chiselled around those plots to divert surface runoff. Despite this, treatment 5 of Plot 3 for the silt loam soil flooded out. No precipitation occurred throughout the sampling period of the silty clay loam soil.

Two methods were used to obtain water content (WC) and bulk density (BD) samples (three per plot from each of the three blocks): an *in situ* water displacement, compliant cavity (CC) method (SCS, 1971) for pretillage treatments, and a core sampler in the manner of Tangie et al. (1990) for post-tillage treatments. The soil from the CC method was immediately placed in Reynolds plastic oven bags, tied, and stored in a freezer, whereas that from the cores was put in pre-weighed steel cans and stored in a cool place. All samples were stored for less than 10 hours before weighing.

The WC and BD samples were weighed and oven dried for 24 hours at 105° C and allowed to cool before weighing. Drying times of some CC samples were

TABLE 2. Treatment sequence, dates, and descriptions

Silt Loam Date (d -m-y)	Treatment Description and Sequence	Silty Clay Loam Date (d -m-y)
08-7-90	Packed with Marliss Drill – 127 kN / m^2 Irrigated: 25.4 mm / hr for about 2 hrs	27-8-90
09-7-90	Entire plots chiselled. Treatment 1 sampled (pre-tillage) Treatment 1 offset disked & sampled	28-8-90
14-7-90	Treatment 2 sampled (pre-tillage) Treatment 2 offset disked & sampled	29-8-90
19-7-90	Treatment 3 sampled (pre-tillage) Treatment 3 offset disked & sampled	01-9-90
	Treatments 4 & 5 covered with plastic sheets	
27-7-90	Treatments 4 & 5 uncovered	
01-8-90	Treatment 4 sampled (pre-tillage) Treatment 4 offset disked & sampled	03-9-90
02-8-90	Treatment 5 uncovered with plactic sheets	
04-8-90	Treatment 5 uncovered Plot 3 flooded out	
10-8-90	Treatment 5 sampled (pre-tillage) Treatment 5 offset disked & sampled	06-9-90

extended because of their large sizes (> 2 kg). These were periodically cooled in a desiccator and weighed until a constant weight, within 1%, was obtained.

Dry aggregate density (AD) and dry aggregate stability (AS) samples were taken from the first 15 cm of soil immediately before and after disking. Twenty spherical, non-crusted aggregates (12.7-19.1 mm dia) and 10 aggregates (> 19.1 mm dia) were hand sieved and collected from three randomly selected locations per plot on each block. Five aggregates were then selected from each sample for aggregate density determination by the clod method (Blake and Hartge, 1986). Five aggregates were also selected from each dry aggregate stability sample and determined in the manner of Skidmore and Powers (1982) with the soil aggregate crushing-energy meter (Boyd et al., 1983).

For ASD, five samples (approx. 10 kg) per plot on each block were taken from the first 15 cm of soil at randomly selected locations (between wheel tracks) in each plot using a 30 × 23 cm flat square-cornered shovel, as described by Chepil (1962), and placed in 46 × 30 × 6 cm plastic tubs. Samples were taken immediately before and after disking. All aggregate size distribution samples were air-dried in a greenhouse prior to sieving.

The ASD samples were sieved using a modified combined rotary sieve (Lyles et al., 1970). Modified geometric mean diameters ($GMD_{D'}$) and geometric standard deviations ($GSD_{D'}$) were determined for the ASD samples. Because many of these samples consisted of high percentages of large aggregates, their size distributions could not be accurately represented with a "normal" or "simple" log-normal distribution. Therefore, an "abnormal" or "modified" log-normal distribution, which assumes a maximum finite size (D_∞), was used to represent the ASD samples as outlined by Irani and Callis (1963). This method introduces a limiting maximum size parameter, D_∞, and uses the transformation:

$$D' = \frac{DD_\infty}{D_\infty - D} \qquad (1)$$

where D is the actual midpoint of the aggregate sieve size cut. Thus, three parameters (D_∞, $GMD_{D'}$, and $GSD_{D'}$) are required to completely describe the "abnormal" log-normal distribution. The $GMD_{D'}$ is the geometric mean diameter of the transformation variable (D′) distribution and does not correspond to the median size of aggregates (D_{50}) as is the case in a "normal" log-normal distribution; therefore, the sieve diameter at which 50% of the aggregate mass exceeds D_{50} is also reported to allow for better comparisons with "normal" log-normal distribution GMD values.

