THE EFFECT OF FERTILIZERS, CROP ROTATIONS, TILLAGE AND CROP RESIDUE MANAGEMENT PRACTICES ON SOIL STRUCTURE

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ABSTRACT

In 1956 a laboratory study was initiated, at the University of Manitoba, to ascertain the effects of barn manure and ammonium phosphate fertilizers, crop rotations, tillage and crop residue management practices on soil structure. Bulk density and aggregation measurements were used to evaluate soil structure.

The results indicate that soil structure improved with the addition of barn manure, and with the application of ammonium phosphate, except where the crop residues were burned. Grass, alfalfa, and grass-alfalfa mixtures sown on soil, previously in crop production, increased aggregation. The tillage operations and burning had a detrimental effect on soil structure, especially within the surface layer.

I. INTRODUCTION

Field experiments have been used by soil scientists for over a hundred years to ascertain the effect of fertilizer treatments, cropping systems, and management practices on soil fertility and crop yields. Comparatively recently scientists have begun to study the effect of these treatments and practices on the physical properties of soil.

Structural changes that take place in soil are relatively slow and studies of such modifications are best conducted on well established experiments in order to obtain a complete picture of the changes occurring as a result of various treatments and practices. The Soil Science Department, University of Manitoba has been conducting several long term experiments to study the effect of various fertilizer treatments, cropping systems, and management practices on soil fertility and crop yields. The first experiments were initiated in 1919. In 1956, the present study was undertaken to measure the effect of these treatments and practices on the sturcture of a fine textured soil.

Two methods were adopted for the evaluation of soil structure. First, the measurement of soil aggregation and second, the determination of bulk density.

II. REVIEW OF LITERATURE

A. DEFINITION OF SOIL STRUCTURE

Soil structure has been defined in several ways. Baver (4) defines soil structure as the arrangement of soil particles. The word "particle" refers not only to the individual mechanical elements but also to the aggregates or structural elements, which have formed by the aggregation of the mechanical fractions. Page (40) states that Baver's definition may be satisfactory from the pedological point of view, but in terms of plant growth it is inadequate. Page (40), therefore, describes soil structure as meaning the extent to which soil is aggregated. He defines "an aggregate" as a cluster of soil particles held together loosely but with sufficient strength so that it behaves in the soil as a unit. The ideal sized aggregates, according to Page (40) are ones between a quarter of a millimeter and five millimeters in diameter and having at least a moderate degree of stability even when saturated. A review of literature also indicates that the term "soil structure" and "aggregation" have been used interchangeably by many soil scientists.

The stability of structure refers to the resistance that the soil aggregates offer to the disintegrating influences of water, wind, and mechanical manipulation. The physical characteristics of the soil may be either favourable or unfavourable depending upon the arrangement, size, and stability of these aggregates.

B. GENESIS OF SOIL STRUCTURE

The genesis of soil structure refers to the causes and methods of formation of aggregates. Page (40) suggests that soil structure formation may be broken down into two phases: (1) the actual formation of aggregates (i.e. the grouping of particles into aggregates); and (2) the stabilization of these structural units.

1. Formation

The mechanisms which have been proposed by Page (40) to explain the formation of aggregates in the soil are: (1) the direct effect of living micro-organisms; (2) the cementing or encapsulating action and the adsorption of organic materials (gums, resins, and waxes); and (3) the cohering, enclosing, and bridging action of clay particles.

Several workers (11, 34, 35, 36, 43, 47) have found that the binding quality of the soil micro-organisms and the by-products of their activity contributed to soil aggregation. Martin and Waksman (36) reported that the extent that the binding of soil particles by micro-organisms was dependent upon: (a) the nature of the micro-organisms; (b) the number of organisms (as controlled by environmental conditions); and (c) the nature of the decomposable material.

Kroth and Page (30) reported that with the use of an electron microscope no evidence of coating or capsuling of micro-aggregates by organic matter was found. Chester <u>et al</u>. (11) and Rennie <u>et al</u>. (46) suggested that undecomposed organic matter had only a minor effect on aggregate formation but that gums, resins, and waxes formed from microbial decomposition of organic matter greatly increased aggregate formation. According to Page (40) colloidal organic compounds may play two important roles in soil aggregate formation; (a) by weakening the potentially strong cohesive bonds between clay particles, thus permitting their formation into aggregates; and (b) by linking the clay particles together through mutual adsorption of such compounds by two or more clay particles to form aggregates.

Of the mechanisms of aggregate formation, that involving the clay fraction appears to be the most important. Page (40) has suggested three ways in which clay particles are thought to be held together: (a) linking with water dipoles or by bridging with divalent absorbed cations; (b) by bridging or tying together with certain types of polar long-chain organic molecules; and (c) by cross bridging and sharing of intercrystalline ionic forces and interactions of exchangeable cations between oriented clay plates.

Page (40) has stated that the linkage of water dipoles on the clay particles may be important under moist conditions, but not under dry conditions. He suspected that water may be active in causing orientation of adjacent clay particles as they are dried out.

Kroth and Page (30) and Martin (34) have indicated that the bridging or tying together of clay particles with certain long-chain organic compounds is of great importance in clay soils. Page (40) reported that there is evidence to show that many organic compounds can be strongly adsorbed by clays and that they could serve as cementing or binding agents to hold soil particles together either by hydrogen bonding or direct bridging. According to Peterson (44), Siders (55) and Winterkorn (68) one mechanism of granulation may be some type of oriented adsorption or complex linkage of organic molecules with the clay particle that are stabilized by subsequent dehydration.

The strongest cohesive forces operating in the soil are probably those existing between clay particles themselves, where a high degree of orientation or contact exists between adjacent clay particles (40). According to Page (40) these intercrystalline forces are at their maximum when the clay particles are in closest contact and have a preferred orientation, so that the number of points of contact as well as the area of contact are both large. Puddling of clay soils favours such orientation and the pieces, resulting after puddled clays are dried are very strong and coherent. Aggregates resulting from drying of dispersed clay soils are usually much stronger than those from flocculated clay soils, since in flocculation the tendency is for random orientation, i.e. the number and area of points of contact of the adjacent clay particles are small. Page (40) also reported that both Ca^{++} and H^{+} ions and many polar organic molecules produce flocculation. He concluded that most clay soils are already flocculated and that changes occurring in soil structure are not primarily changes in degree of flocculation but rather in degree of expression of cohesive forces between already flocculated clay particles. Thus, if soils are in a dispersed state, flocculation is essential for aggregate formation but, if they are puddled, fragmentation into smaller units is essential for aggregate formation.

The fragmentation of large soil units into aggregates of favourable size or the clumping together of soil particles to form aggregates separate from adjacent masses of soil, has been suggested by Page (40) to be brought about by such agencies as: small animals, tillage processes, climatic factors, and growth of plant roots. Page (40) indicated that the action of small animals, particularly earthworms could cause aggregate formation. The tillage processes could either increase or decrease soil aggregation depending upon the soil condition and on the amount of tillage (4). The various tillage processes are important because they expose large masses of soil to the various climatic forces which could cause fragmentation of the large soil masses into more favourable aggregate size. However, tillage of a wet soil (particularly a clay soil) or excessive tillage of a sandy soil could produce an unfavourable structured soil (4). Baver (4) and Page (40) have suggested that such climatic factors as wetting and drying tend to produce aggregates because of unequal strains and stresses set up by swelling and shrinking processes, together with the disruptive action of air entrapped in the pores. They have also indicated that freezing and thawing could cause extreme localized dessication and localized pressures which could cause the soil to break up into smaller units. Page (40) and Low (32) have found a direct relationship between structure and root development. There appeared to be no satisfactory explanation as to the exact nature of the root effects, but it may be a combination of several factors. Wisniewski _et al_. (69) found that roots were responsible for binding some of the smaller aggregates into larger aggregates. Peterson (45) reported that root excretions may have some flocculating or cementing effect on soil particles. Baver (4) and Page (40) have suggested that growing roots separate and compress small clumps of soil, cause shrinking and cracking due to dessication near the root, and make conditions favourable for activity of micro-organisms at the surface of these units.

2. Stabilization

Aggregates once formed in the soil would readily disappear and recombine with others in the soil if not stabilized. Page (40), and Robinson and Page (47) have concluded that the chief role of organic matter is the stabilization of structure. Stabilization, according to Page (40) is thought to be brought about by the adsorption of colloidal organic compounds on the free clay surfaces of the outer portion of the aggregates.

These adsorbed organic compounds serve as a protective layer preventing the complete expression of the cohesive forces between the clay aggregates. The free clay surfaces within the aggregates remain largely unaffected by the organic compounds; therefore the cohesive forces between clay particles within the aggregate would be much stronger than the cohesive forces between the clay particles of the adjacent soil aggregates and each aggregate would exist as a separate entity.

Page (40) has also suggested that many colloidal organic compounds are adsorbed more readily and held more tightly on the clay surface by the same forces which attract water dipoles. Once adsorbed the organic compounds tend to decrease wettability, reduce swelling, and lessen the destructive force of entrapped air within the aggregates.

Summarizing, it would appear that the formation and stabilization of favourable soil structure was dependent upon: the presence of clay; its coagulation or flocculation; the fragmentation of large soil masses into favourable sized aggregates; and the stabilization of these aggregates by colloidal organic compounds.

C. MEASUREMENT OF SOIL STRUCTURE

The complete evaluation of soil structure in its broadest sense is virtually impossible and the task becomes even more involved if the variations in structure with time are to be described. Evaluation of soil structure is made, therefore, in terms of one or more of such related measurements as aggregate-size distribution, aggregate stability, bulk density, porosity, or permeability. The most commonly used measurements for the evaluation of soil structure are aggregate-size distribution of the water-stable aggregates and bulk density.

1. Aggregate-size distribution by wet-sieving

One of the first attempts to measure the aggregate-size distribution of soil was made by Tuilin (61) using the wet-sieving method. Tuilin believed that the agitation of soil aggregates in water would break them down to certain size units which would then resist further breakdown. Using this method the percentage by weight of water-stable aggregates retained on the various mesh-size sieves, was considered a measure of soil aggregation. Several variations of Tuilin's method have been proposed (10, 12, 29, 31, 39, 47, 48, 51, 62, 70, 72, 74) in an attempt to standardize the wet-sieving procedure. The most widely used procedure is that developed by Yoder (72). In this procedure a mechanical lift is employed to raise and lower the sieves. However, the stability of aggregates in water is a relative measure and comparisons among soils can be made only in terms of measurements made under certain arbitrary but well-defined and controlled experimental conditions.

(a) Factors affecting the wet-sieving technique

A review of literature reveals that the greatest difficulty in the method of determining aggregate-size distribution by the wet-sieving technique lies in the standardization of the procedure. The factors that must be considered can be grouped under two headings; namely, the preparation of the sample and the wet-sieving procedure.

(1) Preparation of the soil sample

In preparing the soil sample for aggregate analysis the factors that must be considered are: (a) the size class of the soil that is used (i.e. the entire soil sample or a certain size class such as the 3-5mm. fraction); (b) the moisture content at sampling time and during storage; and (c) the method used to re-wet the air-dry soil prior to wet-sieving.

Yoder (72) has stated that wet-sieving analysis data would be erroneous unless the soil sample was left in its natural state. Other soil workers (10, 29, 31, 33, 47, 51) have suggested the gentle crushing of the soil sample and the use of a certain size class, in order to gain better reproducibility of results. Van Bavel (62) suggested that the soil be passed through a 5mm. screen and that a representative sub-sample be taken for wet-sieving analysis which would contain soil particles ranging in size from 0 to 5mm. Other workers (10, 31, 47, 51, 71, 74) have used the 3-5 mm. size class as a sample for wet-sieving analysis. Robinson and Page (47), and Low (31) have reported that by using the 3-5mm. size class a more accurate reproduction of results are obtained, because of the uniform sub-sample. Clement and Williams (12), and Robinson and Page (47) have also stated that care must be exercised when screening a moist soil sample in order to prevent compression or puddling of the soil.

