TB 485 (1935) USDA TECHNICAL BULLETINS UPDATA
EFFECTS OF PARTICLE SIZE ON THE PROPERTIES AND EFFICIENCY OF FERTILIZERS
MEHRING, A L ET AL 1 OF 1

START

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Technical Bulletin No. 485 — September 1935

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D.C.

EFFECTS OF PARTICLE SIZE ON THE PROPERTIES AND EFFICIENCY OF FERTILIZERS[1]

By A. L. MEHRING, *associate chemist*, L. M. WHITE, *junior chemist*, and W. H. ROSS, *senior chemist, Division of Fertilizer Investigations, Bureau of Chemistry and Soils*, and J. E. ADAMS, *associate soil technologist, Division of Soil Fertility Investigations, Bureau of Plant Industry*

CONTENTS

INTRODUCTION

The cost of fertilizers to the farmer may be lowered either by reducing the price of goods of the same quality or by improving the quality without proportionately increasing the price. In considering ways of accomplishing the latter, consideration should be given the fact that fertilizer particles of one size may be considerably more efficient than those of other sizes and that if the optimum size were known fertilizers might be prepared accordingly with little or no additional cost.

Insoluble fertilizer materials, such as bone meal, basic slag, and limestone are generally recognized to be of greater value when finely ground, but little is known about optimum sizes for the particles of water-soluble fertilizers or of commercial mixtures.

The problem is very complicated because of the large number of factors involved. For example, since fertilizer materials vary widely in their physical and chemical properties, the size of grains best adapted to prevent caking or to insure good mechanical condition might be inefficient in obtaining high crop yields with a given fertilizer and quite efficient with another fertilizer.

[1] Credit is due G. A. Cumings, Division of Mechanical Equipment, Bureau of Agricultural Engineering, for assistance in applying the fertilizers with the improved distributor belonging to that Bureau; to the officials of the South Carolina Agricultural Experiment Station for provision of land, labor, and other facilities in connection with the field work; to Albert Bowen, Division of Soil Fertility Investigations, Bureau of Plant Industry, for assistance in obtaining the emergence counts and yield data; and to the officials of the South Carolina, Georgia, Tennessee, Ohio, New Jersey, New York, and Minnesota fertilizer control laboratories for furnishing representative samples for the mechanical analyses.

Factors in the problem of particle size include the properties of various fertilizers, their behavior during storage, their handling and application to the soil, their movements and reactions in the soil solution, and their efficiency in getting good stands and high crop yields. The purpose of this bulletin is to give the results of experiments upon each factor separately and then to show so far as possible their interrelationships and significance to agriculture.

As a result of this work it appears that the size of fertilizer particles is of real importance to agriculture and some suggestions will be offered for getting greater efficiency in the use of fertilizers in this respect. Much more work must be undertaken, however, to determine fully the relationships of particle size to the efficiency of all types of fertilizers under all sorts of conditions.

MATERIAL AND METHODS

Each recognized factor in the problem of particle size in fertilizers was studied separately both from the theoretical and practical viewpoints. The fertilizers studied included a variety of commercial mixed goods obtained from many different sources in a dozen States, typical fertilizer materials and a considerable number of fertilizers prepared specially for the purpose. Among the latter was a series of grained complete mixed fertilizers alike in every respect except that each member of the series was composed of particles of one size.

The size distribution of the grains composing the average mixed fertilizer and representative fertilizer materials was determined by screening. Bulkiness, caking, segregation, and drillability were studied in relation to the size of the particles in fertilizers by making various laboratory tests, some of them with control of the humidity and temperature of the atmosphere. The behavior of various fertilizers was studied carefully while they were poured, bagged, hauled on trucks, and distributed by commercial implements both in the laboratory under controlled conditions and in the field under normal conditions of farm practice. Field tests were made in 1931, 1932, and 1933 with cotton on several extensive soil types. Series of closely screened complete fertilizers varying only in the size of their grains were applied accurately in side placements and mixed with the soil below the seed in these field experiments. Soil samples were gathered at intervals during the growing season, and various chemical determinations were made to find out what effect size of grain had upon leaching and reactions in the soil solution. Rate of emergence of seedlings and yields of cotton were determined also.

PARTICLE SIZE IN COMMERCIAL FERTILIZERS

The grains composing a fertilizer are sometimes all of approximately the same size, as in pellet-form sodium nitrate, but more often vary in size from mere flecks of dust to that of pebbles 5 millimeters or more in diameter. The average diameter in millimeters is the best measurement when the particles are uniform in size or nearly so, but otherwise size is more clearly indicated by the percentages of material separated by a series of screens. A set of screens for this purpose should start with one having 5 or 6 meshes to the inch, with each succeeding screen having twice as many meshes to the inch as the preceding. Relatively small amounts of material larger than the coarsest or smaller than the finest sieve in the set employed are expressed as on or through the mesh designated. A statement of the proportions of the fertilizer separated by sieves is its mechanical analysis. The mechanical analysis may be reduced to an average diameter if desired by the following method: Multiply the average diameter of the openings of each pair of screens by the percentage of material separated by them, add all the results and divide by 100.

It is necessary to know the actual size distribution of the particles in the more important types of commercial fertilizers to appreciate the practical significance of the results of this study.

Accordingly mechanical analyses were made of a considerable number of samples of commercial fertilizers by weighing the separated portions after 15 minutes treatment in a Rotap screening machine. Some of the samples were obtained directly from manufacturers over a period of several years and others were supplied by officials of the fertilizer control laboratories of New York, New Jersey, South Carolina, Georgia, Tennessee, Ohio, and Minnesota. Table 1 gives the average results. The average for limestone is based on data published by several State fertilizer laboratories.

TABLE 1.—*Average values of mechanical analyses of commercial fertilizers and fertilizer materials*

Fertilizer	Samples	Material separated by screens of mesh sizes indicated						
		On 5	5-10	10-20	20-40	40-80	80-200	Through 200
	Number	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Complete mixtures, 10-19.9 percent plant food	36	1.5	9.7	15.6	25.2	23.3	14.4	10.3
Complete mixtures, 20-29.9 percent plant food	28	.5	7.1	16.0	25.0	25.3	17.4	8.7
Complete mixtures, 30-39.9 percent plant food	6	.4	7.2	15.5	26.6	25.4	19.0	5.9
Complete mixtures, 40-49.9 percent plant food	9	.5	14.6	27.3	22.7	17.4	13.3	4.4
Complete mixtures, 50 or more percent plant food	6	1.3	14.0	13.9	25.4	25.7	15.9	3.8
Superphosphate and potash mixtures	8	.3	5.5	12.9	21.7	36.1	16.9	6.6
Nitrogen and potash mixture	1	.3	.6	11.6	30.8	33.6	20.3	2.8
Sodium nitrate	3	6.7	12.5	26.0	43.9	9.2	1.5	.2
Calcium nitrate	1	.6	10.8	42.3	35.4	9.4	1.7	.1
Leunasalpeter	1	2.4	18.2	8.7	21.4	30.2	19.0	.1
Urea	1				93.4	3.9	2.7	
Ammonium sulphate	3				28.5	59.9	11.3	.3
Ammonium phosphates	1	.4	10.9	24.8	39.9	14.6	8.2	1.2
Raw bone meal	4		3.0	29.5	22.1	20.9	16.4	8.1
Animal tankage	3		12.8	24.2	21.9	20.7	15.9	4.5
Fish scrap	3		4.2	32.6	31.2	16.0	12.3	3.6
Cottonseed meal	1		.4	18.4	25.8	27.1	27.9	.4
Peat	1	.2	1.3	25.6	30.5	19.4	17.5	5.5
Superphosphate, 16-20 percent available phosphoric acid	12	2.8	5.9	7.8	20.8	23.9	10.8	19.0
Double superphosphate, 40-46 percent available phosphoric acid	1	1.1	27.9	20.1	15.6	16.1	11.7	7.5
Muriate of potash	3		4.5	10.7	14.7	32.4	32.3	5.4
Limestone	133		.2	4.0	11.5	13.2	27.1	44.0

The averages for each group of mixed fertilizers in the table are essentially alike but some of the individual analyses in each group differed radically from the average. About half of the mixtures contained no material held on a 5-mesh screen and a few were free of powder that would pass through 80-mesh. The maximum amounts on 5-mesh and through 200-mesh in any of these mixed goods was

4.8 and 23.5 percent, respectively. Only 1 of the 3 sodium nitrate samples was what is known in the trade as coarse grained and yet the average is much coarser than the mixed fertilizers. The urea and ammonium-sulphate samples consisted largely of 20- to 80-mesh material. On the average the 16- to 20-percent superphosphates were composed of much smaller particles than the double superphosphates. The limestone samples were the most finely ground of all the classes of materials or mixtures.

PHYSICAL AND CHEMICAL PROPERTIES AFFECTED BY PARTICLE SIZE

Physical properties of fertilizers that change considerably with the size of the grains and that have a bearing on the present problem are apparent density, surface tension, capillarity, adhesion, and cohesion.

The apparent density (weight of a unit volume of divided material) varies considerably with the size, shape, degree of packing, and distribution of size of the particles composing it, but the absolute density (weight of a unit volume of solid substance) changes very little over the normal range of atmospheric temperature. The absolute densities or specific gravities of pure substances, such as sodium nitrate and potassium sulphate, are given in appropriate textbooks. The apparent densities of commercial samples of the same materials are quite variable, the values ranging as a rule from 40 to 60 percent of the absolute values. Theoretically, the apparent specific gravities of a material in the form of spheres of uniform size in the loosest and closest packing possible are 52 and 74 percent, respectively, of the absolute density.