Results and Discussion

The ASD results indicate that the proportion of pre-tillage aggregates > 76.2 mm was greater than post-tillage aggregates > 76.2 mm at all water contents for both soils (fig. 2). The "creation" of these large aggregates can be attributed to the initial packing of the soil, chisel tool spacing, and tillage depth.

The effect of pre-tillage water content on tillage-induced aggregate size distributions was of primary interest, therefore, a conscious attempt was made to get comparable initial pre-tillage soil conditions for all treatments. This goal was partially achieved. Pre-tillage AS and AD values were not significantly different for both soils (Table 3). Pre-tillage mean BD values were not significantly different for the silty loam soil but one BD value was significantly different for the silty clay loam (Table 3). Also, some of the pre-tillage ASD mean values (D_{50}) showed significant differences for both soils (Table 4). Yet, the mean pre-tillage ASD aggregate fractions > 19.1 mm (Table 5) were not significantly different in either soils except at the

TABLE 3. Pre-tillage temporal soil properties

Soil	Water Content (g/g)	Bulk Density* (Mg/m^3)	Avg. Density (Mg/m^3)	Agg. Stability ln (J/kg)
Silt loam	0.221	1.02 a	1.52 a	4.82 a
	0.180	1.00 a	1.52 a	4.44 bc
	0.154	0.97 a	1.56 a	4.59 ab
	0.130	1.05 a	1.52 a	4.71 ab
	0.102	0.99 a	1.49 a	4.19 c
Silty clay	0.247	0.92 a	1.62 a	5.39 a
Loam	0.218	0.94 a	1.58 a	5.15 ab
	0.190	0.93 a	1.55 a	4.90 b
	0.158	1.05 a	1.61 a	4.99 b
	0.121	0.98 a	1.59 a	4.93 a

* Means with the same letter in a column for each soil are not significantly ($p < 0.05$) different by Fisher's test.

TABLE 4. Aggregate size distribution parameters

Soil	Water Content (g/g)	Pre-Tillage				Post-Tillage			
		$GMD_{D'}$*	$GSD_{D'}$*	D_∞	D_{50}	$GMD_{D'}$*	$GSD_{D'}$*	D	D_{50}
Silt loam	0.221	14.86	9.36	94.96	15.85 [a]	8.50	7.53	94.01	7.80 [a]
	0.180	10.65	9.05	93.26	9.56 [b]	8.53	7.43	90.88	7.80 [a]
	0.154	12.91	9.45	93.45	11.35 [ab]	6.61	8.76	88.68	6.15 [a]
	0.130	13.07	10.40	90.45	11.44 [ab]	8.41	8.88	88.40	7.68 [a]
	0.102	16.78	10.26	91.44	14.17 [a]	6.84	7.47	87.99	6.35 [a]
Silty clay Loam	0.247	142.69	19.37	90.00	55.19 [a]	43.46	8.41	93.98	29.72 [a]
	0.218	85.58	6.02	90.80	44.06 [ab]	55.67	10.72	91.91	34.67 [a]
	0.190	56.97	15.25	91.27	35.08 [b]	15.08	10.53	89.73	12.90 [c]
	0.158†	20.08	11.98	92.89	21.56 [c]	26.54	9.77	92.62	20.63 [b]
	0.121	70.48	18.36	90.39	39.60 [b]	61.24	12.02	91.29	36.65 [a]

Means with the same letter in a column for each soil are not significantly ($p < 0.05$) different by Fisher's test.

* GMD and GSD are, respectively, the geometric diameter and geometric standard deviation of the transformation variable $D' = (DD_\infty) / (D_\infty - D)$. All parameters are in mm except GSD which is dimensionless.

† Due to availability of tubs, 42 × 30 × 9 cm aluminum trays were used for sample collection for this treatment.

0.158 g/g WC for the silty clay loam. (It is possible this may be a sampling anomaly since trays rather than tubs were used for sample collection only at this WC which resulted in smaller sieve sample sizes. Due to the high percentage of large aggregates in these samples, sample size could easily affect the measured ASDs. Supporting this hypothesis, is the fact that the post-tillage ASD values ($GMD_{D'}$) are greater than the pre-tillage values at the same WC, which was not observed in the field.) This exemplifies one of the problems related to field research where experimental conditions cannot necessarily be controlled to the degree desired.