Alderfer (3), Baver and Rhoades (5) state that the soil for wet-sieving analysis should be at the same moisture content as when sampled in the field. They theorized that air-drying the soil caused dehydration and resulted in the formation of water-stable aggregates which were not actually present under field conditions. Several workers (2, 12, 21, 24, 31, 33, 39, 47, 50, 74) have found that wet-sieving the same soil at various moisture contents greatly affected the percentage of water-stable aggregates. Evans (21), Russell and Tomhane (50) state that it is difficult to obtain soil which has a uniform moisture content, if the soil is wet-sieved immediately after being sampled from the field. They also found it difficult to store these soil samples so as to prevent moisture loss and microbial activity. In order to solve the moisture problem, several workers (2, 10, 31, 33, 48, 50, 51, 62, 70, 71, 72) have air-dried the soil samples immediately after sampling and then re-wetted the samples prior to wet-sieving.

A review of the literature indicates that the procedure of re-wetting the air-dried soil for wet-sieving analysis is critical and that some standard procedure should be adopted if results are to be comparable. Rowles (48) and Van Bavel (62) have shown that re-wetting air-dry soils under vacuum conditions produced variable results and has no advantage over the capillary method of wetting. Data presented by Nijhawan and Olmstead (39) indicated that the re-wetting of dry soil by a fine spray or by capillary action gave a much higher percent of aggregation than did wet-sieving the fresh field sample. Vacuum re-wetting of dry soil gave intermediate results. Emerson (19), Low (31), Rowles (48), Russell and Tomhane (50) have reported that with air-dried soil samples the water-stability of the larger aggregates decreased as the rate of wetting was increased. Yoder (78) theorized that the immersion of air-dry aggregates in water caused the destruction of the larger aggregates chiefly by the shattering effect due to entrapped and compressed air in the tiny pores. This view was supported by other workers (20, 39, 68). According to Nijhawan and Olmstead (39) shattering was most severe when the soil was air-dry and decreased with increased moisture content. They concluded that the slightest increase in the amount of moisture from the air-dry state greatly reduced shattering, because the tiny pores were partially filled with moisture and the usual entrapping and compressing of the air in the tiny pores did not occur. Low (31), Panabokke and Quirk (42), and Robinson and Page (47) have reported that in addition to entrapped air, swelling is a factor in causing slaking (or shattering) of soil aggregates. Dettmann (15) also has stated that entrapped air is neither a necessary nor an important factor in slaking of air-dry soils, but that slaking is always associated with rapid intercrystalline swelling of the clay.

(2) Wet-sieving procedure

The mechanical lift designed by Yoder (72) facilitated the standardization of the wet-sieving technique. There are, however, other variations in the wet-sieving procedure and apparatus which significantly affect the results obtained from wet-sieving. These variations can be grouped into: (a) the number of sieves used; (b) the size and shape of mesh of the sieves; (c) the diameter and height of the sieves; and (d) the number of oscillations the sieves undergo while immersed in water.

The number of sieves used in wet-sieving analysis is determined mainly by the kind of information the soil worker wishes to obtain about soil aggregation. Bryant _et al._ (10) and Low (31) used two sieves and Klute and Jacob (29) a single sieve to measure the relative water-stability of a soil, while Yoder (72) and Van Bavel (62) used a nest of four sieves to measure the size-distribution of the water-stable aggregates of a soil.

Several soil workers (10, 12, 31, 51, 59, 72, 74) have recognized the importance of standardizing the size and shape of mesh of the sieves used for wet-sieving analysis. Tanner et al. (59) recommended the use of 2,1,0.5, and 0.25mm. mesh sieves, but not the 0.10 mm. mesh sieve for wet-sieving analysis, as it increased the variation between replicates. The standard U.S.A. round mesh sieve has been more widely used by soil workers (12, 31, 48, 51, 62, 70, 72, 74) than the square mesh type used by Tanner and Bourget (60).

Clement and Williams (12) found that the number of sieves and the size of mesh of the sieves required for wet-sieving analysis is also dependent upon the amount of aggregates retained on each sieve after wet-sieving. They suggested that the number of sieves be decreased or the size of mesh of the sieves be increased so that at least one-tenth of the weight of the original sample used is retained on each sieve after wet-sieving.

The five inch diameter sieves have been found by several workers (10, 62, 70, 72) to be both convenient and satisfactory for wet-sieving analysis. Tanner et al. (59) have recommended the use of the half-height (i.e. 1 inch deep) sieves instead of the full-height (i.e. 2 inch deep) sieves because they were less bulky and more convenient. However, they suggested that the sieve receiving the soil should be full-height in order to prevent overflow of water and soil during wet-sieving.

Variations in the total number of strokes or oscillations for each determination have been shown by several workers (10, 31, 51, 62) to influence the size-distribution of the aggregates of a soil. Low (31) states that the percentage of the aggregates retained on the sieves decreased as the number of oscillations were increased, until approximately five hundred oscillations were reached. Increasing the number of oscillations beyond five hundred did not significantly affect the stability of most of the soils studied. Therefore, Low (31) concluded that five hundred oscillations were suitable for most wet-sieving analysis.

(b) Methods of expressing wet-sieving analysis data

Various methods have been developed and equations derived to obtain wet-sieving data in a simple form which could be easily and accurately interpreted and which would characterize soil aggregation. Several soil workers (12, 14, 24, 31, 39, 66) have suggested that the percentage of aggregates larger than some specific size, but arbitrarily chosen, be used to characterize soil aggregation. Clement and Williams (12), Gish and Browning (24), Low (31), and Wilson <u>et al</u>. (66) have expressed results as percent of water-stable aggregates greater than 2mm.; while Nijhawan and Olmstead (39) and Dawson (14) have expressed results as percent of water-stable aggregates greater than 0.2mm.

Van Bavel (62) has suggested that the mean-weight diameter be used for a statistical index of aggregation.

The mean-weight diameter is measured graphically from the area above the curve when the accumulated percentages by weight of aggregates retained on each sieve are plotted against the upper limits of separation. This method utilizes all the available information on aggregation and permits the presentation of data from wet-sieving analysis as a single figure. Gardner (23) criticized the mean-weight diameter procedure as being time consuming and subject to plotting and planimetering errors. Youker and Guinness (73) have proposed a short method of obtaining mean-weight diameter values which consisted of calculating the product of the midpoints of each size range and the percent retained on each range, respectively. The calculated value usually overestimated the area above the curve and a regression technique was applied to obtain the true mean-weight diameter. Youker and Guinness (73) estimated the calculation method to take only thirty seconds as compared to fifteen minutes by the graphic method (62). Stirk (56) has suggested that Youker's calculation method without the application of the regression would be a satisfactory means of expressing data obtained by wet-sieving.

2. Bulk density measurements

The second measurement that is often employed for the evaluation of soil structure is bulk density. Several soil workers (16, 28, 29, 52, 58, 64) have used bulk density measurements to follow structural changes in soil as influenced by various crop and manure treatments.

The bulk density measurement is determined by dividing the oven dry weight of the soil clod by its volume. The lower the bulk density value the greater the pore volume and this is considered to indicate a more favourable soil structure. There are, however, several factors which influence, and several methods of determining, bulk density measurements.

(a) Factors affecting bulk density measurements

Several soil workers (25, 49, 54) have found that bulk density values are influenced by the method of sampling and by the moisture content of the soil.

Shaw (54) suggested that bulk density investigations should be determined, either on natural soil clods carefully removed from the soil profile or on undisturbed soil cores as obtained by a core sampler. He stated that undisturbed samples gave results representing conditions of the soil in the field.

A review of reports by several workers (25, 29, 49, 54, 64) on bulk density measurements reveal that any method which required or allowed the soil clod or core samples to dry, tended to give erroneous bulk density results. Russell and Balcerek (49) reported that the shrinkage occurring in natural clay clods as they were dried from field capacity to wilting point, was 4.9 percent for manured and 5.9 percent for the nonmanured plots. Haines (25) presented data showing that the volume of the re-wetted soil was greater than that of the original.

(b) Methods for measuring bulk density

The four methods most commonly used for measuring the bulk density of soils are: the immersion of a clod in mercury or lamp paraffin (25); the proofing of a clod's surface against some liquid without increasing the volume of the clod (47); the paraffin-immersion method as described by Russell *et al.* (52); and the core sampler method as used by Klute and Jacob (29), and Van Doren and Klingebiel (64). Shaw (54) determined the bulk density of clods at field moisture content by various methods and found that the paraffin-immersion method was the most accurate.

D. REVIEW OF FIELD EXPERIMENTS

Examination of literature on soil studies reveals that wet-sieving analysis and bulk density measurements have been used by several soil workers to study the effect of various crop and cultural treatments on soil structure. The following review of such field experimental studies is grouped under three headings: (1) organic and inorganic fertilizers; (2) crop rotations; and (3) tillage and crop residue management practices.

1. Organic and Inorganic Fertilizers

The application of organic fertilizer in the form of barn manure has generally been found to maintain or improve the existing structure of a soil. Klute and Jacob (29) on measuring the amount of water-stable aggregates greater than 0.42mm. (of a silt loam soil), found that at least 20 tons of barn manure per acre per year was necessary to significantly increase the aggregate stability as compared to a non-manured check plot. In addition, they reported that the bulk density was lowered by 20 percent at the 0-4 inch depth on the manured plot. Similarly, Russell _et_ _al_. (52) working with a silt loam soil obtained a significant increase in amount of water-stable aggregates greater than 0.42mm. by the application of barn manure. They reported also a significant decrease in bulk density (at both the 0-3 and 7-9 inch depths) on plots which had received 40 tons of barn manure per acre. Alderfer and Merkle (1) presented data showing that the bulk density of a silt loam soil was 1.25 for a check plot and 1.23 and 1.17 for the 6 and 10 ton manure treatment plots, respectively. Baver (4) had found that the favourable effect of barn manure on soil aggregation was only temporary. Bertramson and Rhoades (7) stated that the addition of barn manure had no appreciable effects on the aggregation or the bulk density of a silty clay loam soil over a 15 year period. Low (33) reported a marked decline in the amount of water-stable aggregates greater than 3mm. on a clay soil under cultivation for 10 years despite the addition of 600 tons per acre of barn manure.

Several workers have shown that the application of inorganic fertilizer (usually made to increase the available nutrient supply in a soil) has resulted in increased soil aggregation. Elson (18) reported that soil of plots under corn continuously and under wheat continuously showed an increase in aggregation when inorganic fertilizer was applied. He also reported that the application of inorganic fertilizer had increased aggregation of soil under a rotational wheat cropping system, but had not increased aggregation of soil under a continuous hay cropping system. Baver (4) has suggested that fertilizer application influenced soil structure mainly by increased foliage and root production.

2. Crop rotations

Several workers (8, 18, 24, 27, 37, 41, 57, 63, 64, 71) have reported that the systematic sowing down of fields to grasses, legumes, or both, at regular intervals has resulted in an improvement in soil structure. Elson (18) conducted experiments to determine what effects a four-year rotation of corn, wheat, clover, and timothy hay, and thirty years of continuous timothy hay crops and wheat crops would have on the water-stability of a silt loam soil. He found that the aggregate-stability of the soils from both the continuous and rotational timothy hay plots were approximately the same and that the soil from the rotational wheat plot had only slightly lower aggregate-stability than the soil from the continuous wheat plot. Page and Willard (41) suggested that the inclusion of sod crops (of legumes, or grasses, or a mixture of legumes and grasses) in a cropping system was very important because grain crops (wheat, oats, or corn) in the rotation had a tendency to reduce soil aggregation, whereas the sod crops had a tendency to increase soil aggregation. Bolton and Webber (8) conducting an experiment on clay soils found that the soil under a blue grass sod showed better aggregation than the soils under a first or second year alfalfa-brome sod. They found the soils under both the alfalfa-brome and blue grass sods were much better aggregated than the soil from the cultivated check plot. Wilson and Browning (67) suggested that alfalfa with its tap root is less effective in building a stable soil structure than grass with its numerous fine roots. However, they concluded that grass and legume mixtures are the most desirable as they not only improve aggregate stability, but also supply nitrogen to the soil. Several workers (1, 22, 64) have presented bulk density data indicating improvement of the structure of the soil of plots under grass and legume for several years. Kennedy and Russell (28) presented data showing that bulk density of the 0-3 inch layer of soil changed from 1.25 to 0.97 after having been in a grass-legume sod for several years and that the types of grass which had the greatest development of roots and rhizomes resulted in the lowest bulk density values. However, McHenry and Newell (37) found no significant differences in bulk density among various grass sods, but found a significant difference between a cultivated field and each of the grass sods.