A mass consisting of grains of various sizes has a higher apparent density than another of particles of uniform size because small grains fill the spaces between larger ones. Finely ground materials under the same conditions are considerably lighter than coarse ones. This is shown in table 2. A 100-cc lump of solid material after being comminuted to colloidal proportions will often more than fill a liter vessel. This is explained as follows: When 5- to 10-mesh material is reduced to an impalpable dust the area of exposed surface is increased in proportion millions of times. All solid surfaces adsorb films of condensed gases from the atmosphere and thus pulverized material ordinarily contains enormous quantities of adsorbed gases, which increase its bulk.

TABLE 2.—*Variations in densities of masses composed of particles of different shapes with changes in particle size*

Screen mesh size of particles	Monoammonium phosphate crystals	Potassium nitrate spherical pellets	Ground phosphate rock	Screen mesh size of particles	Monoammonium phosphate crystals	Potassium nitrate spherical pellets	Ground phosphate rock
Solid mass	1.80	2.10	3.06	60-80	0.89	1.24	1.28
5-10	.83	1.20	1.25	80-100	.91	1.24	1.28
10-20	.84	1.22	1.24	100-125	.92	1.23	1.28
20-30	.84	1.24	1.24	125-157	.93	1.22	1.28
30-40	.85	1.24	1.25	157-200	.93	1.20	1.28
40-60	.85	1.25	1.27	Through 200	.70	.95	1.12

Light materials require larger bags to hold the same weight of material. Since large bags cost more than small ones and the storage facilities required for a given tonnage of material vary with the apparent density, it is in the interest of economy to grind materials so as to occupy the least space possible, provided this does not reduce efficiency in some other way. The apparent density approaches its maximum when the pore spaces between the largest particles are filled with smaller ones and the interstices between the latter in turn with still smaller ones and so on until no voids remain.

Molecules in the surface layers of substances behave differently from those in the interior. Molecules inside of a mass are acted on from all sides by the attractive forces of other molecules of the mass but those in the outer layer have one side free from such influences. This leaves residual forces at the surface that give rise to such physical phenomena as surface tension, capillarity, cohesion and adhesion, and the property of adsorption. These forces are all functions of the proportion of surface to mass. The surface area of a particle increases rapidly in proportion to the mass as the size of the particle decreases. When these ratios are plotted against the diameters of the particles the resulting curve is a hyperbola approaching zero with large particles and infinity with those of molecular dimensions. When a mass of particles the size of peas is subdivided finely enough to pass freely through a 300-mesh sieve the free surface of the mass is increased about 1,000 times. By continuing the process of subdivision until the particle diameters are 1 millimicron the free surface of an originally pea-sized grain is increased to about 1 acre. Thus the physical properties of pulverized materials are quite different from those of granular ones. The chemical properties also change when the range of particle size falls between 5 and 200 millimicrons, giving rise to the phenomena of colloid chemistry.

Commercial fertilizers as a rule contain very little material of colloidal proportions but do often contain a fair proportion of minute particles that stick to each other and to almost everything they touch. These small grains also adsorb much larger quantities of gases and moisture from the atmosphere than larger ones do under the same conditions. For these reasons some fertilizers cannot be distributed uniformly by ordinary farm machinery and are unpleasant to handle since they are dusty when dry and sticky when damp. The exact size at which these effects become noticeable varies somewhat with the material and its moisture content.

Experiments were made to determine the size at which physical forces begin to injure drillability or the ability to flow freely as a result of the force exerted by gravity. For this purpose ammonium phosphate was screened into a considerable number of sizes varying from 5- to 8- to 300- to 350-mesh and stored in a constant temperature and humidity room until in equilibrium with the atmospheric conditions. The particles were then tested for steady flow through specially constructed funnels. It was found that when the moisture content was 0.08 percent, masses of particles with diameters of 0.04 mm or less would not flow by gravity but those composed of larger grains did. Similarly the limiting diameters for grains that flowed freely when the substance contained 0.53 and 2 percent of moisture were 0.06 and 0.42 mm, respectively. Thus material drier than that usually found in commerce will not flow by gravity alone when comminuted finely enough to pass through a 300-mesh sieve, although it may flow in the form of 20- to 30-mesh or coarser grains when very damp. Damp materials flow less readily than dry ones of the same particle size because the films of moisture cause the particles to cling together with a tension that increases with the quantity of moisture adsorbed until the capillary spaces between the particles are filled. The smallest sized particles of most fertilizers that would flow by gravity under normal atmospheric conditions were found to be those that pass through a 200-mesh but not through a 250-mesh screen.

Very fine dry powders, such as some ground limestones, that normally show considerable cohesion will, nevertheless, when suddenly jarred flow and surge in waves like a liquid. The jar momentarily separates the particles sufficiently to break the attractive forces between them and as long as they continue to move they flow freely. As soon as they come to rest, however, they cohere again. Many distributors apply such materials with extreme irregularity.

Chemical reactions do not ordinarily occur between molecules that are separated by a space of more than 50 millimicrons (*1*).[2] For this reason coarsely ground materials may be mixed with little or no chemical reaction as long as they are kept dry, while the same materials in solution or pulverized might react instantly or in a fairly short time.

Fertilizer materials when mixed, frequently react to a greater or less extent by double decomposition. The crystal growth of the resulting products often causes the entire mass to harden so that it must be reground before shipment. These reactions between solid materials require considerable time to be completed but the more minutely the materials are subdivided before mixing the shorter this time will be.

BEHAVIOR IN STORAGE AS AFFECTED BY SIZE OF PARTICLES

During storage the moisture content of fertilizers changes with the relative humidity and temperature of the air in contact with them. The amount of moisture held by water-soluble material under a given set of conditions which will not cause actual solution varies little with the size of the grains if they are too large to pass a 200-mesh sieve, but it increases rapidly as the size decreases below this limit.

One of the causes of caking of fertilizers is the alternate absorption of moisture and drying with the diurnal changes of the relative humidity and temperature of the air. When the relative humidity is high a film of moisture is adsorbed upon the surface of the grains and dissolves enough salt from soluble materials to form a saturated solution. When the humidity is lowered water evaporates and crystals are deposited, which cement the grains together. A similar result may also follow variations in the concentration of the solution due to changes in temperature. The extent of this caking varies with the size of the particles.

Caking was studied by screening a variety of fertilizer materials to different sizes and exposing them first to an atmosphere of 90-percent relative humidity and then to one of low humidity. All samples fine enough to pass a 200-mesh sieve were then found to be caked so hard that none could be crushed with the bare hands. The

[2] Italic numbers in parentheses refer to Literature Cited, p. 20.

5- to 10-mesh particles of some materials were slightly stuck together but crumbled easily when squeezed in the hand, and those of other samples showed no caking whatever. As a result of these experiments and observations in the field it may be said that the smaller the particles of a fertilizer are the more readily they will cement together to form a hard cake and the harder will be the mass formed.

EFFECTS OF SHIPMENT AND DISTRIBUTION UPON FERTILIZERS COMPOSED OF GRAINS OF DIFFERENT SIZES

Some commercial fertilizers though properly mixed at the factory do not remain homogeneous while being shipped or distributed. This was found to be the case by Haigh (*6*) in taking samples for analyses and by Mehring and Cumings (*9*) in testing the distribution of fertilizers by machinery. This tendency for some fertilizer mixtures to separate more or less into zones of like particle size is called segregation. While the relative densities of the different kinds of materials mixed are partly responsible, segregation nevertheless is essentially a problem of particle size.

Smith, Hardy, and Gard (*11*) concluded that different materials when ground to pass through a 200-mesh sieve and well mixed will remain a homogeneous mixture permanently no matter how much it may be jarred or shaken subsequently. Mixtures of coarser sizes than this, however, constitute the overwhelming majority of commercial fertilizers. Some fertilizer mixtures tend to segregate while others do not.

Three kinds of treatment that any fertilizer mixture is likely to encounter may cause more or less segregation. They are pouring, settling, and vibration. Each of these treatments acts differently and will be discussed separately, but all tend to unmix commercial fertilizers.

When a mixture of dissimilar materials is poured in air the largest, heaviest, and most symmetrical particles fall fastest and, after landing in a heap, roll farthest and thus tend to accumulate on the bottom and at the outer edges of the pile. The extent to which segregation takes place increases with the distance through which the material travels. Pouring so that the displaced air rushes up through the descending fertilizer greatly increases the degree of separation in a fall of the same distance. Thus segregation due to this cause while filling sacks or distributors may be materially lessened merely by pouring as short a distance as possible and on one side of the receptacle so that the displaced air may flow out on the other.

Fertilizer immediately after being poured is in a loose condition, but if this loose mass is jarred or shaken, as when a bag is jounced up and down to settle it, or a distributor is hauled over a field, the particles rearrange themselves in tighter packing. The contraction in volume is only about 5 percent and this rearrangement is accomplished in such a way as to have no effect upon the homogeneity of the mixture when the grains are all of about the same size. The average commercial fertilizer, which is composed of many sizes of grains, settles on the other hand from 12 to 25 percent with a mean of about 16 percent and this may be accompanied by considerable segregation.

When a heterogeneous mixture settles the powdered materials sift down and gradually pack the pore spaces between the granular ones. If each ingredient of the mixture consists of about the same range of sizes this has no effect on composition but if one ingredient is composed of large grains while another is more or less pulverized serious separation may result.

The manner in which this occurs may be clearly demonstrated on a magnified scale by half filling a glass bottle with spheres 10 mm in diameter and then pouring others 4 mm or less in diameter upon the surface of the larger ones. Any other sizes will do as well provided the diameter of the larger ones is at least two and one-half times as great as that of the others. The little balls will run down in zigzag courses through the interstices and fill them up from the bottom.