The assumption that the pre-tillage ASD would not change appreciably for the duration of the experiments may not be valid since differences in the D_{50} values were measured. Several possible explanations exist. One is that the actual ASD in the field did not change appreciably, but that the process of obtaining and transporting ASD samples at different water contents caused problems. For example, ASD samples collected at the intermediate water contents may have been more susceptible to aggregate destruction from handling than those at the highest and lowest treatment water contents. Another possibility is that the natural drying process and the shrinkage associated with it was breaking the aggregates down. However, since it is unlikely that the drying process would be "creating" aggregates over the duration of this experiment, the significant increase in D_{50} values (Table 4) at the lowest treatment water content over the intermediate values for both soils could not be explained. It could also be that de-aggregation processes were sufficiently different between the natural field drying and the greenhouse drying of ASD samples (samples collected at the higher water contents were subjected to more greenhouse drying and less field drying than the lower water content samples) to create the different ASDs. Without additional studies to specifically address this issue no conclusions can be made.

TABLE 5. Aggregate fraction > 19.1 mm

Soil	Water Content (g/g)	Pre-Tillage*	Post-Tillage	Difference	Percentage Difference
Silt loam	0.221	0.445 [a]	0.327 [a]	−0.118	−26.5
	0.180	0.441 [a]	0.346 [a]	−0.095	−21.5
	0.154	0.418 [a]	0.280 [b]	−0.138	−33.0
	0.130	0.387 [a]	0.334 [a]	−0.053	−13.7
	0.102	0.382 [a]	0.312 [a]	−0.070	−18.3
Silty clay Loam	0.247	0.653 [a]	0.643 [ab]	−0.010	−1.5
	0.218	0.642 [a]	0.610 [bc]	−0.032	−5.0
	0.190	0.618a	0.433 [d]	−0.185	−29.9
	0.158	0.532 [b]	0.548 [c]	0.016	3.0
	0.121	0.627 [a]	0.679 [a]	0.052	8.3

* Means with the same letter in a column for each soil are not significantly ($p < 0.05$) different by Fisher's test.

Tillage-induced de-aggregation appears to be greatest when the disk tillage was performed near the soils optimum Proctor water contents as shown by the minimum post-tillage D_{50} values at the middle water contents (Table 4). However, the minimum D_{50} value for the silt loam is not significantly lower than the values obtained at other treatment water contents. The greatest percentage changes in the fraction of aggregates > 19.1 mm following tillage, 33.0% on the silt loam and 29.9% on the silty clay loam, also occurred at the 0.154 and 0.190 g/g water contents, respectively (Table 5), which were the treatment water contents nearest the optimum Proctor water contents for the soils. Comparing the relative fractional values in the three largest sieve cut sizes for both soils in figure 2 reveal that smaller amounts of aggregates in these size classes are generally present at the "middle" water contents than at any other water contents.

Thus, maximum, tillage-induced soil aggregate breakdown appears to occur at these "middle" water contents which correspond to the optimum Proctor water