3. Tillage and crop residue management practices

The destruction of natural aggregation of the soil by various tillage practices has been indicated by several workers (1, 14, 16, 24, 37, 52, 57, 63, 71). Russell <u>et al.</u> (52) has shown that aggregation of the soil of a plot previously in sod, steadily declined when the plot was continuously cropped to corn because of increased cultivation and poorer protection given to the surface soil. McHenry and Newell (37) found that the soil of a cultivated field as compared with a sod field had significantly decreased in aggregation at the 1-3 inch depth; had slightly decreased in aggregation at the 5-7 inch depth; and had approximately the same aggregation at the 11-13 inch depth. Dawson (14), and Dreibelbis and Nair (16) have indicated that plowing as compared to discing reduced the percent aggregation in the surface layer of the soil. However, Dreibelbis and Nair (16) found that plowing as compared to discing of a soil resulted in slightly higher bulk density values at the 0-2 inch depth and much lower bulk density values at the 3-6 inch depth. According to Woodruff (71) the decline in soil structure by cultivation is due, in part, to the increased decomposition of the protective organic colloids without supplying fresh organic matter to replace them.

The effects of various mulches on soil aggregate structure has been investigated by several workers (3, 6, 9, 14, 38, 41, 65, 74). Alderfer (3) reported that the presence of an organic mulch maintained soil aggregation at the 1-3 inch depth when compared to a check. Dawson (14) indicated that a wheat straw mulch increased aggregation over that of an alfalfa mulch. However, Browning and Milam (9) reported that the incorporation of alfalfa into the soil as compared to the incorporation of straw resulted in an increase in aggregation. Similarly, Woodruff (71) found that sweet clover plowed down as a green manure increased soil aggregation over that of a check plot.

III. MATERIAL AND METHODS

A. DESCRIPTION OF SOILS

The soils on which the plots were located have been described by Ehrlich <u>et al</u>. (17) as members of the Red River and Fort Garry Associations. The imperfectly drained (Red River) and poorly drained (Osborne) are soil associates of the Red River Association and are classified as Blackearth-like and Meadow soils, respectively. Both of these soils have developed on lacustrine clay deposits greater than thirty inches thick. The imperfectly drained soil associate of the Fort Garry Association contains free lime carbonate to the surface and is classified as a Calcareous Black. This soil has developed on a clay or silty clay mantle less than thirty inches thick that tongues into underlying sediments, which are strongly calcareous and vary in texture from very fine sandy loam to silty clay.

The Red River and Osborne soil associates of the Red River Association are the dominant soils in the plot area. The imperfectly drained associate of the Fort Garry Association is confined to narrow strips within the plot area.

B. EXPERIMENTAL DESIGN AND PLOT LAYOUT

Several long term experiments have been initiated by the Department of Soil Science to study the effects of organic and inorganic fertilizer treatments, cropping systems, tillage, and crop residue management practices on crop yields. Some of the plots from three of these experiments were selected to determine what effects the above treatments and practices had on soil structure.

1. The effect of barn manure on soil structure (Experiment 68)

Experiment 68, initiated in 1919, consists of a four year rotation of corn, wheat, fallow, and wheat. In 1956 these rotation years were represented by Ranges 22, 23, 24, and 25, respectively. Each range consists of eleven plots 1/40 of an acre in size. Barn manure was applied (in the fall) only to that range which would be in corn the next season. A field plan of Range 23 in Experiment 68 showing the location of and the treatments for each of the plots, is presented in Figure 1.

Soil samples were taken at both the 0-3 and 3-6 inch depths from Plots 5, 6, 8, 10, and 11 of Range 23, in the fall of 1956 for wet-sieving analysis and in the spring of 1957 for both wet-sieving analysis and bulk density measurements. Since the plots for Range 23 were not tilled in the fall of 1956 or in the spring of 1957, the soil samples obtained in 1956 and in 1957 were essentially the same except for the lapse of time between sampling dates.

2. The effect of crop rotations and barn manure on soil structure (Experiment 70)

Ranges 26 and 27 of Experiment 70, established in 1919, have eleven main plots which are cropped as follows:

Range 23	Plot No.
* Check	11
* 30 tons of rotted barn manure	10
25 tons of rotted barn manure	9
* 20 tons of rotted barn manure	8
15 tons of rotted barn manure	7
* Check	6
* 10 tons of rotted barn manure	5
5 tons of rotted barn manure	4
10 tons of fresh barn manure (short straw)	3
10 tons of fresh barn manure (long straw)	2
Check	1

* Plots sampled in 1956 and 1957

FIGURE 1

FIELD PLAN OF RANGE 23 OF EXPERIMENT 68

(1) Plots 1 and 2 - a fallow, wheat rotation

(2) Plots 3, 4, and 5 - a fallow, wheat, wheat rotation

(3) Plots 6, 7, 8 and 9 - a fallow, wheat, wheat, wheat rotation

(4) Plot 10 - a continuous wheat cropping system

(5) Plot 11 of Range 26 - a continuous corn cropping system

(6) Plot 11 of Range 27 - a continuous oat cropping system

In 1957, Plots 1, 4 and 8 were fallow years for the three rotations outlined above. However, since the plots were not tilled in the fall of 1956 nor in the spring of 1957 the treatments at sampling time were essentially those of 1956. Thus Plots 1, 4 and 8 represented final crop years for their respective rotations.

All the plots of Range 27 received barn manure applications at the rate of 4 tons per acre. Since the barn manure applications were made each fall prior to a crop year, it is readily seen that the plots in the continuous cropping system received the greatest tonnage of barn manure since the initiation of the experiment, whereas plots in the two-year rotation received the least amount of barn manure. The plots in Range 26 did not receive any manurial treatments.

In the spring of 1957 only the south half of Plots 1, 4, 8, 10, and 11 in Ranges 26 and 27 were sampled. Soil samples were taken from the 0-6 inch depth for wet-sieving analysis and from the 0-3 inch depth for bulk density measurements.

3. The effect of crop rotations, tillage and crop residue management practices, and fertilizer treatments on soil structure (Experiment 70-A)

Experiment 70-A, initiated in 1943, consists of a six-year hay-grain rotation and a three year fallow-grain rotation. The cropping treatments for each year of these rotations are as follows:

	Hay-grain rotation	Fallow-grain rotation
Year 1	Fallow	Fallow
Year 2	Seed down for hay	Wheat
Year 3	Hay	Wheat
Year 4	Hay and break	Fallow
Year 5	Wheat	Wheat
Year 6	Wheat	Wheat

Since the fallow-grain rotation requires three years for a complete cycle and the hay-grain rotation requires six years, the former rotation completes two cycles for every complete cycle of the latter.

The arrangement of the four ranges and three blocks of plots and the rotation years represented by these plots, for 1956 are shown in Figure 2, on page 30. In 1957, since the sampling was completed prior to any spring tillage the soil was yet undisturbed and the treatments for Ranges 18, 19, 20, and 21 in Block 2 were essentially those of rotation years 3 and 6 of the hay-grain rotation. Details of the cropping practices and the tillage and crop residue management practices for each plot in rotation years 3 and 6 are shown in Figure 3, on page 31. The plots of Experiment 70-A had been split lengthwise into two parts 1/80 of an acre in size, however, the tillage and crop residue management practices are the same for each part. In the hay-grain rotation there are three hay crops grown, namely; alfalfa alone on Plots 1 and 11; an alfalfa-meadow fescue-timothy mixture on Plots 2 and 10; and a meadow fescue-timothy mixture on Plots 3 and 9. In the fallow-grain rotation there are five tillage and crop residue management practices, namely; plow under stubble on Plot 4; disc in straw and stubble on Plot 5; leave trash cover and cultivate on Plot 6; burn straw and stubble and cultivate on Plot 7; and plow under straw, stubble and alfalfa on Plot 8. In rotation year 3 the plots of the hay-grain rotation have completed two years of hay; while the plots of the fallow-grain rotation have completed two years of wheat. In rotation year 6 all the plots of the hay-grain and fallow-grain rotations have completed two years of wheat.

The fertilizer treatments for Experiment 70-A are as follows:

(1) check with no fertilizer
(2) Ammonium phosphate (11-48-0) at 45 lbs per acre
(3) Ammonium phosphate (16-20-0) at 108 lbs per acre
(4) Barn manure at 8 tons per acre