The same experiment may now be used to show what happens when a mixture is vibrated with a horizontal thrust. To do this the bottle is turned on its side and tapped vigorously on the bottom with the palm of the hand a few times, whereupon the large spheres accumulate on top of the small ones.

The phenomenon of stratification as a result of horizontal vibration occurs at times in distributors with knocking devices and may also take place to some extent in moving freight cars and under other circumstances. This kind of segregation was studied in glass bottles so that the effects could be watched with a wide variety of mixtures composed of two well-mixed substances of known properties. In some cases complete separation into layers was effected by tapping the bottom of the bottle only a few times. Figure 1 shows 8- to 10-mesh superphosphate completely separated in this way from 10- to 16-mesh nitrate of soda. In other tests the materials did not stratify nor even tend to separate. From these tests it may be concluded that when the density of the two materials is approximately the same, the average diameter of one kind must be more than double that of the other before complete separation can be obtained in this way.

Horizontal vibration and settling tend to correct the segregation produced by pouring.

In view of the ease with which some of these mixtures separated, it becomes a matter of interest to know what happens when commercial mixtures are being handled and applied to the soil. This was studied by distributing under controlled conditions a number of typical fertilizers bought on the open market.

Each fertilizer was tested in a star-wheel grain-drill attachment. The fertilizer was first thoroughly remixed in a rotating drum and then placed in the hopper with a scoop to avoid pouring or shaking. After the distributor had been operating for 3 minutes, a sample was collected in a pan placed under the delivery spouts for 1 minute. Every 3 minutes thereafter a sample was gathered for 1 minute. The first, middle, and last samples obtained under normal operating conditions were subjected to chemical and mechanical analyses, the results of which are given in table 3.

FIGURE 1.—A mixture of 8- to 10-mesh superphosphate and 10- to 16-mesh nitrate of soda completely separated by horizontal vibration. The average diameters of the particles are 2.20 millimeters and 1.61 millimeters, and the apparent densities are 0.90 and 1.30, respectively.

TABLE 3.—*Chemical and mechanical analyses of the first, middle, and last portions (samples nos. 1, 2, and 3, respectively) of commercial fertilizers delivered by a grain-drill fertilizer attachment and the difference*[1] *between the first and last sample*

Fertilizer no.	Sample no.	Plant food: N	Plant food: P_2O_5	Plant food: K_2O	Material separated by screens of sizes indicated: On 10-mesh	10- to 20-mesh	20- to 40-mesh	40- to 80-mesh	80- to 200-mesh	Through 200-mesh
		Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
1	1	3.84	10.41	7.07	6.9	12.7	20.9	17.7	16.3	25.5
	2	3.80	10.58	6.88	9.2	15.0	21.3	15.6	14.6	24.4
	3	3.92	10.49	6.11	7.8	12.9	23.3	16.7	18.1	21.2
	Difference	+.08	+.08	−.96	+.9	+.2	+2.4	−1.0	+1.8	−4.3
2	1	3.47	8.99	2.75	5.9	10.4	28.9	24.6	16.2	14.0
	2	3.50	9.05	2.97	6.5	13.6	29.1	22.8	13.6	14.4
	3	3.50	8.15	3.02	7.1	13.9	29.1	22.7	15.4	11.7
	Difference	+.02	−.84	+.27	+1.2	+3.5	+.2	−1.9	−.8	−2.3
3	1	5.63	7.58	3.99	9.7	9.6	22.3	15.5	26.9	15.8
	2	5.63	7.31	3.94	9.2	12.0	24.5	21.2	14.0	19.1
	3	5.13	7.17	4.58	15.1	14.0	27.5	15.7	18.0	9.6
	Difference	−.50	−.41	+.59	+5.4	+4.4	+5.2	+.2	−8.9	−6.2
4	1	3.55	8.34	2.71	9.5	8.8	23.4	22.7	10.1	25.5
	2	3.55	8.50	2.50	9.2	12.3	24.7	22.3	11.9	19.5
	3	3.53	8.13	2.98	9.9	10.9	25.0	24.6	12.6	16.9
	Difference	−.02	−.21	+.27	+.4	+2.1	+1.6	+1.9	+2.5	−8.6
5	1	3.25	8.32	10.75	7.4	12.6	19.6	23.6	16.7	20.0
	2	3.25	8.21	10.54	7.9	14.0	18.0	22.9	16.6	20.6
	3	3.25	8.35	10.72	7.7	11.9	19.9	22.4	16.4	21.8
	Difference	.00	+.03	−.03	+.3	−.7	+.3	−1.2	−.3	+1.8
6	1	3.03	7.67	4.09	5.6	12.3	26.9	26.9	8.8	19.4
	2	3.03	7.81	4.24	7.2	13.2	27.0	25.1	11.3	16.1
	3	3.03	7.85	4.02	9.6	15.8	28.3	22.2	7.1	17.0
	Difference	.00	+.18	−.07	+4.0	+3.5	+1.4	−4.7	−1.7	−2.4
7	1	3.64	16.26	10.24	6.6	10.0	26.4	28.6	9.3	19.0
	2	3.67	16.02	9.79	8.4	14.0	28.9	27.0	12.5	11.3
	3	3.67	18.00	8.70	10.3	16.5	29.2	24.1	10.6	9.2
	Difference	+.03	+1.74	−1.51	+3.7	+6.5	+2.8	−4.5	+1.3	−9.8
8	1	6.84	9.14	18.06	10.8	15.9	21.0	19.4	32.8	.1
	2	7.28	10.06	16.06	14.0	20.4	23.1	16.6	25.9	0.0
	3	8.20	12.63	11.97	26.5	25.2	20.4	11.6	16.3	0.0
	Difference	+1.36	+3.49	−6.09	+15.7	+9.3	−.6	−7.8	−16.5	−.1
9	1	4.61	12.88	4.29	9.1	18.2	26.5	23.5	12.0	10.7
	2	4.71	13.07	4.33	10.9	20.3	25.3	23.2	10.5	9.8
	3	4.72	13.10	4.57	12.6	20.7	23.4	25.3	9.3	8.7
	Difference	+.11	+.22	+.28	+3.5	+2.5	−3.1	+1.8	−2.7	−2.0
10	1	4.05	13.91	3.92	3.7	17.3	33.3	26.1	12.8	6.6
	2	4.09	13.80	4.61	7.8	22.7	31.7	22.4	10.6	4.8
	3	4.10	13.53	4.47	12.7	25.7	27.3	19.9	10.2	4.1
	Difference	+.05	−.38	+.55	+9.0	+8.4	−6.0	−6.2	−2.6	−2.5

[1] Plus (+) indicates that the result for sample 3 is greater and minus (−) that it is less than that for sample 1 of the same fertilizer.

The mechanical analyses of all these fertilizers except no. 5 show an unmistakable tendency for the dust to be delivered first and the gravel sizes last. The chemical composition of a few of these fertilizers remained practically constant throughout the test but in others considerable variation occurred. The analyses of fertilizer no. 8 show that it segregated very badly. It differed from the others in containing no material fine enough to pass through a 200-mesh sieve, and a larger than usual proportion of big granules.

Since the fertilizer that contained no powdered material segregated most, several special mixtures were prepared for study which also were free of powder. Table 4 gives the essential facts regarding the composition of these mixtures and table 5 the results obtained with them in the distributor.

Table 4.—*Specifications of special mixtures prepared to study segregation*

Fertilizer no.	Material	Size of particles, screen mesh	Apparent density	Quantity in 100 pounds of mixture
				Pounds
11	Nitrate of soda	20 to 40	1.31	29
	Superphosphate	5 to 10	1.11	61
	Sulphate of potash	80 to 150	1.30	10
12	Nitrate of soda	20 to 40	1.31	29
	Superphosphate	20 to 40	1.04	61
	Sulphate of potash	20 to 40	.05	10
13	Nitrate of soda	20 to 40	1.31	29
	Superphosphate	80 to 150	1.11	61
	Sulphate of potash	5 to 10	.07	10

Table 5.—*Chemical analyses of portions of special mixtures delivered at intervals by a grain-drill fertilizer attachment and from different parts of a sack that had been subjected to vibration*

Description of sample	Plant food content of fertilizer—								
	No. 11			No. 12			No. 13		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Entire mixture	4.75	12.87	4.81	4.75	13.06	4.81	4.75	13.52	4.81
First portion delivered	9.21	6.32	6.72	4.95	12.84	4.86	4.73	13.59	4.69
Middle portion delivered	4.05	13.50	3.60	4.88	12.86	4.88	4.68	13.55	4.92
Last portion delivered	1.30	18.69	1.50	4.70	13.09	4.77	5.01	13.37	4.86
Difference[1]	−7.91	+12.37	−5.22	−.25	+.25	−.09	+.28	−.22	+.17
Top of sack	1.94	18.04	1.00	4.80	13.22	4.69	4.88	13.41	4.65
Middle of sack	6.23	10.23	6.56	4.85	13.12	4.70	4.76	13.58	4.63
Bottom of sack	7.05	7.58	10.33	5.00	13.02	4.91	4.65	13.72	4.65
Difference[1]	+5.11	−10.46	+9.24	+.20	−.20	+.22	−.23	+.31	0.00

[1] Plus (+) indicates that the last portion delivered contained more and minus (−) that it contained less than the first portion delivered, by the amount shown

Some tests were made to determine what might happen to the material in a sack owing to vibration such as might occur in transporting it. For this purpose the special mixtures just mentioned were remixed and packed into burlap sacks, placed on a truck with iron wheels, and hauled about on a cement floor for several minutes. Analyses were then made on samples removed from the top, middle, and bottom of the bag and these results also appear in table 5.

