SVERIGES GEOLOGISKA UNDERSÖKNING

SER. C. Avhandlingar och uppsatser. N:o 450

ÅRSBOK 36 (1942) N:o 7.

SOIL CONSOLIDATION.

SOIL-SETTLING PROCESS

BY

SIMON JOHANSSON

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STOCKHOLM 1943
KUNGL. BOKTRYCKERIET. P. A. NORSTEDT & SÖNER
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Content.

Introduction.

The processes that cause a decrease in the pore-volume of the soil and a degeneration of its structure are mainly of two kinds, elutriation, when soil materials suspended in the gravitational water settle in pores and fissures and fill them more or less, and soil-settling, when the aggregates are pressed together by the weight of the soil.

I have studied both these processes but intend here to give an account mainly of an investigation of the soil-settling process. As the extent of these processes depends upon the stability of the aggregates, I will first give a brief summary of investigations of the soil structure and aggregate stability.

Soil structure and aggregate stability.

Soil structure and soil porosity, which are both influenced by the settling process, have been intensely studied during the last decennia. There are two kinds of porosity, one dependent on the distribution of the soil particles of various sizes or on the soil texture as demonstrated by mechanical analysis, and one where the pores are of a larger order, being the interspaces between isolated lumps of soil or aggregates, and cracks and channels made by worms and the roots of plants. The former kind of porosity is usually called capillary porosity after DOJARENKO, and the latter kind noncapillary porosity. NIKIFOROFF (13) has proposed the terms textural and structural porosity, which, indicating the nature of the porosity, seem better to me than those previously used.

The fineness of the textural pores determines the capillarity of the soil, and the pore-volume together with the fortuitous swelling determines such an important matter as the water capacity of the soils. The structural porosity is considered to influence the permeability to water and air, the root-penetration, and the retention of moisture in the soil. To a certain degree it also influences the fertility of the soil and thus indirectly affects the biological and chemical reactions (14).

In spite of these characters so very important to the cultivation of plants, the structural porosity has been studied closely only during the last few years, this mainly due to the variable nature of the soil structure, which even during the vegetation period is highly influenced by natural processes and, as regards cultivated soil, also by the cultivation (1) and manuring (10). The consequence is that the structure of cultivated soil is highly variable from place to place and a large number of parallel samples must be examined and statistically treated, making the structural examination extremely time-wasting.

Russian soil-scientists have long distinguished and described in detail different structural forms characteristic for different climates. These works have generally been considered to be of purely academical interest. In recent years close studies of the colloid-chemical and physical processes active in forming the aggregates, especially those carried out by SIDERI (15) and TYULIN (16), have actualized the Russian investigations and structural studies in general. Especially in the U. S. A. structural studies are now carried out on a large scale, since it has been demonstrated that the capability of the soil quickly to absorb great rainfalls is dependent on the structural pores, rainfalls which, if drained superficially, would cause devastating water-erosion. The resistance to wind-erosion is also quite different when the soil-particles form aggregates to what it is when they are separated and resemble pulverous and fugitive dust.

Under certain circumstances stable aggregates are formed which do not disperse in water. The fertile Russian *tjernozem* is a classic example of a soil of such a stable structure. By oxidation of the organic substances, promoted by the climate, especially huminnic acids generate, which according to SEDIRI unite with the clays in the soil to stable aggregates which do not swell in water. From a colloid-chemical point of view they are irreversible colloids.

The Russian soil-scientists mentioned are of opinion that the weathering process in a podzolic climate mainly produces humic acids soluble in water, which are not able to form stable aggregates. Sesquioxides being present, humic acids can, however, form irreversible colloids, according to TYULIN, and this may be the explanation of the existence of certain soils of stable structure even in our podzolic climate. The stable structures in »gyttja» and clay-»gyttja» are well-known in our country. Cracks caused by the drying out of these soils have been characterized as permanent cracks and the aggregate structure is so predominant in them, that they have been named »grain» clays. If these soils are subjected to unsuitable cultivation, the lumps of soil formed can become as hard as bone with a high water-resistance.

By oxidation after draining the soil the great quantity of sulphides resulting from the »gyttja» is oxidized to acid sulphates of iron and aluminium, which together with the humic acids formed by the oxidation of the organic substances form compounds difficult to disperse. Evidently there exist conditions suitable for the formation of the stable aggregates called »grains», consisting of humus, sesquioxides and clay-substance, though the actual mechanism forming the »grains» is not known.

In our clays, especially the heavy clays, these soils are often after the frozen ground thawing in the spring found to be of a grainy structure formed when the soils froze. Several investigations of this phenomenon have already been carried out, lately by S. ERIKSSON (4), who has studied the formation of aggregates and its dependence on the original moisture content, on the packing, and on frequent freezings. The experiments were performed in laboratories with kneaded clay samples and the results, therefore, cannot be directly transferred to soils in nature, this especially due to the fact that when kneading plastic soil samples discontinuity surfaces always arise, on which ice-crystallization preferably sets in. The roentgenograms presented in his work illustrate these surfaces in a beautiful way but the ice-crystallization has played only a secondary rôle at their formation.