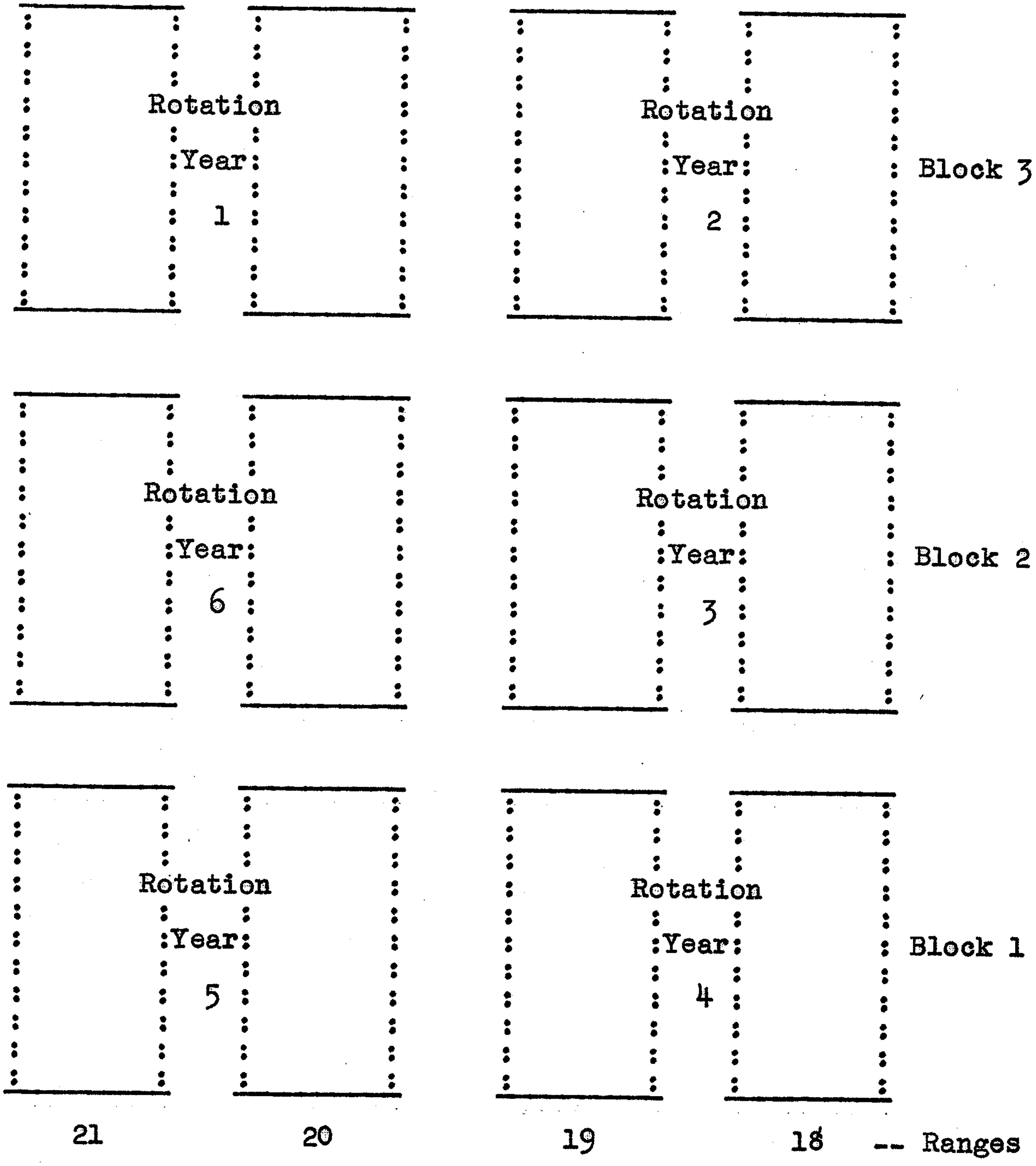

FIGURE 2

POSITION OF ROTATION YEARS 1 TO 6
OF EXPERIMENT 70-A IN 1956

Rotation Year 6			Rotation Year 3	
Range 21	Range 20	Plot No.	Range 19	Range 18
Wheat		11	Alfalfa-hay	
Wheat		10	Alfalfa-grasses-hay	
Wheat		9	Grasses-Hay	
Wheat-plow under alfalfa and straw		8	Wheat-plow under alfalfa and straw	
Wheat-burn straw and stubble-cultivate		7	Wheat-burn straw and stubble-cultivate	
Wheat-leave stubble and straw-cultivate		6	Wheat-leave stubble and straw-cultivate	
Wheat-disc in straw and stubble		5	Wheat-disc in straw and stubble	
Wheat-plow under stubble		4	Wheat-plow under stubble	
Wheat		3	Grasses-hay	
Wheat		2	Alfalfa-grasses-hay	
Wheat		1	Alfalfa-hay	

FIGURE 3

FIELD PLAN OF THE CROPPING PRACTICES, TILLAGE,
AND CROP RESIDUE MANAGEMENT PRACTICES
FOR EXPERIMENT 70-A IN 1956

The ammonium phosphate was applied to the soil at seeding time each year. The barn manure was applied in the fall prior to a crop year. The fertilizer treatment for the sub-plots of Ranges 18, 19, 20, and 21 of Block 2 are shown in Figure 4.

In 1957 only the check and the 11-48-0 fertilized sub-plots in Ranges 18, 19, 20, and 21 of Block 2 were sampled. Soil samples were taken from the 0-3 and 3-6 inch depths for wet-sieving analysis.

C. INVESTIGATION PROCEDURES

The investigation procedures, for this study are divided into three parts: (1) field sampling and sample preparations; (2) wet-sieving analysis; and (3) bulk density measurements.

1. Field sampling and sample preparation

Two sample sites were selected on each plot or sub-plot at points one-quarter the distance from each end and along a centre line of the plot or sub-plot.

Soil samples for aggregate analysis were taken from each site at the desired depth and air-dried. The air-dry soil was then gently crushed to pass through a 5mm. screen. The four soil samples from each plot were combined into two samples; one containing soil from the 0-3 inch depth and the other containing soil from the 3-6 inch depth. The soil of each of these samples were thoroughly mixed and a representative sample taken for aggregate analysis.

Rotation Year 6			Rotation Year 3	
Range 21	Range 20	Plot No.	Range 19	Range 18
Manure	Check	11	Manure	Check
16-20-0	11-48-0		16-20-0	11-48-0
16-20-0	Manure	10	16-20-0	Manure
11-48-0	Check		11-48-0	Check
11-48-0	Check	9	11-48-0	Check
Manure	16-20-0		Manure	16-20-0
Check	Manure	8	Check	Manure
11-48-0	16-20-0		11-48-0	16-20-0
16-20-0	11-48-0	7	16-20-0	11-48-0
Manure	Check		Manure	Check
16-20-0	Check	6	16-20-0	Check
11-48-0	Manure		11-48-0	Manure
Manure	11-48-0	5	Manure	11-48-0
Check	16-20-0		Check	16-20-0
Check	11-48-0	4	Check	11-48-0
16-20-0	Manure		16-20-0	Manure
Manure	16-20-0	3	Manure	16-20-0
11-48-0	Check		11-48-0	Check
16-20-0	Manure	2	16-20-0	Manure
Check	11-48-0		Check	11-48-0
Check	11-48-0	1	Check	11-48-0
Manure	16-20-0		Manure	16-20-0

FIGURE 4

FIELD PLAN OF FERTILIZER TREATMENTS
FOR EXPERIMENT 70-A IN 1956

Three soil clod samples for bulk density measurements were taken from each site at the desired depths by driving a spade into the ground and turning up the soil. The clods selected were immediately placed in waxed containers for storage until they were analyzed.

2. Wet-sieving analysis

The apparatus and method used for the wet-sieving analysis was similar to that used by Yoder (72). The wet-sieving apparatus shown in Figure 5, consisted of two nests of sieves, two containers, and a mechanical lift with cradle attachment for raising and lowering the sieves in water. The nest of sieves consisted of four sieves (6 inches in diameter) with openings of 2.0, 1.0, 0.5, and 0.25 mm. The sieves were assembled in order of their decreasing mesh size and the joints between the sieves were sealed with rubber bands. Each nest of sieves was placed in the cradle attachment of the mechanical lift which had been positioned directly over the containers.

The wet-sieving method used for wet-sieving analysis was as follows: The containers were filled three-quarters full with tap water and then the sieves were lowered at an angle into the water, thus eliminating air locks between the sieves. The sieves were immersed into the water to such a depth that the water surface was even with the mesh of the top sieve when the mechanism was at the highest position in its oscillation stroke. Four 50-gram sub-samples were weighed

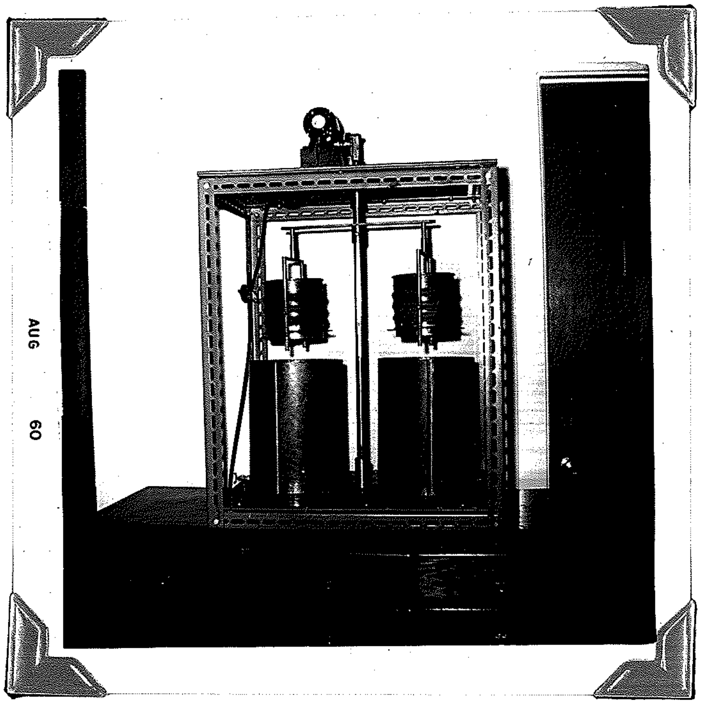

FIGURE 5

WET-SIEVING APPARATUS USED TO DETERMINE AGGREGATE-SIZE DISTRIBUTION OF SOILS out from each plot sample and re-wetted on a tension table for 24 hours under a tension of 10cm. of water. After re-wetting, the soil was transferred to the centre of the top sieve and the mechanical lift set into motion. The sieves were allowed to oscillate in the water for 10 minutes (approximately 290 strokes), and then raised from the water to drain. The particles remaining on each sieve were transferred to tared beakers, dried at 110°C, weighed and recorded as weight of water-stable aggregates retained on each sieve. The weight of particles passing through the bottom sieve was found by subtracting the total weight of soil retained on the sieves from the initial weight of sample used. The percentage by weight of soil passing through the 0.25mm. (or bottom) sieve and that retained on the 0.25, 0.50, 1.0, and 2.0mm. sieves was first calculated and then the accumulated percentage of soil passing through each sieve was calculated, beginning with the 0.25mm. sieve. The appropriate values thus calculated for each wet-sieving determination were substituted in the following equation[*], to determine the Arithmetic Mean-Size[**] of a soil:

$$\text{A.M.S.} = \frac{1400 - (Y_1 + 3/2\, Y_2 + 3\, Y_4 + 8\, Y_8)}{400}$$

The accumulated percentage values for each wet-sieving determination were substituted in the above equation as follows:

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[*] Derived by N. S. Mendelsohn, Professor of Mathematics at the University of Manitoba

[**] Hereafter referred to as the A.M.S. values

Y_1 = Percentage passing through the 0.25mm. sieve
Y_2 = Accumulated percentage passing through the 0.50mm. sieve
Y_4 = Accumulated percentage passing through the 1.0mm. sieve
Y_8 = Accumulated percentage passing through the 2.0mm. sieve

3. Bulk density measurements

The bulk densities were determined by the method suggested by Russell and Balcerek (49). Each soil clod was suspended on a thread and after all loose particles were removed, the clod was weighed, and immersed in melted paraffin (at 60°F). The clod was removed from the paraffin, allowed to cool and weighed again to determine the weight of the paraffin coat. The volume of the paraffin coat was then determined by multiplying the weight of paraffin by 0.9, the specific gravity of paraffin. Each soil clod was immersed in water and weighed again. The difference between the weight of the soil clod plus paraffin while immersed in water and the original weight of soil clod plus paraffin is equivalent to the volume of clod and paraffin. The volume of the paraffin determined previously was then subtracted to give the volume of the soil clod alone. Each soil clod was then broken open and samples taken for moisture content determination (oven dried at 110°C). The bulk density value was calculated by dividing the weight of the oven dry soil clod by the volume of the soil clod.

IV. RESULTS AND DISCUSSION

A. THE EFFECT OF BARN MANURE ON SOIL STRUCTURE (EXPERIMENT 68)

Wet-sieving data for Experiment 68 are summarized in Table I. The analysis of variance of these data (Table II) indicate that the components that show significant differences ($P = .05$) are treatments, sampling depths, and sampling date X treatment. However, when the mean square for treatments is tested against the mean square due to the interaction the resulting F value is 1.19. Since this F value is smaller than the limit $F_{0.05}(4,4) = 6.39$, the differences between treatments are not significant and therefore much of the variability in treatments is due to interaction.