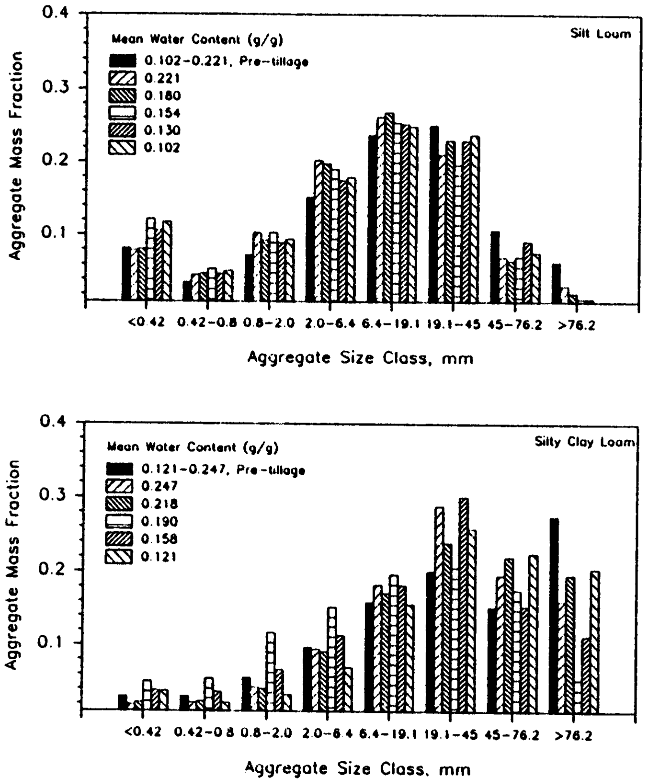

Figure 2–Pre- and post-tillage ASD sieve cuts at various water contents.

content for these soils while less aggregate breakdown occurs at other soil water contents. A comparison between each soil's Proctor density curve and the tillage-induced ASD (represented by D_{50} and aggregate fraction > 19.1 mm values) is shown in figure 1.

If aggregate breakdown at various water contents can be explained in terms of water content effects on soil cohesion (the manner in which individual soil particles are held to each other at various water contents) and the soil's response at any given compaction effort, the following qualitative implications could be made:

- At soil water contents below the optimum water content for maximum compaction derived from the Proctor test for a soil, contact between soil particles is high; the soil particles are more coherent and resistant to compaction. Soil coherence at low water contents is determined in part by the high degree of particle-to-particle bonding, interlocking, and/or frictional resistance to deformation (Hillel, 1980). Therefore, aggregate resistance to breakage can be attributed to high frictional forces within the large aggregates, the cementation of aggregates along sheared areas upon drying (Baver, 1956), and possibly Van der Waals forces (Payne, 1988).

- As soil water content exceeds the optimum water content for maximum compaction, the volume of air remaining in the soil decreases as water films surrounding individual particles fill up aggregate pore spaces (Baver, 1956). Since the water is incompressible, the soil's susceptibility to compaction is greatly reduced. When soil is tilled at these high water contents, aggregates tend to slide over one another rather than breaking because of the reduction in both frictional and shear forces.

- The optimum water content for compaction determined from a Proctor test appears to coincide with the water content at which a soil is most manageable. Vilensky and Germanova (1934) called this water content, "*moisture content for optimum structure formation*". Baver (1956) states that soil at this water content has just enough water to minimize cohesiveness between particles but yet not enough to render the soil plastic. The absence of plasticity and a weaker aggregate strength, less than that of the bulk soil (Payne, 1988), account for the easy breakdown of large soil aggregates (fig. 1) at this water content.

Summary and Conclusions

1. Soil water content at the time of disk tillage had a significant effect on tillage-induced, soil aggregate size distribution for the silty clay loam soil. A similar trend was also apparent for the silty loam soil, although it was not statistically significant due to the large variance that existed in the experimental data. Therefore, soil water content's influence on tillage-induced aggregate size distribution appears to be greater for fine-textured soils than coarse-textured soils with that influence becoming insignificant for cohesionless soils.

2. Maximum aggregate breakdown occurred near the optimum water content determined from standard Proctor density curves (PDC) for both soils. This was apparent from the minimum values obtained for D_{50}. The quantity of large post-tillage aggregates (> 19.1) mm was minimized at the treatment water contents corresponding to the soils' Proctor optimum water contents. This maximum breakdown of large aggregates near the optimum water content was statistically significant for both soils.

3. Although the data suggests there is an inverse relationship between water content and tillage-induced aggregate size distribution across soil types, more data are needed to quantify that relationship. Additional studies are also needed to determine the effects of tillage tool and pre-tillage aggregate size distribution on post-tillage aggregate size distribution.

4. Experiment and sampling techniques need to be further improved to decrease the variance of experimental data.

References

Adam, K. M. and D. C. Erbach. 1990. Disk and cultivator effects on soil aggregation. ASAE Paper No. MC90-101. St. Joseph, MI: ASAE.

Blake, G. R. and K. H. Hartge. 1986. Bulk density. In Methods of soil analysis, 2nd Ed., Part 1. ed. A. Lkute. *Agronomy* 9:363-375.

Boyd, D., E. L. Skidmore and J. G. Thompson. 1983. A soil-aggregate crushing-energy meter. *Soil Sci. Soc. Am. J.* 47:313-316.