The facts already presented indicate that segregation is greatest when the bulk of the mixture is coarse material and inconsequential when it consists entirely of pulverized material. To make a practical test of these conclusions a bag of commercial 4–8–4 fertilizer was divided into two portions and one part was reground somewhat more finely. The mechanical analyses of the two portions and the results of tests with them in the drill are given in table 6, which proves that while other conditions remain identical finer grinding does greatly decrease the extent of segregation.

TABLE 6.—*Effect of grinding on segregation of a fertilizer*

	Distribution for screen-mesh sizes indicated						Portion of delivery by distributor	Plant food content		
	5- to 10-mesh	10- to 20-mesh	20- to 40-mesh	40- to 80-mesh	80- to 200-mesh	Through 200-mesh		N	P_2O_5	K_2O
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*		*Percent*	*Percent*	*Percent*
Before grinding	52.0	10.8	20.7	8.6	7.2	0.7	First	4.30	7.38	4.22
							Middle	4.06	8.51	4.01
							Last	3.92	8.54	3.79
							Difference [1]	−.38	+1.16	−.43
After grinding	4.7	10.8	21.7	23.4	12.7	26.7	First	3.85	7.83	4.06
							Middle	3.93	7.07	3.99
							Last	3.94	8.08	4.00
							Difference [1]	+.09	+.25	−.06

[1] See footnote Table 5.

In the various experiments just described the nitrogen content of the commercial fertilizers remained much more constant during distribution than did the P_2O_5 and K_2O, but the nitrogen percentages of the special mixtures varied as much as those of the other plant foods. This may have been due in part to the possibility that basing or ammoniation of superphosphate had distributed nitrogen through all the particles in the preparation of the commercial mixtures. It seems, however, to have been due also to the fact that the special mixtures contained only one source of nitrogen, while the commercial mixtures all contained three or more materials supplying it.

PARTICLE SIZE AND DRILLABILITY

The effects of particle size on the drillability of fertilizers have been investigated by Mehring and Cumings (*9*). They found that the rate of delivery and uniformity of distribution along the row by commercial distributors are affected by the dimensions of the particles and under the conditions employed found 20- to 80-mesh the most satisfactory range of size. Drillability was very unsatisfactory when the fertilizer consisted largely of pulverized material. Powders are dusty when dry and pasty when damp. During distribution in windy weather considerable quantities are often carried away to other fields and irritate the eyes and respiratory passages of the operator and team. Such substances will not flow and cannot be distributed satisfactorily. This is illustrated in figure 2, which shows the relative quantities of fairly dry crystalline, granular, and powdered samples of the same fertilizer material delivered by three separated identical units of a grain-drill attachment operating simultaneously.

RELATION OF PARTICLE SIZE TO ACTION IN THE SOIL

Much study has been devoted to finding out the effects of fineness upon the reactions of limestone in the soil. Walker, Brown, and Young (*14*) give a review of a number of these studies. No previous work has been done, so far as is known, to determine the effect of particle size upon the changes in composition, solubility, etc., of commercial fertilizers when they are placed in the soil. From the results obtained with limestone, however, commercial fertilizers also seemed to be worth investigating in this respect.

Special fertilizers were prepared in several closely screened sizes in such a way as to eliminate the possibility of segregation. This was done by first grinding the materials shown in table 7 to pass through an 80-mesh sieve. The weighed quantities of the proper

FIGURE 2.—Comparison of the quantities delivered, by three separated units of a drill operating simultaneously, of different samples of the same fertilizer material: *A*, Oblong crystals; *B*, granular; *C*, powdered.

ingredients to give the desired grade were then thoroughly dry mixed in a rotating drum and while being mixed were sprayed with water in the form of a mist. The damp material was then dumped into a grainer and agitated at 105° C. until dry. This treatment produced hard pellets most of which contained each of the ingredients in the mixture. The sizes desired were screened out and the oversize material was crushed and also screened. These grained fertilizers were prepared in 5 different sizes of 4–8–4 grade, 4 of 8–16–8, and 3 of 12–24–12. Dry-mixed fertilizers also were prepared in which only the superphosphate particles varied in size. The other ingredients of the latter mixtures all passed through an 80-mesh sieve. In one of these 4–8–4 mixtures all the phosphoric acid was derived from 5- to 10-mesh superphosphate, in another from 20- to 40-mesh and in the third from finer than 80-mesh particles of the same superphosphate.

TABLE 7.—*Formulas of mixed fertilizers*

Ingredient	Nos. 16 to 23, 4–8–4	Nos. 24 to 30, 8–16–8	Nos. 31 to 36, 12–24–12	Ingredient	Nos. 16 to 23, 4–8–4	Nos. 24 to 30, 8–16–8	Nos. 31 to 36, 12–24–12
	Pounds per ton	*Pounds per ton*	*Pounds per ton*		*Pounds per ton*	*Pounds per ton*	*Pounds per ton*
Sodium nitrate	120	448		Double superphosphate		712	
Ammonium sulphate	104	340		Potassium sulphate	150		
Ammonium nitrate			200	Potassium muriate		320	480
Ammonium phosphates			1,196	Filler (sand, etc.)	380		124
Cottonseed meal	303			Dolomite		32	
Dried blood		148					
Superphosphate	844			Total	2,000	2,000	2,000

The analyses given in table 8 show that the fertilizers in each grade were essentially alike in chemical composition. The same fertilizers were used in other phases of this study, to be described later, and were therefore given numbers so that the same fertilizer can be identified in various tests.

TABLE 8.—*Analyses of fertilizers used in the field work*

Fertilizer no.	Physical measurements: Screen mesh sizes [1]	Physical measurements: Apparent density	Physical measurements: Angle of repose	Chemical analyses: Total nitrogen	Ammonia nitrogen	Total P_2O_5	Citrate-insoluble P_2O_5	Available P_2O_5	0.002 N H_2SO_4 soluble P_2O_5	Water-soluble P_2O_5	Water-soluble potash	Total water-soluble salts	Moisture
			°	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
16	5 to 10	0.96	39	4.01	2.03	8.44	0.12	8.32	6.88	5.09	4.19	37.5	2.93
17	10 to 20	.93	30	4.23	2.01	8.40	.11	8.29	6.76	5.00	4.25	37.9	2.68
18	20 to 40	.92	39	4.32	2.11	8.48	.10	8.38	6.88	5.09	4.24	38.4	2.64
19	40 to 80	.94	38	4.01	1.91	8.15	.09	8.06	6.90	4.94	3.82	37.6	2.42
20	Through 80	.90	41	3.98	1.91	8.43	.10	8.33	6.78	5.08	3.88	37.3	2.97
21	(2)	1.35	43	4.12	2.05	8.06	.09	7.97	6.75	5.01	3.90	37.9	2.78
22	(3)	1.32	43	3.87	1.95	8.29	.10	8.19	6.80	5.06	3.95	38.1	2.44
23	Through 80 [4]	1.12	44	3.89	1.89	8.44	.11	8.33	6.91	5.10	3.80	38.5	2.40
24	5 to 10	1.02	38	8.24	3.97	16.90	.46	16.44			7.90		1.88
25	20 to 40	1.01	36	8.31	3.99	16.81	.40	16.41			7.93		1.88
26	80 to 150	.97	35	8.11	3.58	16.83	.43	16.40			7.98		2.03
27	2 to 3	.98	38	7.66	(5)	(5)	(5)	17.75			8.55		2.45
28	5 to 10	1.05	39	7.64	(5)	(5)	(5)	17.75			8.49		1.90
29	20 to 40	1.07	37	7.64	(5)	(5)	(5)	17.82			8.48		1.88
30	80 to 150	1.04	34	7.70	(5)	(5)	(5)	17.75			8.51		1.52
31	5 to 10	.87	36	11.87	10.03	25.08	.04	25.04			13.55		5.99
32	20 to 40	.88	35	12.18	10.57	24.56	.04	24.52			13.56		5.06
33	80 to 150	.87	35	11.86	10.10	24.61	.04	24.57			14.14		5.30
34	5 to 10	.93	38	12.02	(5)	(5)	(5)	25.38			13.73		4.67
35	20 to 40	.93	37	12.26	(5)	(5)	(5)	24.68			13.65		4.81
36	80 to 150	.96	35	11.92	(5)	(5)	(5)	24.76			14.24		4.77

[1] All ingredients were grained together in particles of the size indicated except in fertilizers nos. 21, 22, and 23.
[2] 5- to 10-mesh superphosphate, other ingredients through 80-mesh; dry mixed.
[3] 20- to 40-mesh superphosphate, other ingredients through 80-mesh; dry mixed.
[4] All ingredients ground to pass an 80-mesh sieve and dry mixed.
[5] Not determined.

The grained 4–8–4 fertilizers, of five different particle sizes and the dry-mixed fertilizers each containing superphosphate of a different grain size, were planted with cottonseed in South Carolina in 1931. The fertilizers were applied at the rate of 800 pounds per acre in narrow bands 1½ inches to the sides of the seed on a 2-inch lower level in one test, and were mixed with the soil below the seed in another. The soils used for the experiment were Norfolk very fine sandy loam at Pee Dee Experiment Station, Norfolk coarse sand at Sand Hill Experiment Station, and Cecil sandy clay loam at Clemson College. The planting was done with the distributor described in Department of Agriculture Circular No. 264 (*5*), which gives accurate delivery rates and placements and uniform distribution.