This interaction becomes more apparent when the A.M.S. values for the 0-6 inch depth, in Table I are examined. The data for the 0-6 inch depth shows that the treatments did not maintain the same relative positions for the two sampling dates. For example, in 1956 the A.M.S. values for the 10, 20, and 30 ton rates were 1.88, 1.81, and 1.69, respectively. In other words, in 1956 the lower rates of barn manure resulted in better soil aggregation. However, when the data for 1957 are examined, the relative positions of the treated plots are reversed and the treatments are not significantly different. It would appear that the same beneficial effect was obtained from the lower rate (10 tons) as was obtained from the higher rates (20 or 30 tons). Similarly, results reported by

TABLE I

A.M.S. VALUES FOR THE VARIOUS BARN MANURE TREATMENTS OF EXPERIMENT 68 FOR THE YEARS 1956 and 1957

Plot No.	Treatments (Tons/ac.)	Sampling Date	A. M. S. Values		
			Ave. of 4 sub-samples at		Ave. of 8 sub-samples at
			0-3 inch	3-6 inch	0-6 inch (0-3 and 3-6)
5	10	1956	1.57	2.19	1.88
		1957	1.45	2.03	1.74
6	None	1956	1.32	2.00	1.66
		1957	1.37	1.87	1.62
8	20	1956	1.45	2.17	1.81
		1957	1.41	2.08	1.74
10	30	1956	1.37	2.02	1.69
		1957	1.63	2.12	1.87
11	None	1956	1.15	1.75	1.45
		1957	1.47	1.99	1.73

L.S.D. (P = .05) for the A.M.S. values at the 0-6 inch depth is 0.16

TABLE II

ANALYSIS OF VARIANCE OF WET-SIEVING DATA FOR EXPERIMENT 68

Source of variation	Sum of squares	D. F.	Mean square	F. values	Limits
Treatments	0.61	4	0.153	11.77	
Sampling depths	7.25	1	7.250	557.70	$F_{0.05}(1,60)=4.00$
Sampling dates	0.04	1	0.040	0.31	
Sampling date x treatment	0.51	4	0.128	9.85	$F_{0.05}(4,60)=2.52$
Sampling date x sampling depth	0.05	1	0.050	3.85	
Treatment x sampling depth	0.04	4	0.010	0.77	
Treatment x sampling depth x sampling date	0.03	4	0.0073	0.56	
Error	0.78	60	0.013		
Total	9.31	79			

Heinonen (26) show that increasing the application rate of organic matter had a highly beneficial effect on the aggregation of clay soils up to a certain organic content, beyond which the effect was small. It is also important to note that the check plots did not maintain the same relative position for the two sampling dates. One could conclude that the aggregation of the treated plots were approximately the same, but they were better aggregated than the check plots. The difference between the 1956 and 1957 data could have been due to seasonal variations or error in sampling. Similar studies reported by Alderfer (2) and Rowles (48) show that seasonal differences in soil aggregation were as great as or greater than the effect of the various soil treatments. In addition, Rowles (48) reported that variations in aggregation among several sample sites on the same plot were as high as 24 percent.

The variance, shown for sampling depths in Table II is also significant. Table I shows that the A.M.S. values for the 3-6 inch depth are consistently higher than those for the 0-3 inch depth. In general, one would expect that the soil aggregates in the 0-3 inch layer are subjected to the destructive action of tillage implements and climatic conditions such as wind, rain, and frost, more often than the soil aggregates in the 3-6 inch layer. Similar findings have been reported by McHenry and Newell (37), Russell <u>et al</u>. (52), and Woodruff (71).

The bulk density data for Experiment 68 are summarized in Table III. An analysis of variance of these data (Table IV) shows that there are significant (P = .05) differences in bulk density values among treatments.

The data for the 0-6 inch depth, in Table III indicates that the bulk density value for plot 5, receiving 10 tons of barn manure, was significantly lower than those for the remaining plots and that the values for the remaining plots were not significantly different. In other words, the soil of the plot receiving the lowest rate of barn manure had the most favourable bulk density and thus the most favourable soil structure.

The reason for the association of the most favourable bulk density with the lower rate is difficult to explain. One possible reason is that the sampling procedure was inadequate and that the values obtained did not show the true condition of the soil. A review of bulk density studies reveals that Bertramson (7), experimenting with a fine textured soil was not able to detect significant changes in bulk density on plots where various rates of barn manure had been applied over a period of years.

B. THE EFFECT OF CROP ROTATIONS AND BARN MANURE ON SOIL STRUCTURE (EXPERIMENT 70)

1. Crop rotations

Wet-sieving data for Range 26 (non-manured) of Experiment 70 are summarized in Table V on page 46. The analysis

TABLE III

BULK DENSITY VALUES FOR THE VARIOUS BARN MANURE TREATMENTS OF EXPERIMENT 68

Plot No.	Treatment (tons/ac.)	Bulk Density Values		
		Average of 3 values at		Average of 6 values at
		0-3 inch	3-6 inch	0-6 inch (0-3 and 3-6)
5	10	1.08	1.13	1.10
6	None	1.21	1.17	1.19
8	20	1.16	1.14	1.15
10	30	1.19	1.18	1.19
11	None	1.18	1.16	1.17

L.S.D. (P = .05) for the bulk density values at the 0-6 inch depth is 0.05.

TABLE IV

ANALYSIS OF VARIANCE OF BULK DENSITY DATA FOR EXPERIMENT 68

Source of variation	Sum of squares	D.F.	Mean square	F. values	Limits
Treatments	0.03023	4	0.00756	4.94	$F_{0.05}(1,20)=4.35$
Sampling depths	0.00022	1	0.00022	0.14	
Treatment x sampling depth	0.00715	4	0.00178	1.16	$F_{0.05}(4,20)=2.87$
Error	0.03060	20	0.001530		
Total	0.06820	29			

of variance of these data (Table VI on page 47) shows that the crop rotation systems are significantly different (P = .05).

The data in Table V indicate that the type of crop rotation system had a marked effect on the A.M.S. value of each plot. For example, the continuous wheat, the four-year, the three-year, and the two-year rotations have A.M.S. values of 1.83, 1.71, 1.48, and 1.51, respectively. It can be seen that the greater the number of fallow years in a crop rotation system the lower the A.M.S. value and consequently the poorer the soil aggregation. The two-year rotation and the continuous corn cropping system have approximately the same soil aggregation, the A.M.S. values being 1.51 for the former and 1.49 for the latter.

The steady decline in soil aggregation with increased fallow, in the fallow-grain rotation, is probably due to both the destruction of soil aggregates and the loss of organic matter. The destruction of soil aggregates in the fallow year may be caused by tillage implements or by exposure of the soil surface to such climatic forces as wind, rain, or frost. Conversely, the more favourable aggregation of the four-year rotation and the continuous wheat cropping system may be attributed to the return of organic matter to the soil (in form of straw, stubble, and roots) and also because they received less tillage and were protected from the climatic forces for a greater portion of their rotation cycle. Similar findings have been reported by Russell et al. (52) and Woodruff (71).

TABLE V

A. M. S. VALUES FOR THE VARIOUS CROP ROTATION SYSTEMS IN RANGE 26 (NON-MANURED) OF EXPERIMENT 70

Plot	Crop rotation systems	A.M.S. Values (ave. of 4 sub-samples)
10	Wheat continuous	1.83
8	Four-year rotation	1.71
4	Three-year rotation	1.58
1	Two-year rotation	1.51
11	Corn continuous	1.49

L.S.D. (P = .05) = 0.05

TABLE VI

ANALYSIS OF VARIANCE OF THE A.M.S. VALUES FOR RANGE 26 (NON-MANURED) OF EXPERIMENT 70

Source of variation	Sum of squares	D. F.	Mean square	F. values	Limits
Crop rotation systems	0.3356	4	0.0839	15.06	$F_{0.05}(4,15)=3.01$
Error	0.0836	15	0.00557		
Total	0.4192	19			

2. Crop rotation and barn manure interaction

Wet-sieving data for Ranges 26 and 27 (non-manured and manured ranges, respectively) of Experiment 70 are summarized in Table VII. An analysis of variance of these data (Table VIII) shows that the components that have significant ($P = .05$) F values are crop rotation systems, barn manure treatments, and crop rotation X barn manure treatment. However, if the mean squares for crop rotations and barn manure treatments are tested against the mean square for their interaction the resulting F values are 1.75 and 2.07, respectively. A comparison of these F values with their respective limits $F_{0.05}(3,3) = 9.28$ and $F_{0.05}(1,3) = 10.10$, indicates that there are no significant differences among the crop rotation systems and the barn manure treatments and therefore, much of the variability in each of these components is due to the interaction.

The significant interaction of crop rotation with barn manure treatment is apparent in Table VII. The data show that the magnitude of the A.M.S. values was influenced by both the type of rotation system and the application of barn manure. For example, the A.M.S. values for the non-manured plots under the two year, three-year, four-year, and continuous wheat rotations, were 1.51, 1.58, 1.70, and 1.83, respectively. Thus, soil aggregation of the non-manured plots increased as the number of fallow years in the rotational cropping system decreased. However, the A.M.S. values for the manured plots, show that the effect of barn manure on soil aggregation, was

TABLE VII

A.M.S. VALUES FOR THE VARIOUS CROP ROTATION SYSTEMS IN RANGES 26 AND 27 (NON-MANURED AND MANURED RANGES, RESPECTIVELY) OF EXPERIMENT 70

Crop rotation system	Fertilizer treatments (tons/ac. of barn manure)	A.M.S. Values (ave. of four sub-samples)
Two-year rotation	None	1.51
	2.0	1.89
Three-year rotation	None	1.58
	2.7	1.62
Four-year rotation	None	1.70
	3.0	1.70
Wheat continuous	None	1.83
	4.0	1.92

L.S.D. (P = .05) = 0.16

TABLE VIII

ANALYSIS OF VARIANCE OF THE A.M.S. VALUES FOR RANGES 26 AND 27 (NON-MANURED AND MANURED RANGES, RESPECTIVELY) OF EXPERIMENT 70

Source of variation	Sum of squares	D. F.	Mean square	F. values	Limits
Crop rotation systems	0.3233	3	0.1068	17.37	
Barn manure treatments	0.1263	1	0.1263	20.54	$F_{0.05}(1,24)=4.26$
Crop rotation system x barn manure treatment	0.1831	3	0.0610	9.92	$F_{0.05}(3,24)=3.01$
Error	0.1476	24	0.00615		
Total	0.7803	31			

more apparent where the cropping system had a higher number of fallow years. For example, the A.M.S. value for the two-year rotation, increased significantly from 1.51 to 1.89; whereas, the three-year rotation increased (but not significantly) from 1.58 to 1.62 and the four-year rotation remained unchanged with an A.M.S. value of 1.70. It is important to note, that the effect of fallow in the rotational cropping system, was apparent in the manured as well as the non-manured plots; and also, that the combination of a non-fallow cropping system with a high application rate of barn manure resulted in a high A.M.S. value for the continuous wheat plot.

The effect of fallow in the cropping system was discussed previously under Crop Rotations. However, any explanation of the effect of the interaction (crop rotation X barn manure treatment) is closely related to the explanation of the effect of fallow on soil aggregation. Probably, the high frequency of fallow in the two-year rotation system had destroyed many of the soil aggregates and much of the organic matter. Thus, the improvement in soil aggregation resulting from the application of barn manure was very noticeable. The application of barn manure to the three-year and four-year rotations did not increase soil aggregation appreciably because these rotation systems, having a lower frequency of fallow, maintained soil aggregation and organic matter content at a higher level than that of the two-year rotation.

Bulk density data for Ranges 26 and 27 of Experiment 70 are summarized in Appendix 1, on page 82. An analysis of variance for these data (Table IX) indicates that the treatments are not significant. The failure to detect any appreciable differences among the treatments suggests that either the treatments were not significantly different or the method of determining bulk density was inadequate to measure them.

C. THE EFFECT OF CROP ROTATIONS, TILLAGE AND CROP RESIDUE MANAGEMENT PRACTICES, AND FERTILIZER TREATMENTS ON SOIL STRUCTURE (EXPERIMENT 70-A)

1. Hay crops and crop rotations

Wet-sieving data for the hay-grain rotation of Experiment 70-A are summarized in Appendix 2, on page 83. The analysis of variance of these data (Table X) shows that the F values for the hay crops, rotation years, and their interaction are significant ($P = .05$). However, when the mean squares for hay crops and rotation years are tested against the mean square due to the interaction the resulting F values are 2.75 and 9.24, respectively. A comparison of these values with their respective limits $F_{0.05}(2,2) = 19.00$ and $F_{0.05}(1,2) = 18.51$, reveals that there are no significant differences among the hay crops nor between the rotation years and therefore much of the variability in each is due to the interaction.