Braunack, M. V. and A. R. Dexter. 1989. Soil aggregation in the seedbed: A review. II. effect of aggregate sizes on plant growth. *Soil and Tillage Research* 14:281-298.

Canadian Soil Research Laboratory. 1949. Soil moisture, wind erosion, and fertility of some canadian prairie soils. Canada Dept. of Agriculture Technical Bull. 71, 78.

Chepil, W. S. 1950. Properties of soil which influence wind erosion: The governing principle of surface roughness. *Soil Science* 69:403-414.

———. 1953. Factors that influence clod structure and erodibility of soil by wind: II. Water stable structures. *Soil Science* 76:389-399.

———. 1962. A compact rotary sieve and the importance of dry sieving in physical soil analysis. *Soil Science Society of America* 26(1):4-6.

Cole, R. C. 1939. Soil macro-structure as affected by cultural treatments. *Hilgardia* 12:427-472.

Gupta, S. C. and W. E. Larson. 1982. Modeling soil mechanical behavior during tillage. p 151-178. In *Predicting tillage effects on soil physical properties and processes*, eds. P. W. Unger and D. M. Van Doren, Jr. ASA Special Publication No. 44. Madison, WI: American Society of Agronomy and Soil Science Society of America.

Hillel, D. 1980. *Fundamentals of Soil Physics*. New York: Academic Press, Inc.

Irani, R. R. and C. F. Callis. 1963. *Particle Size: Measurement, Interpretation and Application*. New York: John Wiley & Sons.

Lyles, L., J. D. Dickerson and L. A. Disrud. 1970. Modified rotoary sieve for improved accuracy. *Soil Science* 109(3).

Lyles, L. and N. P. Woodruff. 1963. Effects of moisture and soil packers on consolidation and cloddiness of soil. *Transactions of the ASAE* 6(4):273-275.

Lyles, L. and N. P. Woodruff. 1962. How moisture and tillage affect soil cloddiness for wind erosion control. *Agricultural Engineering* 43(3):150-153,159.

Payne, D. 1988. The mechanical behaviour of soils. In *Russeu's Soil Condition and Plant Growth*, ed. A. Wild, 407-8. New York: John Wiley & Sons.

Russell, E. W. 1938. Soil structure. Imperial Bureau of Soil Science. Technical Communication, 37:20-24.

SCS. 1971. Handbook of soil survey investigations field procedures. USDA, Soil Conservation Service. Washington, DC: GPO.

Skidmore, E. L. and D. H. Powers. 1982. Dry soil-aggregate stability: Energy-based index. *Soil Science Soc. Am. J.* 46(6):1274-1279.

Siddoway, F. H. 1956. Annual research report. Soil and Water Conservation Research Branch. USDA-ARS, Cooperative with Tetonia Branch Agricultural Experiment Station, Univ. of Idaho.

Tangie, N. M., L. E. Wagner and J. W. Slocombe. 1990. Effect of moisture content on aggregate size distribution. ASAE Paper No. MC90-102. St. Joseph, MI: ASAE.

Tisdall, J. M. and H. H. Adem. 1988. An example of custom prescribed tillage in south-eastern Australia. *Journal of Agricultural Engineering Research* 40:23-32.

———. 1986. Effect of water content on soil at tillage on size-distribution of aggregates and infiltration. *Australian Journal of Experimental Agriculture* 26:193-195.

Vassilenko, P. and A. Setzinksy. 1933. Resistance of soils to compression as one of the factors determining the work of agricultural implements. *Pedology* 443-463.

Vilensky, D. G. and V. N. Germanova. 1934. Experimental study of the problem of structure formation. *Pedology* 34-60.

Woodruff, N. P., C. R. Fenster, W. S. Chepil and F. H. Siddoway. 1965. Performance of tillage implements in a stubble system. II. Effects on soil cloddiness. *Agronomy Journal* 57:49-51.

Woodruff, N. P. 1964. Residue maintenance by various types of farm machines. Prepared for: Guide for wind erosion control on cropland in the Great Plains states. SCS, USDA 96-97.

Woodruff, N. P. and W. S. Chepil. 1958. Influence of one-way-disk and subsurface-sweep tillage on factors affecting wind erosion. *Transactions of the ASAE* 1(1):81-85.