A core of soil 1 inch in diameter with the cottonseed at its center and parallel to the fertilizer band was removed from the row every few days after planting to determine with a soil bridge the amount of soluble salts that had diffused from the fertilizer into this area which will be called the seed zone. This was done by removing a small part of the row and exposing a cross section at right angles to it. The cross section was then whittled down with a spatula until a seed was found, whereupon a 1-inch cork borer was shoved into the soil parallel to the row with the seed in its center. Further details of the method of obtaining the samples and of making the determinations together with rainfall and soil-moisture data, applying equally well to these experiments, are given in Circular 264 (*5*).

Table 9 gives the results of the analyses, which show that more soluble salt was carried into the seed zone from the fertilizer mixed with the soil below the seed than from that at the sides. Any differences in the amounts of salts so transported due to the size of the fertilizer grains are obscured by the errors involved in making the test.

TABLE 9.—*Concentration of soluble salts in the seed zone as a result of 800-pound-per-acre applications of 4–8–4 fertilizers composed of differently sized grains and at several placements*

Fertilizer no.	Size, screen mesh	Fertilizer placement	Concentration of soluble salts in parts per million of soil									
			Norfolk very fine sandy loam [1]			Norfolk coarse sand [2]				Cecil sandy clay loam [3]		
			Apr. 18	Apr. 21	May 1	Apr. 25	Apr. 28	May 7	May 13	May 9	May 16	May 25
([4])	...	...	113	120	81	41	25	45	27	52	37	63
16	5 to 10	Bands 1½ inches each side 2 inches below level of seed	117	116	252	42	34	96	36	...	...	...
17	10 to 20	Bands 1½ inches each side 2 inches below level of seed	100	119	305	78	36	77	93	...	...	...
18	20 to 40	Bands 1½ inches each side 2 inches below level of seed	115	117	297	63	38	178	84			
19	40 to 80	Bands 1½ inches each side 2 inches below level of seed	168	120	410	73	31	98	42			
20	Through 80	Bands 1½ inches each side 2 inches below level of seed	109	118	344	50	37	96	45			
16	5 to 10	Mixed with soil below seed	130	375	895	198	34	222	109	150	432	1,761
17	10 to 20	Mixed with soil below seed	126	832	1,152	269	478	879	632	146	240	318
18	20 to 40	Mixed with soil below seed	120	755	763	60	550	458	312	725	350	1,241
19	40 to 80	Mixed with soil below seed	117	735	974	97	292	539	153	234	1,177	697
20	Through 80	Mixed with soil below seed	143	156	827	1,622	145	960	2,180	285	1,027	1,243
21 [5]	5 to 10	Bands 1½ inches each side 2 inches below level of seed	118	120	403	62	37	67	143	55	80	102
22 [5]	20 to 40	Bands 1½ inches each side 2 inches below level of seed	129	123	434	18	60	257	70	39	50	95
23 [5]	Through 80	Bands 1½ inches each side 2 inches below level of seed	123	121	328	41	35	74	52	36	44	83

[1] Fertilizer applied Apr. 17.
[2] Fertilizer applied Apr. 24.
[3] Fertilizer applied May 1.
[4] No fertilizer.
[5] Superphosphate varied in size; all other ingredients through 80-mesh.

Samples of soil from the fertilizer zone also were removed 100 days after application in order to determine changes that may have occurred in composition and availability of plant food. Duplicate composite samples, each composed of four 1-inch cores of soil with part of the fertilizer band at the center, were analyzed chemically as follows: A weighed quantity of the well-mixed sample was placed in a collodion sack and dialysed. Water-soluble P_2O_5 was determined by the improved Deniges method (*13*) and K_2O by the Association of Official Agricultural Chemists' method on aliquots of this extract. Dilute sulphuric acid-soluble P_2O_5 was determined on another portion of soil by Truog's method (*12*). Total P_2O_5 was determined volumetrically on a solution made by evaporating to dryness a suspension of the soil in magnesium nitrate solution, igniting and extracting with hydrochloric acid. Base exchange K_2O was extracted with N/20 HCl and then determined by the official method. Total soluble salts were estimated with a soil bridge. Total nitrogen and moisture were also determined by official methods. Table 10 gives the average results. The determinations show the sum of the plant food already in the soil plus that from the added fertilizer.

TABLE 10.—*Analyses of soil to which 4–8–4 fertilizers of varying particle size had been applied 100 days previously*

Soil	Fertilizer		Total P_2O_5	0.002 N H_2SO_4 soluble P_2O_5	Water-soluble P_2O_5	Total N	Base exchange K_2O	Water-soluble K_2O	Total soluble salts	Moisture
	No.	Particle size, screen mesh								
			Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Norfolk very fine sandy loam.	No fertilizer		0.056	0.009	0.002	0.11	0.002	0.001	0.007	7.28
	16	5 to 10	.222	.094	.015	.10	.041	.019	.274	
	17	10 to 20	.128	.052	.009	.14	.010	.009	.199	
	18	20 to 40	.128	.046	.010	.14	.019	.009	.203	
	19	40 to 80	.133	.056	.012	.14	.018	.014	.173	
	20	Through 80	.098	.034	.005	.12	.016	.003	.034	
	No fertilizer		.040	.010	.002	.04	.009	.001	.006	5.00
	21 [1]	5 to 10	.278	.129	.038	.06	.021	.013	.226	
	22 [1]	20 to 40	.072	.021	.006	.03	.008	.001	.035	
	23 [1]	Through 80	.084	.032	.007	.04	.009	.006	.050	
Norfolk coarse sand.	No fertilizer		.041	.010	.000	.02	.002	.001	.005	3.68
	16	5 to 10	.113	.048	.006	.05	.003	.002	.231	
	17	10 to 20	.080	.039	.003	.05	.004	.003	.178	
	18	20 to 40	.102	.041	.006	.04	.003	.001	.151	
	19	40 to 80	.104	.062	.008	.04	.011	.007	.152	
	20	Through 80	.076	.034	.002	.03	.006	.003	.083	
Cecil sandy clay loam.	No fertilizer		.103	.008	.000	.12	.005	.001	.014	6.32
	16	5 to 10	.308	.084	.008	.15	.018	.016	.315	
	17	10 to 20	.290	.072	.006	.16	.025	.021	.262	
	18	20 to 40	.344	.085	.008	.16	.037	.014	.237	
	19	40 to 80	.309	.075	.006	.16	.032	.011	.323	
	20	Through 80	.254	.083	.004	.14	.042	.010	.260	

[1] Superphosphate varied in size. All other ingredients through 80-mesh.

Comparison of the determinations directly is not satisfactory since the fertilizer was mixed with different amounts of soil in each sample. Differences in behavior may be seen readily, however, first by reducing to ratios the amounts by which one kind of determination exceeds that on the soil alone as compared with a similar excess of another kind of determination on the same sample and then by comparing these ratios with corresponding ones for samples of other-sized fertilizers.

Actual analyses made on the soil 1 day after application and 100 days later show that most of the P_2O_5 added to the loam soils was still there at the later date, although in the coarse sand the quantity was reduced to less than half with the largest grains and the amount removed increased as the diameters decreased. Since the value of total P_2O_5 changed very little in some instances and much less than did any of the other determinations in every case, the value for total P_2O_5 was used as the numerator in all of the fractions expressing these ratios.

An increase in value of the ratios for the fertilizer that had lain in the soil over those for the corresponding original fertilizer indicates a loss of the component represented by the denominator either by conversion to a form not soluble in the solvent employed in the determination or by removal from the soil included in the sample either by the cotton plants, by percolating rain water, or by other means.

Table 11 shows that P_2O_5 was reverted to less soluble forms in all cases but in the 5- to 10-mesh superphosphate dry mixture more P_2O_5 remained in a water-soluble condition than in any other fertilizer. When the ingredients were all grained together, reversion appears to have been greatest with the smallest grains, and the net effect was even greater than indicated because a little less total P_2O_5 remained in the smallest particles.

TABLE 11.—*Ratios between determinations of plant food in fertilizers (nos. 16–23, inclusive) of varying particle size, and between the same determinations 100 days after application in soils*

Kind of ratio	Size of particles, screen mesh	Fertilizer alone	Norfolk very fine sandy loam	Norfolk coarse sand	Cecil sandy clay loam
$\frac{\text{Total } P_2O_5}{\text{Dilute } H_2SO_4 \text{ soluble } P_2O_5}$	5 to 10	1.2	2.0	2.0	2.7
	10 to 20	1.2	1.7	2.1	2.9
	20 to 40	1.2	2.0	2.2	[illegible]
	40 to 80	1.2	1.6	1.9	2.9
	Through 80	1.2	1.7	2.2	2.4
	Superphosphate 5 to 10	1.2	2.0	(1)	(1)
	Superphosphate 20 to 40	1.2	2.3	(1)	(1)
	Superphosphate through 80	1.2	2.0	(1)	(1)
$\frac{\text{Total } P_2O_5}{H_2O \text{ soluble } P_2O_5}$	5 to 10	1.7	13.7	11.7	25.5
	10 to 20	1.7	12.7	9.5	30.8
	20 to 40	1.7	10.8	9.4	29.8
	40 to 80	1.7	8.5	8.3	30.9
	Through 80	1.6	18.3	17.0	41.8
	Superphosphate 5 to 10	1.7	6.7	8.9	20.3
	Superphosphate 20 to 40	1.7	8.0	13.5	28.5
	Superphosphate through 80	1.7	8.8	16.0	62.2
$\frac{\text{Total } P_2O_5}{N}$	5 to 10	2.1	3.4	3.5	20.6
	10 to 20	2.0	6.1	2.0	4.2
	20 to 40	2.0	5.3	2.4	9.3
	40 to 80	2.0	2.9	4.5	20.2
	Through 80	2.1	9.2	6.5	11.9
	Superphosphate 5 to 10	2.0	11.9	(1)	(1)
	Superphosphate 20 to 40	2.1	10.7	(1)	(1)
	Superphosphate through 80	2.2	12.3	(1)	(1)
$\frac{\text{Total } P_2O_5}{H_2O \text{ soluble } K_2O}$	5 to 10	2.0	8.8	14.5	12.4
	10 to 20	2.0	7.8	12.0	10.0
	20 to 40	2.0	7.3	19.7	18.8
	40 to 80	2.1	7.8	19.2	22.8
	Through 80	2.2	17.5	34.5	17.9
	Superphosphate 5 to 10	2.0	29.8	(1)	(1)
	Superphosphate 20 to 40	2.1	32.0	(1)	(1)
	Superphosphate through 80	2.2	11.0	(1)	(1)
$\frac{\text{Total } P_2O_5}{\text{Base exchange } K_2O}$	5 to 10	2.0	4.7	26.0	10.1
	10 to 20	2.0	4.5	7.5	10.8
	20 to 40	2.0	8.4	30.1	10.0
	40 to 80	2.1	7.0	5.8	10.7
	Through 80	2.2	5.6	10.0	5.2

[1] Tests were not conducted.