TABLE IX

ANALYSIS OF VARIANCE OF THE BULK DENSITY VALUES FOR THE VARIOUS TREATMENTS OF EXPERIMENT 70

Source of variation	Sum of squares	D. F.	Mean square	F. values	Limits
Treatments	0.1302	9	0.0145	0.54	$F_{0.05}(9,20)=2.40$
Error	0.0538	20	0.0269		
Total	0.1840	29			

TABLE X

ANALYSIS OF VARIANCE OF WET-SIEVING DATA FOR THE HAY-GRAIN ROTATION OF EXPERIMENT 70-A

Source of variation	Sum of squares	D. F.	Mean square	F. values	Limits
Hay crops	1.1675	2	0.5837	57.68	
Rotation years	1.9602	1	1.9602	193.70	
Hay crop x rotation year	0.4241	2	0.2120	20.95	$F_{0.05}(2,178)=3.06$
Sampling depths	2.4390	1	2.4390	241.01	
Hay crop x sampling depth	0.857	2	0.0428	4.23	
Rotation year x sampling depth	0.1452	1	0.1452	14.35	
Fertilizer treatments	1.2192	1	1.2192	120.47	
Hay crop x fertilizer treatment	0.0642	2	0.0321	3.17	$F_{0.05}(1,178)=3.91$
Rotation year x fertilizer treatment	0.0026	1	0.0026	0 0.26	
Error	1.8006	178	0.01012		
Total	9.3083	191			

2. Hay crop and crop rotation interaction

This interaction can be readily seen in Table XI where in every case the A.M.S. value for rotation year 3 was significantly greater than that for rotation year 6, but the amount that each A.M.S. value increased was dependent upon the type of hay crop. In rotation year 3, for example, the A.M.S. values for the alfalfa-grass, grass, and alfalfa plots were 1.94, 1.86, and 1.65, respectively. The major effect on soil aggregation occurred where there was grass. However, most of this effect had disappeared by rotation year 6. For example, the A.M.S. values of 1.66, 1.61, and 1.57 for the alfalfa-grass, grass, and alfalfa plots respectively, were approximately the same, only the A.M.S. values for the alfalfa-grass and alfalfa plots were significantly different. Thus during the hay crop years of the hay-grain rotation the plots containing grass had considerably better soil aggregation than the alfalfa plot. Much of the aggregation of the grass plots had disappeared at the completion of rotation year 6, and the three hay plots had approximately the same soil aggregation. It should be noted that in both rotation years 3 and 6 the effect of alfalfa-grass mixture, on soil aggregation was greater than the effect of grass alone.

The higher degree of aggregation produced by the meadow fescue-timothy mixture as compared to that of alfalfa may be attributed to the inherently different root systems

TABLE XI

A.M.S. VALUES OF THE VARIOUS HAY CROPS FOR ROTATION YEARS 3 AND 6 AT THE 0-6 INCH DEPTH

Hay crop	Rotation year	A.M.S. values
Alfalfa + Grasses*	3	1.94
	6	1.66
Grasses*	3	1.86
	6	1.61
Alfalfa	3	1.65
	6	1.57

L.S.D. (P = .05) = 0.07

* Grasses are Meadow fescue and Timothy

of these plants. The grasses have a fibrous root system consisting of many lateral roots spreading throughout the soil. The alfalfa has one main tap root with only a few lateral roots. The binding, compressing, and separating actions of roots, which is important for soil aggregate formation, would be much greater in the case of grass than alfalfa. However, because alfalfa is able to fix nitrogen from the atmosphere it is of great importance in grass - alfalfa mixtures. The utilization of this fixed nitrogen by the grasses greatly stimulates growth and consequently the formation of soil aggregates. Wilson and Browning (67) reported that alfalfa is less effective than grass for improving soil aggregation, but the mixture of grass and alfalfa was the most effective.

In rotation year 3 the soil aggregation of the hay plots, particularly the grass plots was favourable. However, in rotation 6 soil aggregation had declined. This decline may be attributed to the break down of the soil aggregates by tillage implements and such climatic forces as wind, rain, and frost during the fallow and wheat crop years.

3. Sampling depths (hay-grain rotation)

The analysis of variance of the data for the hay-grain rotation (Table X, on page 54) indicates that the variances for sampling depths, hay crops, and their interaction are significant ($P = .05$). But, when the mean square for sampling depths and hay crops are tested against the mean square for this interaction the resulting F values are 56.99 and 13.64, respectively. A comparison of these values with their respective limits $F_{0.05}(1,2) = 18.51$ and $F_{0.05}(2,2) = 19.00$ indicates that the difference between sampling depths is significant regardless of the hay crops and that much of the variability among hay crops is due to the interaction.

Table XII shows that the A.M.S. values for the 0-3 inch depth are consistently lower than those for the 3-6 inch depth, regardless of the type of hay crop. This difference may be attributed to the destruction of the aggregates in the surface layer of soil by such factors as tillage and climate.

4. Hay crops and sampling depths interaction

The interaction between hay crops and sampling depths is apparent when Table XII is examined. It shows that the effect of the three types of hay crops on soil aggregation at the 0-3 and 3-6 inch depths were different. For example, at the 0-3 inch depth the A.M.S. values for the alfalfa-grass, grass, and alfalfa plots were 1.69, 1.64, and 1.47, respectively; but, at the 3-6 inch depth the A.M.S. values for the same plots were 1.91, 1.83, and 1.75. The alfalfa-grass and grass plots maintained soil aggregation of the surface layer (0-3 inch) at approximately the same level. The soil aggregation in the alfalfa plot was significantly lower than that in the grass or grass-alfalfa plots. At the 3-6 inch depth, however, the three types of hay plots had significantly different levels of soil aggregation.

TABLE XII

A.M.S. VALUES OF THE VARIOUS HAY CROPS FOR THE COMBINED ROTATION YEARS 3 AND 6 AT THE 0-3 AND 3-6 INCH DEPTHS

Hay crop	Depth (inches)	A.M.S. values
Alfalfa + Grasses*	0-3	1.69
	3-6	1.91
Grasses*	0-3	1.64
	3-6	1.83
Alfalfa	0-3	1.47
	3-6	1.75

L.S.D. (P = .05) = 0.07

*Grasses are Meadow fescue and Timothy

The destruction of soil aggregates within the surface layer (0-3 inch) by such forces as tillage implements, wind, rain, or frost and the importance of grasses in the formation of aggregates has been discussed. However, the interaction between the type of hay crop and sampling depth, in Table XII shows that at the 0-3 inch depth, where the soil is subjected to the destructive forces of tillage and climate, the grasses maintained soil aggregation at a much higher level than did the alfalfa. At the 3-6 inch depth, the destructive forces which break down soil aggregates are considerably reduced, and the influence of the type of vegetation is not so obvious.

5. Rotation years and sampling depths interaction

The variance shown for the interaction of rotation years with sampling depths, in Table X (on page 54) is also significant ($P = .05$). Consequently the mean square for sampling depths is tested against the mean square for this interaction. A comparison of the resulting F value of 16.80 with its respective limit $F_{0.05}(1,1) = 161.00$ indicates that an interaction occurred between rotation years and sampling depths.

These data shown in Table XIII, indicates that the A.M.S. values for the 0-3 and 3-6 inch depths of rotation year 6 were significantly lower than those for the corresponding depths of rotation year 3. However, this decrease in A.M.S. value was greater for the 0-3 inch depth than for the 3-6 inch depth. For example, the A.M.S. values at the 0-3

TABLE XIII

A.M.S. VALUES OF THE COMBINED HAY CROPS FOR ROTATION YEARS 6 AND 3 AT THE 0-3 AND 3-6 INCH DEPTHS

Rotation year	Depth (inches)	A.M.S. values
6	0-3	1.47
	3-6	1.76
3	0-3	1.73
	3-6	1.90

L.S.D. (P = .05) = 0.06

inch depth were 1.47 and 1.73 for rotation years 6 and 3, respectively; while the A.M.S. values at the 3-6 inch depth were 1.76 and 1.90 for rotation years 6 and 3. Thus the fallow and wheat years (i.e. years 4, 5, and 6 of the hay-grain rotation), which followed the hay years, appreciably reduced soil aggregation at both the 0-3 and 3-6 inch depths. The 0-3 inch depth, however, showed the greatest decline in soil aggregation. In rotation year 3 the soil aggregation at the 3-6 inch depth was significantly greater than at the 0-3 inch depth, even though the plots had been in hay for two years.

The decline in soil aggregation during the wheat years was probably due to the break down of soil aggregates by tillage implements and climatic forces. In general, one would expect that this decline would be greater in the surface soil (0-3 inch) than in the soil at the 3-6 inch depth, since these destructive forces are more active near the surface. The difference in aggregation between the 0-3 and 3-6 inch depths of rotation year 3 (i.e. at the conclusion of the hay years) may be attributed to two factors. Firstly, the destruction of the surface soil by climatic forces occurred in spite of the protection provided by the alfalfa or grass crops. Secondly, since soil aggregation in the 0-3 inch was reduced to such a low level during the fallow and wheat years, the two years of hay had not been sufficient to improve aggregation of the surface soil to a level equal to that of the soil at the 3-6 inch depth.

6. Fertilizer treatments (hay-grain rotation)

The analysis of variance of the data for the hay-grain rotation (Table X, on page 54) shows that the variances for fertilizer treatments and interaction of hay crop with fertilizer treatment are significant ($P = .05$). When the mean square for fertilizer treatments is tested against the mean square for this interaction the resulting F value is 37.98. A comparison of this value with the limit $F_{0.05(1,2)} = 18.51$, indicates that the fertilizer treatments are significant and the difference between these treatments is not due to the interaction alone.

The A.M.S. values in Table XIV reveal that the application of ammonium phosphate (11-48-0) at 45 lbs. per acre had considerably improved soil aggregation. This improvement was greater on the grass plots than on the alfalfa plot. It appears that the application of ammonium phosphate resulted in greater root production and consequently improved soil aggregation. Similar findings have been reported by Baver (4).

7. Tillage and crop residue management practices and sampling depths

Wet-sieving data for the fallow-grain rotation of Experiment 70-A are summarized in Appendix 3, on page 84. The analysis of variance of these data (Table XV) shows that the management practices, sampling depths, and their inter-

TABLE XIV

A.M.S. VALUES AT THE 0-6 INCH DEPTH FOR THE VARIOUS HAY CROPS OF THE FERTILIZED AND CHECK PLOTS OF EXPERIMENT 70-A

Hay crop	Treatment	A.M.S. values
Alfalfa + Grasses*	Fertilized	1.90
	Check	1.69
Grasses*	Fertilized	1.80
	Check	1.66
Alfalfa	Fertilized	1.67
	Check	1.55

L.S.D. (P = .05) = 0.07

*Grasses are Meadow fescue and Timothy

action have significant ($P = .05$) F values. When the mean squares for sampling depths and management practices are tested against the mean square for their interaction the resulting F values are 57.46 and 4.13, respectively. A comparison of these F values with their respective limits $F_{0.05}(1,4) = 7.71$ and $F_{0.05}(4,4) = 6.39$ indicates that the sampling depths are still significant but the management practices are not significant.

Table XVI shows that the A.M.S. values for the 0-3 inch depth are consistently lower than those for the 3-6 inch depth, regardless of the tillage or crop residue management practice. This difference could be attributed to the slow break down of soil aggregates in the surface layer by such factors as tillage and climate.