Leaching of nitrogen appears to have been greater from the smallest sized particles and this was actually somewhat greater than indicated by the ratios for the reason again that the total P_2O_5 was a little less.

Water-soluble potash disappeared from the soil in all cases but to a greater extent when the smallest sized particles were used. In the Norfolk soils much of it was lost but in the clay loam a considerable percentage was still present as base-exchange potash.

Some similar experiments were made in 1933 on the Norfolk coarse sand with 8–16–8 and 12–24–12 fertilizers, but only a few determinations could be made on each sample of soil. The results of the analyses are given in table 12, which shows that removal of water-soluble salts proceeded much more rapidly from the smallest particles of both fertilizers and varied inversely with the size of the particles. The 12–24–12 fertilizers were composed of more readily soluble materials and the amount of loss from them was also greater. Nitrogen constituted about 20 percent of the soluble salts of the original fertilizers but after 100 days in the soil it was about 1 percent or less. Thus nitrogen was removed either by the plants, by leaching rain water, or by micro-organisms much more rapidly than were soluble salts as a whole and it disappeared most rapidly from the smallest particles. The rainfall during the period of the 1933 experiments is given in table 13.

TABLE 12.—*Water soluble salts and nitrogen remaining in the fertilizer placement zone of the Norfolk coarse sand 100 days after application*

Screen mesh size	8–16–8 fertilizers nos. 27 to 30		12–24–12 fertilizers nos. 34 to 36	
	Water-soluble salts	Nitrogen	Water-soluble salts	Nitrogen
	P.p.m.	*P.p.m.*	*P.p.m.*	*P.p.m.*
2 to 3	518±25	2.0±0.8		
5 to 10	443±69	1.1± .2	86±8	0.7±0.005
20 to 40	200±81	1.0± .1	63±2	.5± .04
80 to 150	122±50	.9± .02	39±13	.7± .03
No fertilizer	<15	<0.3	<15	<0.3

TABLE 13.—*Daily rainfall on the Norfolk coarse sand from Apr. 1 to Aug. 1, 1933*

Date	Rainfall	Date	Rainfall	Date	Rainfall	Date	Rainfall
	Inches		*Inches*		*Inches*		*Inches*
Apr. 7	0.25	May 17	0.06	July 1	0.06	July 21	1.19
Apr. 10	.27	May 28	.31	July 2	.08	July 27	.49
Apr. 15	.11	May 31	1.04	July 4	.10	July 28	.02
Apr. 16	.09	June 7	.41	July 11	.41	July 30	.15
Apr. 19	.23	June 13	.25	July 12	.67		
Apr. 25	.65	June 25	1.71	July 13	.02	Total	11.80
May 3	1.41	June 28	.06	July 18	.73		
May 8	.25	June 30	.06	July 20	.69	Normal	15.50

AGRONOMIC RESULTS

Some previous work that has a bearing on the effects of particle size of fertilizers in relation to crop yields should be mentioned. Lyon (*8*) found that of the sizes tested 50- to 80-mesh limestone particles were most effective. Very large grains required years to produce expected effects, while pulverized material gave quick results.

Conner and Adams (*4*) experimented with rock phosphate that varied from fairly coarse material to that of colloidal dimensions and found it to be more efficient as the size was reduced all the way down the scale. Recently Conner (*3*) compared powdered and granulated soluble phosphates on corn. The powdered superphosphate was found to be much more efficient than the granular product when applied in a band and less so when mixed with the soil. On the other hand Chucka and Lovejoy (*2*) found that granular cyanamid was superior to the pulverized form for potatoes. Leaching of soluble salts and fixation of phosphates are so excessive in certain Hawaiian sugarcane soils that Hance (*7 pp. 59–60*) pressed commercial fertilizer into briquettes and covered them with paraffin in an attempt to combat too rapid loss of available plant food. One of these briquettes applied to each plant gave much better results than the untreated fertilizer distributed in the usual way.

As a part of the present study, tests were made with cotton in South Carolina during 1931, 1932, and 1933. All the plantings previously described were used for this phase of the study as well, and some additional plantings were made on the same soils for this part of the study only.

The preparation and composition of the fertilizers have been described in the previous section. The seed were acid-delinted and of high germinating power. They were planted simultaneously with the fertilizers in several placement relationships by the improved machine already mentioned at a rate of 1 bushel per acre. The 4–8–4, 8–16–8, and 12–24–12 fertilizers were applied at rates of 800, 400, and 267 pounds per acre, respectively. The plots consisted of 50-foot rows spaced 3.5 feet apart and were guarded at ends and sides by additional planting. Every test was replicated from 10 to 16 times, usually 12 times, in different parts of the field in a random arrangement. Checks for each test were treated in exactly the same way except that no fertilizer was applied to them.

The criteria used for determining relative efficiencies are stand counts and yields of seed cotton.

The number of living plants aboveground on each plot was counted every few days after planting and table 14 gives the average results for each treatment, with their probable errors. The soil moisture at planting time and some pertinent rainfall data which may be of interest in interpreting these results are given in table 15. Seedlings with fertilizer of the largest sized particles located at the sides came up just a little more rapidly than the unfertilized ones but when powdered fertilizer was employed in the same placement emergence of seedlings was delayed, especially when the soil moisture was high. All the fertilizers seriously delayed the appearance of plants aboveground when they were mixed with the soil below the seed and those of intermediate size appear to have done so to a greater extent than those of either the largest or smallest size.

Table 14.—*Number of cotton plants appearing aboveground per 50-foot row when fertilized with complete mixtures of various particle sizes*

Fertilizer			Norfolk very fine sandy loam, planted Apr. 17, 1931			Norfolk coarse sand, planted Apr. 24, 1931			Cecil sandy clay loam, planted May 1, 1931		
Number [1]	Screen mesh size	Placement	Apr. 29	May 6	May 19 [2]	May 4	May 11	May 22 [2]	May 10	May 13	May 23 [2]
No fertilizer		Bands 1.5 inches to each side—2 inches below level of seed.	203±11	221±12	169±11	354± 8	345±11	276±10			
16	5 to 10		224± 7	216±10	167± 8	358± 8	335±10	281±11			
17	10 to 20		196± 8	186±10	144± 8	354±10	326± 9	259±12			
18	20 to 40		161± 8	155±12	118± 9	324± 7	318± 8	259±10			
19	40 to 80		158±10	150±12	120±10	316± 7	302± 7	242± 8			
20	Through 80		166±10	162±12	129±11	320± 6	306± 3	263± 5			
No fertilizer		Mixed with soil below seed	155±16	192±20	140±15	268± 8	241± 7	217± 6	123± 6	395±11	430± 7
16	5 to 10		29± 7	54±14	31± 8	217±15	279±10	216±10	74± 6	282± 9	304±10
17	10 to 20		36±12	52±16	33±11	107±15	178±11	128± 7	67± 8	312±13	326±11
18	20 to 40		8± 2	21± 5	13± 3	174±16	225±15	185±14	64± 6	335±12	345±11
19	Through 80		15± 3	35±10	25± 7	180±13	245±12	211±14	69± 8	344±11	338± 7
20			31± 8	60±16	42± 8	118±15	190±16	144±13	77± 7	362± 7	399± 8
No fertilizer		Bands 1.5 inches to each side—2 inches below level of seed.	203±11	221±12	169±11	354± 8	345±11	276±10	148±10	429± 6	443± 5
21	Superphosphate 5-10.		140±18	175±22	141±19	316± 7	318±11	255±16	145± 1	417± 3	433± 5
22	Superphosphate 20 to 40.		132±14	173±21	137±18	321±11	313± 9	258±12	133± 6	408± 5	430± 5
23	Superphosphate through 80.		131±17	169±21	134±19	352±18	344±13	292±14	135± 5	410± 4	413± 6
		Bands 3 inches to each side—2 inches below level of seed.	Planted Apr. 14, 1932			Planted Apr. 21, 1932					
			Apr. 25	May 2	May 12 [2]	Apr. 30	May 6	May 16 [2]			
No fertilizer			213±9	306±8	348±4	173±17	441±10	586±5			
24	5 to 10		230±4	355±3	360±3	192±25	443±10	554±6			
25	20 to 40		223±9	341±7	363±3	214±21	452±12	581±6			
26	80 to 150		223±5	323±5	346±4	210±22	473±15	599±6			
31	5 to 10		203±5	310±4	348±3	155±17	412± 8	559±5			
32	20 to 40		202±8	307±6	346±4	146±17	443± 6	574±6			
33	80 to 150		195±7	286±6	327±4	168±15	414±10	548±6			
			Planted Apr. 18, 1933			Planted Apr. 21, 1933					
			May 2	May 9	May 16 [2]	May 3	May 12	May 20 [2]			
No fertilizer			372±12	503±5	511±4	248±10	369±6	321±9			
27	2 to 3		381± 7	494±5	489±4	241± 8	387±4	361±5			
28	5 to 10		385± 4	505±2	513±4	285± 8	384±5	365±4			
29	20 to 40		365± 7	506±5	513±5	280± 8	404±4	382±5			
30	80 to 150		379± 6	507±5	516±4	282± 6	406±5	388±4			
34	5 to 10		377± 5	500±6	510±5	299± 8	422±4	395±4			
35	20 to 40		376± 5	510±3	514±4	268± 7	396±3	371±4			
36	80 to 150		365± 7	483±4	492±4	254±10	386±6	365±7			

[1] For particulars about the fertilizers see tables 7 and 8.