8. Tillage and crop residue management practices and sampling depths interaction

Since the management practices are not significant much of the variability among them must be due to an interaction. This interaction is apparent when Table XVI is considered. The A.M.S. values show that the soils at the 0-3 and 3-6 inch depths were affected differently by the various tillage and crop residue management practices. For example, a comparison of plots 4, 5, and 6 indicates that at the 0-3 inch depth the A.M.S. values for the plowed, disced, and cultivated plots were 1.40, 1.18, 1.50, respectively; while at the 3-6 inch depth the A.M.S. values for the same

TABLE XV

ANALYSIS OF VARIANCE OF WET-SIEVING DATA FOR THE FALLOW-GRAIN ROTATION OF EXPERIMENT 70-A

Source of variation	Sum of squares	D. F.	Mean square	F. values	Limits
Management practices	2.2588	4	0.5647	57.04	
Sampling depths	7.8544	1	7.8544	793.37	$F_{0.05}(1,145)=3.92$
Management practice x sampling depth	0.5468	4	0.1367	13.81	
Fertilizer treatments	0.8955	1	0.8955	90.45	$F_{0.05}(4,145)=2.44$
Management practice x fertilizer treatment	0.1541	4	0.0385	3.89	
Error	1.4398	145	0.0099		
Total	13.1496	159			

TABLE XVI

A.M.S. VALUES AT THE 0-3 AND 3-6 INCH DEPTHS FOR THE VARIOUS TILLAGE AND CROP RESIDUE MANAGEMENT PRACTICES OF THE COMBINED FERTILIZED AND CHECK PLOTS

Plot	Crop residue management practice	Depth (inches)	A.M.S. values
4	Plow under stubble	0-3	1.40
		3-6	1.74
5	Disc in straw and stubble	0-3	1.18
		3-6	1.76
6	Leave trash cover - cultivate	0-3	1.50
		3-6	1.85
7	Burn straw and stubble - cultivate	0-3	1.18
		3-6	1.77
8	Plow under stubble, straw, and alfalfa	0-3	1.61
		3-6	1.95

L.S.D. (P = .05) = 0.10

plots were 1.74, 1.76, and 1.85. If the cultivated plot is used as a standard for comparison the state of aggregation of the surface soil (0-3 inches) was considerably lower on the disced plot and slightly lower on the plowed plot. However, at the 3-6 inch depth there was a smaller range in soil aggregation of the disced, plowed, and cultivated plots.

Aggregation of the cultivated plot was better than that of either the disced or plowed plots, probably because the soil had been pulverized very little and the trash cover had protected the surface soil against such destructive forces as wind and rain. The marked difference in aggregation between the 0-3 and 3-6 inch depths of the disced plot indicates that the discing implement pulverized the surface soil considerably, but had a less detrimental effect on the soil at the 3-6 inch depth. The data for the plowed plots suggests that the soil within the 0-3 and 3-6 inch depths had been either moderately pulverized or partly mixed by the plowing implement. If the latter process had occurred, then part of the pulverized surface soil could have been mixed with the better aggregated soil from the 3-6 inch depth, thereby improving aggregation at the 0-3 inch depth and lowering it at the 3-6 inch depth.

The data for plots 6 and 7 presented in Table XVI show that burning the straw and stubble greatly decreased the A.M.S. values at the 0-3 inch depth but did not significantly affect them at the 3-6 inch depth. For example, the A.M.S. values at the 0-3 inch depth for the trash covered and burned plots were 1.50 and 1.18, respectively, while the A.M.S. values at the 3-6 inch depth for the same plots were 1.85 and 1.77. These data indicate that the trash cover may have acted as a protective layer against such destructive forces as wind or rain.

A comparison of data for plots 4 and 8 in Table XVI (on page 67) indicates that plowing under straw and alfalfa increased the A.M.S. values at both the 0-3 and 3-6 inch depths. To illustrate, the A.M.S. values at the 0-3 inch depth for plots 4 and 8 were 1.40 and 1.61, respectively, while the A.M.S. values at the 3-6 inch depth for the same plots were 1.74 and 1.95. This improvement in soil aggregation may be attributed to both the alfalfa and the straw. However, according to the literature the former contributes much more to soil aggregation than the latter. For example, Browning and Milam (9) reported that alfalfa plowed under improved soil aggregation appreciably as compared with straw plowed under. Also, Woodruff (71) found that sweet clover plowed under increased soil aggregation over that of a check.

9. Fertilizer treatments (fallow-grain rotation)

The analysis of variance of the data for the fallow-grain rotation (Table XV, on page 66) also indicate that the variances for fertilizer treatments and the interaction of management practice with fertilizer treatment are significant ($P = .05$). However, since the mean square due to the interaction was significant, the mean square for fertilizer treatments is tested against it. Since the resulting F value of 23.26 is considerably greater than the limit $F_{0.05}(1,4) = 7.71$ the difference between fertilizer treatments is significant.

Table XVII reveals that the application of ammonium phosphate (11-48-0) at 45 lbs. per acre increased aggregation regardless of the management practice. However, the data also indicates that the magnitude of this increase in aggregation varies with the type of management practice. For example, in plot 7 where all the residues had been removed by burning, the A.M.S. value was increased from 1.44 to 1.52 (not significant) by the application of fertilizer. In the remaining plots, where the different types of residues had been returned to the soil, the A.M.S. values for plots 4, 5, 6, and 8 were significantly increased by the application of fertilizer. In other words, the increase in soil aggregation, resulting from the application of ammonium phosphate (11-48-0) was more apparent on those plots where the largest amount of crop residues had been returned to the soil.

TABLE XVII

A.M.S. VALUES AT THE 0-6 INCH DEPTH FOR THE VARIOUS TILLAGE AND CROP RESIDUE MANAGEMENT PRACTICES OF THE FERTILIZED AND CHECK PLOTS OF EXPERIMENT 70-A

Plot	Crop residue management practice	Fertilizer treatment	A.M.S. values
4	Plow under stubble	Fertilized	1.63
		Check	1.50
5	Disc in straw and stubble	Fertilized	1.54
		Check	1.40
6	Leave trash cover-cultivate	Fertilized	1.75
		Check	1.60
7	Burn straw and stubble - cultivate	Fertilized	1.52
		Check	1.44
8	Plow under stubble, straw, and alfalfa	Fertilized	1.91
		Check	1.65

L.S.D. (P = .05) = 0.10

The improvement in soil aggregation, resulting from the application of ammonium phosphate fertilizer could have been due to increased root and foliage growth. The decomposition of this plant material when returned to the soil may have indirectly improved soil aggregation. Similar conclusions were reported by Baver (4).

V. SUMMARY AND CONCLUSIONS

Experiments have been carried on in the Soil Science Fertility Field for many years to study the effects of barn manure and ammonium phosphate fertilizers, crop rotations, tillage and crop residue management practices on crop yields. In 1956 a laboratory study was initiated to determine if the above treatments and practices had any effect on soil structure.

To evaluate the structural status of the clay soil it was decided to measure soil bulk density by the paraffin-immersion technique and soil aggregation by the wet-sieving method. In order to characterize the whole size-distribution of aggregates (obtained by wet-sieving) in one single representative figure the arithmetic mean-size values were calculated.

CONCLUSIONS

1. In the fertilization of a clay soil it was immaterial whether 10, 20, 30 tons per acre of barn manure was applied, as the improvement was approximately the same in each case.
2. Fallow had a detrimental effect on soil structure.
3. The beneficial effect of the application of barn manure to soils under intense tillage operations was greater than to soils receiving less tillage.
4. The use of ammonium phosphate at 45 lbs. per acre improved soil structure, except where the crop residues had been burned.

5. Grasses as compared to alfalfa maintained soil in a better structural condition.
6. A grass + alfalfa mixture had a distinct advantage over grass in improving soil structure.
7. The structure of soil deteriorated, particularly in the surface layer when brought into crop production after two years of hay.
8. The use of a cultivator was less detrimental to soil structure than that of a plow or disc. Discing destroyed the structure considerably more than plowing.
9. When crop residues were burned the structure of the surface soil was detrimentally affected.

VI. BIBLIOGRAPHY

1. Alderfer, R. B. and F. G. Merkle. 1941. The Measurement of Structural Stability and Permeability and the Influence of Soil Treatments upon these Properties. Soil Sci. 51: 201.

2. Alderfer, R. B. 1950. Influences of Seasonal and Cultural Conditions on Aggregation of Hagerstown Soil. Soil Sci. 69: 193-203.

3. ______________ 1946. Seasonal Variability in the Aggregation of Hagerstown Silt Loam. Soil Sci. 62: 151-168.

4. Baver, L.D. 1956. Soil Physics 3rd Ed. John Wiley and Sons, N. Y.

5. Baver, L. D. and H. F. Rhoades. 1932. Aggregate Analysis as an Aid in the Study of Soil Structure Relationships. Jour. Amer. Soc. Agron. 24: 920-930.

6. Beale, O. W., G. B. Nutt and T. C. Peele. 1955. The Affects of Mulch Tillage on Runoff, Erosion, Soil Properties, and Crop Yields. Soil Sci. Soc. Amer. Proc. 19: 244.

7. Bertramson, B. R. and H. F. Rhoades. 1938. The Effects of Cropping and Manure Application on some Physical Properties of a Heavy Soil in Eastern Nebraska. Soil Sci. Soc. Amer. Proc. 3: 32-36.

8. Bolton, E. F. and L. R. Webber. 1952. Effect of Cropping Systems on the Aggregation of a Broakston Clay Soil at Three Depths. Sci. Agr. 32: 555-558.

9. Browning, G. M. and F. M. Milam. 1941. Rate of Application of Organic Matter in Relation to Soil Aggregation. Soil Sci. Soc. Amer. Proc. 6: 96-97.

10. Bryant, J. C., T. W. Bendixen and C. S. Salter. 1948. Measurement of the Water-stability of Soils. Soil Sci. 65: 341-345.

11. Chesters, G., O. J. Attoe and O. N. Allen. 1957. Soil Aggregation in Relation to Various Soil Constituents. Soil Sci. Soc. Amer. Proc. 21: 272-277.

12. Clement, C. R. and T. E. Williams. 1958. An Examination of the Method of Aggregate Analysis by Wet-Sieving in Relation to the Influence of Diverse Leys on Arable Soils. Jour. Soil Sci. 9: 252-266.

13. Cole, R. C. 1939. Soil Macrostructure as Affected by Cultural Treatments. Hilgardia 12: 429-472.

14. Dawson, R. C. 1945. Effect of Crop Residues on Soil Micro-population, Aggregation and Fertility under Maryland Conditions. Soil Sci. Soc. Amer. Proc. 10: 180-184.

15. Dettmann, M. G. 1958. Water Uptake by Pure Clays and Soil Crumbs. Jour. Soil Sci. 9: 306-315.

16. Dreibelbis, F. R. and M. S. Nair. 1951. Comparison of Effects of Disking and Plowing on some Properties of Soil. Agron. Jour. 43: 25-33.

17. Ehrlich, W. A., E. A. Poyser, L. E. Pratt and J. H. Ellis. 1953. Report of Soil Survey of Winnipeg and Morris Map Sheet Area. Report #5.

18. Elson, Jesse. 1940. A Comparison of the Effect of Certain Cropping and Fertilizer and Manuring Practices on Soil Aggregation of Dunmore Silt Loam. Soil Sci. 50: 339-353.

19. Emerson, W. W. 1954. The Determination of the Stability of Soil Crumbs. Jour. Soil Sci. 5: 233-250.

20. Emerson, W. W. and G. M. Grundy. 1954. The Effect of Rate of Swelling on Water Uptake and Cohesion of Soil Crumbs. Jour. Agr. Sci. 44: 249-253.

21. Evans, D. D. 1954. Effect of Prewetting and Incubation of Soil on Aggregate Analysis. Soil Sci. Soc. Amer. Proc. 18: 10-12.

22. Fletcher, P. W. and R. B. Livingston. 1949. Structure Improvement following Legume Growth on Unfertilized Subsoil. Soil Sci. Soc. Amer. Proc. 14: 347-350.

23. Gardner, W. R. 1956. Representation of Soil Aggregate-Size Distribution by a Logarithmic- Normal Distribution. Soil Sci. Soc. Amer. Proc. 20: 151-153.

24. Gish, R. E. and G. M. Browning. 1948. Factors Affecting the Stability of Soil Aggregates. Soil Sci. Soc. Amer. Proc. 13: 51-55.

25. Haines, W. B. 1923. The Volume-changes Associated with Variation of Water Content in Soil. Jour. Agr. Sci. 13: 296-310.

26. Heinonen, Reijo. 1955. Soil Aggregation in Relation to Texture and Organic Matter. Agrogeologisia Julkaisuta N:o 64 Department of Soil Science, Helsinki.

27. Johnston, J. R., G. M. Browning and M. B. Russell. 1942. The Effect of Cropping Practices on Aggregation, Organic Matter Content and Loss of Soil and Water in the Marshall silt loam. Soil Sci. Soc. Amer. Prac. 7: 105-107.

28. Kennedy, W. K. and M. B. Russell. 1948. Relationship of Tap Growth, Root Growth, and Apparent Specific Gravity of the Soil under Different Clipping Treatments of a Kentucky Bluegrass-Wild White Clover Pasture. Jour. Amer. Soc. Agron. 40: 535-540.

29. Klute, A. and W. C. Jacob. 1949. Physical Properties of Sassafras Silt Loam as Affected by Long Time Organic Matter Additions. Soil Sci. Soc. Amer. Proc. 14: 24-28.

30. Kroth, E. M. and J. B. Page. 1946. Aggregates Formation in Soils with Special Reference to Cementing Substances. Soil Sci. Soc. Amer. Proc. 11: 27-34.

31. Low, A. J. 1954. The Study of Soil Structure in the Field and the Laboratory. Jour. Soil Sci. 5: 57-74.

32. ________ 1955. Improvement in the Structural State of Soils Under Leys. Jour. Soil Sci. 6: 179.

33. ________ Rate of Build-up of Water-stable Aggregates and Soil Crumb Structure. Jealott's Hill Res. Stn., Bull. 193.

34. Martin, J. P. 1945. Microorganisms and Soil Aggregation: I. Origin and Nature of some of the Aggregating Substances. Soil Sci. 59: 163-174.

35. ____________ 1946. Microorganisms and Soil Aggregation: II. Influence of Bacteria Polysaccharides on Soil Structure. Soil Sci. 61: 157-166.

36. Martin, J. P. and S. A. Waksman. 1940. Influence of Microorganisms on Soil Aggregation and Erosion. Soil Sci. 50: 29-47.

37. McHenry, J. R. and L. C. Newell. 1947. Influence of Some Perennial Grasses on the Organic Matter Content and Structure of an Eastern Nebraska Fine Textured Soil. Jour. Amer. Soc. Agron. 39: 981-994.

38. Moody, J. E., J. H. Lillard and T. W. Edminster. 1952. Mulch Tillage: Some Effects on Plant and Soil Properties. Soil Sci. Soc. Amer. Proc. 16: 190-194.

39. Nijhawan, S. D. and L. B. Olmstead. 1947. The Effect of Sample Pretreatment upon Soil Aggregation in Wet-Sieve Analysis. Soil Sci. Soc. Amer. Proc. 12: 50-53.

40. Page, J. G. 1955. Clays and Clay Technology. Proc. of the 1st. National Conference on Clay and Clay Technology. Bull. 169.

41. Page, J. B. and C. J. Willard. 1946. Cropping Systems and Soil Properties. Soil Sci. Soc. Amer. Proc. 11: 81-88.

42. Panabokke, C. R. and J. P. Quirk. 1957. Effect of Initial Water Content on Stability of Soil Aggregates in Water. Soil Sci. 83: 185-195.

43. Peele, T. C. 1940. Microbial Activity in Relation to Soil Aggregation. Jour. Amer. Soc. Agron. 32: 204-212.

44. Peterson, J. B. 1946. The Role of Clay Minerals in the Formation of Soil Structure. Soil Sci. 61: 247-256.

45. ______________ 1947. Granule Formation: I. Calcium Linkage, A Mechanism in Soil Granulation. Soil Sci. Soc. Amer. Proc. 12: 29-34.

46. Rennie, D. A., E. Truog and O. N. Allen. 1954. Soil Aggregation as Influenced by Microbial Gums, Level of Fertility and Kind of Crop. Soil Sci. Soc. Amer. Proc. 18: 399-403.

47. Robinson, D. O. and J. B. Page. 1950. Soil Aggregate Stability. Soil Sci. Soc. Amer. Proc. 15: 25-29.

48. Rowles, W. 1948. Physical Properties Related to Structure of Ste. Rosalie Clay and Their Seasonal Variations. Sci. Agr. 28: 558-573.

49. Russell, E. W. and W. Balcerek. 1944. The Determination of the Volume of air space of Soil Clods. Jour. Agr. Sci. 34: 123-132.

50. Russell, E. W. and R. V. Tomhane. 1940. The Determination of the Size Distribution of Soil Clods and Crumbs. Jour. Agr. Sci. 30: 210-234.

51. Russell, M. B. and C. L. Feng. 1947. Characterization of the Stability of Soil Aggregates. Soil Sci. 63: 299-304.

52. Russell, M. B., H. K. Klute and W. C. Jacob. 1952. Further Studies on the Effect of Long-time Organic Matter Additions on the Physical Properties of Sassafras Silt Loam. Soil Sci. Soc. Amer. Proc. 16: 156-159.

53. Schaller, F. W. and K. R. Stockinger. 1953. A Comparison of Five Methods for Expressing Aggregation Data. Soil Sci. Soc. Amer. Proc. 17: 310-313.

54. Shaw, C. F. 1917. A Method for Determining the Volume Weight of Soils in Field Condition. Jour. Amer. Soc. Agron. 9: 38-42.

55. Sideri, D. I. 1936. On the Formation of Structure in Soil: II. Synthesis of Aggregates; on the Bonds Uniting Clay with Sand and Clay with Humus. Soil Sci. 42: 461-479.

56. Stirk, G. B. 1958. Expression of Soil Aggregate Distributions. Soil Sci. 86: 133-135.

57. Strickling, Edward. 1957. Effect of Cropping Systems and V. A. M. A. on Soil Aggregation, Organic Matter, and Crop Yields. Soil Sci. 84: 489.

58. ________________ 1950. The Effect of Soybeans on Volume Weight and Water Stability of Soil Aggregates, Soil Organic Matter Content and Crop Yield. Soil Sci. Soc. Amer. Proc. 15: 30-34.

59. Tanner, C. B., R. W. Wengel and D. S. McIntyre. 1956. Influence of Half-Height Sieves and of Incomplete Sieve Nests on Wet Sieve Aggregate Analysis. Agron. Jour. 48: 379-381.

60. Tanner, C. B. and S. J. Bourget. 1952. Particle-Shape Discrimination of Round and Square Holed Sieves. Soil Sci. Soc. Amer. Proc. 16: 88.

61. Tiulin, A. F. 1928. Questions on Soil Structure. II. Aggregate Analysis as a Method for Determining Soil Structure. Report 2, pp. 77-122. Perm. Agr. Exp. Sta. Div. Agr. Chem.

62. Van Bavel, C. H. 1949. Report of the Committee on Physical Analysis 1951-1953, Soil Science Society of America. Soil Sci. Soc. Amer. Proc. 17: 416.

63. Van Bavel, C. H. and F. W. Schaller. 1950. Soil Aggregation, Organic Matter, and Yields in a Long-time Experiment as Affected by Crop Management. Soil Sci. Soc. Amer. Proc. 15: 399-404.

64. Van Doren, C. A. and A. A. Klingebiel. 1949. Permeability Studies on Some Illinois Soils. Soil Sci. Soc. Amer. Proc. 14: 51-55.

65. Van Doren, C. A. and R. S. Stauffer. 1943. Effect of Crop and Surface Mulches on Runoff, Soil Losses, and Soil Aggregation. Soil Sci. Soc. Amer. Proc. 8: 97-101.

66. Wilson, H. A., R. Gish and G. M. Browning. 1947. Cropping System and Season as Factors Affecting Aggregate Stability. Soil Sci. Soc. Amer. Proc. 12: 36-38.

67. Wilson, H. A. and G. M. Browning. 1945. Soil Aggregation, Yields, Runoff, and Erosion as Affected by Cropping Systems. Soil Sci. Soc. Amer. Proc. 10: 51-57.

68. Winterkorn, Hans, F. 1942. Mechanism of Water Attack on Dry Cohesive Soil Systems. Soil Sci. 54: 259-273.

69. Wisniewski, A. J., M. Salomon and J. B. Smith. 1958. Restoration of Soil Structure with Red Top and other Sod Crops. Soil Sci. Soc. Amer. Proc. 22: 320-322.

70. Woodburn, R. 1944. Aggregation Studies of Houston Clay in Mississippi. Soil Sci. Soc. Amer. Proc. 9: 30-36.

71. Woodruff, C. M. 1939. Variations in the State and Stability of Aggregation as a Result of Different Methods of Cropping. Soil Sci. Soc. Amer. Proc. 4: 13-18.

72. Yoder, R. E. 1936. A Direct Method of Aggregate Analysis of Soils and a Study of the Physical Nature of Erosion Losses. Jour. Amer. Soc. Agron. 28: 337-351.

73. Youker, R. E. and J. L. McGuinness. 1957. A short Method of Obtaining Mean Weight-Diameter Values of Aggregate Analysis of Soils. Soil Sci. 83: 291-294.

74. Zobler, L. and L. T. Kardos. 1943. Exchangeable Cations Status and Structure of Palouse Silty Clay Loam as Influenced by Various Cropping and Fertility Practices. Soil Sci. 55: 147-158.

APPENDIX 1

BULK DENSITY VALUES FOR THE VARIOUS CROP ROTATION SYSTEMS IN RANGES 26 AND 27 OF EXPERIMENT 70

Crop rotation system	Fertilizer treatments (tons/ac. of barn manure)	Bulk density (ave. of 3 values)
Two-year rotation	None	0.96
	2.0	1.06
Three-year rotation	None	1.09
	2.7	1.04
Four-year rotation	None	1.05
	3.0	1.10
Wheat continuous	None	1.11
	4.0	1.08
Corn continuous	None	1.23
Oats continuous	4.0	1.12

APPENDIX 2

A.M.S. VALUES FOR THE HAY-GRAIN ROTATION OF EXPERIMENT 70-A

Plots	Hay Crops	Sampling depths (inches)	A.M.S. values (Ave. of 8 sub-samples)			
			Fertilized Plots Rotation Year		Check Plots Rotation Year	
			6	3	6	3
1,11	Alfalfa	0-3	1.46	1.64	1.33	1.45
		3-6	1.85	1.75	1.66	1.74
2,10	Alfalfa-Meadow fescue-Timothy mixture	0-3	1.65	1.95	1.40	1.76
		3-6	1.85	2.17	1.73	1.88
3,9	Meadow fescue-Timothy mixture	0-3	1.59	1.85	1.41	1.72
		3-6	1.79	1.99	1.65	1.88

APPENDIX 3

A.M.S. VALUES FOR THE FALLOW-GRAIN ROTATION OF EXPERIMENT 70-A

Plot	Tillage and crop residue management practices	Sampling depths (inches)	A.M.S. values (ave. of 8 sub-samples)	
			Fertilized	Check
4	Plow under stubble	0-3	1.43	1.37
		3-6	1.82	1.66
5	Disc in straw and stubble	0-3	1.27	1.08
		3-6	1.81	1.71
6	Cultivate-leave trash cover	0-3	1.57	1.43
		3-6	1.93	1.78
7	Burn off straw and stubble-cultivate	0-3	1.26	1.10
		3-6	1.77	1.77
8	Plow under straw and alfalfa	0-3	1.78	1.43
		3-6	2.04	1.86