[2] The final counts include only living plants.

TABLE 15.—*Soil moisture at planting and rainfall during first 6 weeks after planting and during period from April 1 to October 1*

Year	Norfolk very fine sandy loam			Norfolk coarse sand			Cecil sandy clay loam		
	Soil moisture	Rainfall		Soil moisture	Rainfall		Soil moisture	Rainfall	
		First 6 weeks	Apr. 1–Oct. 1		First 6 weeks	Apr. 1–Oct. 1		First 6 weeks	Apr. 1–Oct. 1
	Percent	*Inches*	*Inches*	*Percent*	*Inches*	*Inches*	*Percent*	*Inches*	*Inches*
1931	9.63	7.38	23.09	5.30	4.69	20.37	12.41	10.47	21.98
1932	9.78	4.23	25.26	3.60	2.48	23.10	.....	.....	.....
1933	7.94	5.80	20.13	7.92	3.75	17.11	.....	.....	.....

After the third count the plants were thinned to a stand of two to the foot wherever possible. The final stand at picking time was practically perfect wherever the fertilizer was applied at the sides but was broken wherever it was mixed with the soil below the seed.

Table 16 presents the total yields of seed cotton. In most cases these are the sum of three separate pickings.

TABLE 16.—*Yields per acre of cotton from fertilizers with grains of various sizes*

Fertilizer no.[1]	Size of particles, screen mesh	Norfolk very fine sandy loam		Norfolk coarse sand		Cecil sandy clay loam	
		Narrow bands to each side of seed, 2 inches lower level	Mixed with soil below seed	Narrow bands to each side of seed, 2 inches lower level	Mixed with soil below seed	Narrow bands to each side of seed, 2 inches lower level	Mixed with soil below seed
1931							
		Pounds	*Pounds*	*Pounds*	*Pounds*	*Pounds*	*Pounds*
No fertilizer		818±67	361±41	244±17	352±15	658±25	633±32
16	5 to 10	1,492±64	608±65	640±32	544±18	...	1,014±28
17	10 to 20	1,355±48	305±73	552±24	503±17		982±22
18	20 to 40	1,558±56	265±48	578±26	498±17	...	960±10
19	40 to 80	1,285±42	414±84	517±21	570±30	...	956±16
20	Through 80	1,540±84	554±75	534±20	524±13	...	957±17
21	Superphosphate 5 to 10	1,087±101	...	512±27	...	982±25	...
22	Superphosphate 20 to 40	1,077±87	...	564±27	...	956±21	...
23	Superphosphate through 80.	1,221±92	...	605±22	...	991±25	...
1932							
No fertilizer		1,791±47	...	159±15	...	...	...
24	5 to 10	1,895±47		671±34	...		
25	20 to 40	1,841±46	...	721±33	...		
26	80 to 150	1,932±47		734±24			
31	5 to 10	1,829±29		537±37	...	...	
32	20 to 40	1,906±26		598±41	...		...
33	80 to 150	1,810±38		600±38			
1933							
No fertilizer		1,792±30	...	123±19	...	...	...
27	2 to 3	2,139±30	...	668±23	...	...	...
28	5 to 10	2,138±32	...	637±26	...	...	...
29	20 to 40	2,053±35	...	740±21	...	...	...
30	80 to 150	2,156±40	...	705±24	...	...	...
34	5 to 10	2,110±30	...	365±31	...	...	...
35	20 to 40	2,084±27	...	444±32	...	...	...
36	80 to 150	2,183±45	...	540±32	...	...	...

[1] For description and analyses of fertilizers see tables 7 and 8.

In 8 of the 13 trials using grained fertilizers the smaller than 80-mesh particles produced the highest yields and 7 of these 8 occurred in 1932 and 1933. The largest sized grains were best in this respect in 3 of the 5 remaining tests, all of which happened to be in 1931. In a majority of the tests the intermediate-sized particles gave poorest yields.

The differences in yield in nearly all of these 13 tests is from 3 to 6 times as large as the probable error, and similar tests gave consistent results as a rule. It may be concluded, therefore, that the differences in yield in general are due to differences in the size of the fertilizer particles, but the significance of individual determinations should be interpreted with caution for it is possible by chance for one average to be 3 times the probable error too high and another in the same test three times the probable error too low, although extreme cases of this kind are not likely to happen often.

Two or three individual determinations are not consistent with the others. If these are assumed to be erratic and due to uncontrolled variance, it is clear that two factors are operating, one to make the little particles most efficient in increasing yields and the other favoring the big grains. Both appear to operate simultaneously, but the latter appears to have been more important in 1931 and the other far more influential in 1932 and 1933. This fact suggests the possibility of weather conditions being involved.

Table 15 gives the rainfall during the first 6 weeks after each planting and for the entire growing seasons. There is a very close correlation between the amount of rainfall during the first 6 weeks and the different results in different seasons, although the total rainfall is essentially the same in each season. During 1931 the rainfall was above normal during the first 6 weeks after planting at each of the three points in this experiment. In 1 week, immediately after planting, 7.7 inches of rain fell on the Cecil soil. This unusually heavy rainfall on the Cecil soil may account for the largest particles producing the largest yields on this soil. In both 1932 and 1933 the rainfall during the month immediately after planting on the Norfolk coarse sand was only about half of the normal amount. In these cases the largest particles of both fertilizers were poorest and the smallest best in increasing yields.

In the case of the dry-mixed fertilizers the one containing the smallest sized superphosphate was most efficient in each of the three trials and in both of the Norfolk soils decidedly more so.

When only the size of the superphosphate particles was varied the tendency for the smallest to be most effective in increasing yields was much more marked than when the size of all the ingredients was varied in the grained fertilizers. This fact seems to indicate that some other ingredient of the mixture was more efficient in larger particles. The soil analyses show that nitrogen disappeared very rapidly under the conditions of these experiments from particles of all sizes but most quickly from the little ones. On the other hand the phosphoric acid was undoubtedly more readily available to the plants from the smallest particles but the soil analyses show that very little loss of P_2O_5 from leaching could have occurred in any case. These differences between phosphates and nitrogenous salts may be the explanation for maxima at both ends of the yield curves in some cases. No experiments were conducted in which the sizes of the nitrate or the potash particles were varied while those of the other materials were held constant, but such tests would be of value.

GENERAL DISCUSSION

The problem of what size of particle is preferable in the manufacture of fertilizers is very complicated. Even if the best size for every phase of fertilizer efficiency were definitely known the problem would still be involved because there are so many phases. The best size for one purpose may be bad for another and it is difficult to evaluate the relative importance of each.

Without doubt the most important consideration is the ability to increase crop yields under average conditions. Under the conditions of these experiments the smallest sized fertilizers used increased yields most, but there were indications that a combination of small superphosphate and large nitrogenous particles would be better in years of heavy rainfall. These observations are entirely consistent with the conclusions of Conner (*3*) and of Chucka and Lovejoy (*2*) but much more work with various crop, soil, placement, and climatic conditions needs to be done before this phase of the problem can be considered as solved.

In the present experiments the fertilizer was applied uniformly, but many of the machines used by farmers apply fertilizers irregularly. Mehring and Cumings (*10*) have shown that fertilizers are at least half again as efficient when uniformly applied as when distributed in the manner typical of many commercial distributors. Most farm implements cannot apply pulverized fertilizers uniformly but, as a rule, do a fairly good job with granular materials.

Reasons for avoiding powders are: That they are more difficult to distribute uniformly; they absorb more moisture from the air, and do it more rapidly; they show a much greater tendency to cake; they are dusty in dry weather and sticky in damp weather; they are wasteful and annoying to distribute in windy weather; they are bulky and require larger sacks and more storage room; they sometimes sift through burlap sacks, and in general are more disagreeable to handle than granular materials.

On the other hand powdered materials do not segregate when mixed, while mixtures consisting mostly of large particles may segregate badly. Aside from the misunderstandings that arise when the control chemist analyzes such mixtures, segregation is very undesirable from the standpoint of the consumer because if a certain ratio of the plant-food elements is best for a crop under any given set of conditions and a segregating fertilizer is used of even the best composition to meet these conditions, nevertheless very few of the plants in the field will get the plant food needed for optimum results. Segregation can be prevented by grinding the mixture finely enough to pass through a 200-mesh sieve. Grinding fertilizers to this fineness, however, is difficult, and produces an undesirable product in other ways. Fortunately other methods are available for preventing or greatly minimizing segregation. For example, it has been found that when all the ingredients for a mixture are ground together rather than separately the lightest material is comminuted most because density and hardness usually vary together. This treatment greatly reduces the tendency to separate. When all the well-mixed components are cemented together, as by basing or graining operations, separation through handling of the mixture is impossible.

At present prices the average cost of the plant food in the grained fertilizers used in these experiments would be $9.86 per acre. The average difference in yield of cotton resulting from the use of the 80- to 150-mesh fertilizers over that obtained with 20- to 40-mesh in 13 tests was 59 pounds per acre, by itself worth at present prices about $7, or nearly as much as the total cost of the fertilizer. The dry-mixed fertilizers with 5- to 10-, 20- to 40- and through 80-mesh superphosphate produced 269 ± 16,[3] 301 ± 5, and 375 ± 17 pounds more cotton per acre, respectively, than the unfertilized checks. The difference of 106 pounds between the yields with the largest and smallest superphosphate particles is highly significant and at 12 cents per pound is alone worth $12.72, or considerably more than the entire cost of the fertilizer.

It will be recalled that the average 16- to 20-percent superphosphate examined in this study contained only 38.8 percent of material finer than 80-mesh and that the average double superphosphate contained less than 20 percent.

It does not seem desirable at present to grind and screen fertilizers to definite sizes as special operations, because this would add unnecessarily to the cost of manufacture. In the process of making commercial fertilizers, however, certain grinding and screening operations are necessary and in many cases it will be a simple matter to substitute another mesh screen for one already in use or to adjust the crushing and grinding equipment so as to prepare the bulk of the material in the grain size that appears likely under the circumstances to be most efficient.

SUMMARY

A study was made of the effects of size of particles on the properties and behavior of fertilizers during preparation and use. In the field tests nonsegregating fertilizers with grains ranging in size from 2- to 3-mesh to 80- to 150-mesh, and dry-mixed fertilizers with the superphosphate particles only varying in size, were applied accurately and uniformly to cotton in 3 soil types for 3 seasons in South Carolina. Of the grained fertilizers 80- to 150-mesh particles produced highest yields in a majority of the 13 trials. The smallest superphosphate particles were best in every test, and the average difference in yield as between the smallest and largest particles was alone more than enough to pay for all the fertilizer used. Chemical analyses were made on the soil to which the fertilizers had been applied to determine differences in leaching and change in solubility of the fertilizer elements. Laboratory tests were also made to determine the present range of particle size in typical fertilizers and the effects of particle size on various properties of fertilizers and their behavior during handling and distribution.

The average mixed fertilizer consists almost entirely of material that will pass through a 5-mesh and be held on a 200-mesh screen. No significant difference in the distribution of particle size exists between various classes of mixed fertilizers. Double superphosphates

[3] These probable errors have been corrected to eliminate as much as possible the variance due to factors other than particle size.

appear to be composed of coarser particles on the average than ordinary superphosphates.

Small particles of fertilizer adsorb moisture from the air and tend to cake more readily than large ones.

Apparent density varies with the size distribution of fertilizer particles, and therefore the size of bag required to hold a given weight of substance depends upon its particle-size distribution.

Segregation of fertilizer mixtures is caused largely by differences in the sizes of the grains of the different components. Segregation occurs to a slight extent in most commercial mixtures during shipment and application to the soil. In most cases this is so slight as to be of little consequence, but in 1 of the 10 mixtures tested the composition changed seriously during distribution. Regrinding a segregating mixed fertilizer a little finer considerably reduces segregation.

Nitrogen, potash, and total soluble salts were found to be removed from the placement area in the soil in greater proportion as the size of the particles diminished. Nitrogen disappeared relatively much more rapidly than other soluble salts.

Decrease in the size of fertilizer particles containing phosphates was followed by greater reversion of P_2O_5 to insoluble forms in the loam soils and by disappearance of larger quantities of total P_2O_5 from the immediate zone of application in the coarse sand soil.

Large fertilizer particles in side placements under the conditions of this work slightly hastened emergence of plants and powdered fertilizers delayed it. When mixed with the soil below the seed all sizes usually found in commercial fertilizers delayed germination.

Finer than 80-mesh superphosphate grains applied in a band were decidedly superior to very coarse ones in increasing yields of cotton, but large grains of readily soluble nitrogenous materials were better in this respect than small particles of the same substance.

The most efficient particle size under the average circumstances encountered in this study with grained fertilizers was 80- to 150-mesh.

LITERATURE CITED

(1) ALEXANDER, J.
1929. COLLOID CHEMISTRY; THEORETICAL AND APPLIED. V. 2, illus. New York.

(2) CHUCKA, J. A., and LOVEJOY, D. B.
1933. MACHINE-APPLIED POTASH TEST. Maine Agr. Expt. Sta. Bull. 369: 533.

(3) CONNER, S. D.
1934. EFFICIENCY OF PHOSPHATE FERTILIZERS AS AFFECTED BY DISTRIBUTION IN THE SOIL. Amer. Fert. 81 (10): 9, 20, 22.

(4) ——— and ADAMS, J. E.
1926. AVAILABILITY OF TENNESSEE RAW ROCK PHOSPHATE IN RELATION TO FINENESS AND OTHER FACTORS. Jour. Amer. Soc. Agron. 18: 1103–1107.

(5) CUMINGS, G. A., MEHRING, A. L., SKINNER, J. J., and SACHS, W. H.
1933. MECHANICAL APPLICATION OF FERTILIZERS TO COTTON IN SOUTH CAROLINA, 1931. U. S. Dept. Agr. Circ. 264, 32 pp., illus.

(6) HAIGH, L. D.
1927. VARIATIONS IN FERTILIZER SAMPLES DRAWN BY OFFICIAL METHODS. Jour. Assoc. Off. Agr. Chem. 10: 222–227.

(7) HANCE, F. E.
1934. CHEMISTRY. Hawaiian Sugar Planters' Assoc. Expt. Sta. Rept. 1933: 46–63.

(8) LYON, T. L.
1931. RELATIVE EFFECTIVENESS OF LIMESTONE PARTICLES OF DIFFERENT SIZES. N. Y. (Cornell) Agr. Expt. Sta. Bull. 531, 13 pp., illus.

(9) MEHRING, A. L., and CUMINGS, G. A.
1930. FACTORS AFFECTING THE MECHANICAL APPLICATION OF FERTILIZERS TO THE SOIL. U. S. Dept. Agr. Tech. Bull. 182, 96 pp., illus.

(10) ——— and CUMINGS, G. A.
1932. EFFECTS ON COTTON OF IRREGULAR DISTRIBUTION OF FERTILIZERS. Jour. Agr. Research 44: 559–570, illus.

(11) SMITH, G. F., HARDY, L. V., and GARD, E. L.
1929. THE SEGREGATION OF ANALYZED SAMPLES. Indus. and Engin. Chem., Anal. Ed. 1: 228–230, illus.

(12) TRUOG, E.
1930. THE DETERMINATION OF THE READILY AVAILABLE PHOSPHORUS OF SOILS. Jour. Amer. Soc. Agron. 22: 874–882.

(13) ——— and MEYER, A. H.
1929. IMPROVEMENTS IN THE DENIGES COLORIMETRIC METHOD FOR PHOSPHORUS AND ARSENIC. Indus. and Engin. Chem., Anal. Ed. 1: 136–139, illus.

(14) WALKER, R. H., BROWN, P. E., and YOUNG, A. W.
1932. SOME CHEMICAL AND BACTERIOLOGICAL EFFECTS OF VARIOUS KINDS AND AMOUNTS OF LIME ON CERTAIN SOUTHERN IOWA SOILS. PART I. LABORATORY AND GREENHOUSE EXPERIMENTS. Iowa Agr. Expt. Sta. Research Bull. 148, 120 pp., illus.

ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

Secretary of Agriculture	HENRY A. WALLACE.
Under Secretary	REXFORD G. TUGWELL.
Assistant Secretary	M. L. WILSON.
Director of Extension Work	C. W. WARBURTON.
Director of Personnel	W. W. STOCKBERGER.
Director of Information	M. S. EISENHOWER.
Director of Finance	W. A. JUMP.
Solicitor	SETH THOMAS.
Agricultural Adjustment Administration	CHESTER C. DAVIS, *Administrator.*
Bureau of Agricultural Economics	A. G. BLACK, *Chief.*
Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief.*
Bureau of Animal Industry	JOHN R. MOHLER, *Chief.*
Bureau of Biological Survey	J. N. DARLING, *Chief.*
Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Bureau of Dairy Industry	O. E. REED, *Chief.*
Bureau of Entomology and Plant Quarantine	LEE A. STRONG, *Chief.*
Office of Experiment Stations	JAMES T. JARDINE, *Chief.*
Food and Drug Administration	WALTER G. CAMPBELL, *Chief.*
Forest Service	FERDINAND A. SILCOX, *Chief.*
Grain Futures Administration	J. W. T. DUVEL, *Chief.*
Bureau of Home Economics	LOUISE STANLEY, *Chief.*
Library	CLARIBEL R. BARNETT, *Librarian.*
Bureau of Plant Industry	FREDERICK D. RICHEY, *Chief.*
Bureau of Public Roads	THOMAS H. MACDONALD, *Chief.*
Soil Conservation Service	H. H. BENNETT, *Chief.*
Weather Bureau	WILLIS R. GREGG, *Chief.*

This bulletin is a joint contribution from

Bureau of Chemistry and Soils	H. G. KNIGHT, *Chief.*
Division of Fertilizer Investigations	C. H. KUNSMAN, *Chief.*
Bureau of Plant Industry	FREDERICK D. RICHEY, *Chief.*
Division of Soil Fertility Investigations	O. SCHREINER, *Principal Biochemist, in Charge.*

U. S. GOVERNMENT PRINTING OFFICE: 1935

For sale by the Superintendent of Documents, Washington, D. C. - - - - - - Price 5 cents

END