Theoretically, the drying up of a clay ought to have a similar effect on the formation of aggregates as has freezing. During the drying up the moisture content decreases more rapidly near the surface than deeper down, and this results in tension, which may produce visible cracks or invisible discontinuity surfaces which the water moistens and easily pervades, bursting the body of clay. If during the drying the moisture content has decreased beyond a certain point (the *omslag*-point), further drying brings about a slight shrinkage only, while the adjacent deeper layers above the *omslag*-point shrink fairly quickly. In this case an especially strong tension causing cracks arises in the boundary layer. The heavier a clay is, the slower is the transport of water from one layer to another. The moisture content, therefore, rapidly increases with the depth and a strong tension arises between the layers due to shrinkage, resulting in cracking.

Drying up caused by the transpiration of plants must be still more effective. In view of the fact that the water absorption of the plants is effected by numerous roothairs distributed throughout the whole layer, cracking caused thereby must be more detailed than the cracking caused by the more even drying by evaporation.

The aggregates formed, whether by freezing or by drying up, are, however, of an ephemeral nature. In water they swell and disperse more or less quickly. They are also called false aggregates.

The aggregates in the shape of large and small clods or lumps obtained when tilling a consolidated soil are of the same nature; they are really only fragments of the consolidated body or of larger lumps and have nothing in common with the true aggregates (8).

The aggregates formed in this way by natural physical processes or by the cultivation of the soil are, as stated above, but little stable. Besides a usually small quantity of concretionary grains of ferric oxide these false aggregates are the common type in our ordinary clay soils and a study of them is of great practical interest. Which size of aggregates is most favourable for the vegetation during its different stages of development and under different climatic conditions, what cultivation is best to obtain this favourable situation, and how are the aggregates to be preserved against degeneration? These questions illustrate the great compass of these studies and at the same time indicate their practical value. Whether the investigations will lead to more rational methods of cultivation remains to be seen, but in any case they are expected to lead to a deepened knowledge of the influence of the different methods of cultivation on the soil and vegetation.

Much work has been done, especially in the U. S. A., in order to find out ways and means to increase the stability of the aggregates, but the results have so far been of little practical value. A small effect has been obtained by mixing the soil with organic material and particularly such of lucerne and clover (9). A greater effect, however, has been obtained by stimulating the bacterial activity by the addition of sucrose. The bacterial secretion produced is sticky and can at least for some time have a cementing effect on the aggregates (10). Liming has no or very little effect; in many cases the lime even had a negative influence. The good effect of lime on the soil structure demonstrated in practice has not been verified by laboratory experiments. The dispersing effect of the hydrophilous Na-ion has long been known. It has also been shown that soil with a low pH-content is more stable than soil with a higher one, this due to the relatively small water-combining capacity of the H-ion (2).

Several investigations have proved that soil under permanent grass has a better structure than cultivated soil, the former containing a larger percentage of relatively stable aggregates. The soil with a protecting cover of plants is less exposed to the destructive effect of the rain-drops than a bare soil, and furthermore the aggregates of the uncultivated soil are surrounded with a net of root-hairs or myceliums of aspergillus which all naturally protect against dispersion.

When the soil is tilled the existing aggregates are mechanically crushed by the implements and the permeability thus produced is soon reduced either by soil-settling or by loosened particles accompanying the sinking rain-water and settling here and there in the hollows. In both cases a consolidation or a reduction of the porevolume takes place, resulting in a reduced permeability. The stabler the aggregates the less apparent will these processes be and the better will the soil preserve the permeability once obtained.

Several investigations have been made of the structural porosity of the soil. This porosity can be found by determining the volume of solid soil substance in a certain soil volume with its natural structure preserved. The remaining volume is then the sum of the textural and structural pore-volumes. The textural part is then determined from the water-capacity of the soil (field capacity). Or, in a certain volume of soil the volume of the air-filled pores is determined directly with the aid of the air-pycnometer, the soil having been saturated with water corresponding to the field capacity. The saturation method used gives, however, a greater value than the field capacity.

In this way we ascertain the absolute structural pore-volume but not the size-distribution of the pores. Experiments of various kinds have been carried out to ascertain that distribution but without results of practical value. Instead the size-distribution of the aggregates is nowadays determined in the same way as the primary particles are divided into size-classes by mechanical analysis. But the method suffers from certain disadvantages. The aggregates are washed clean of primary particles by submersion in water a certain number of times or by rinsing. In this way aggregates of a certain stability are obtained though the degree of stability is arbitrarily chosen and the treatment cannot be said to correspond to the effect of the rainfall on the soil. Generally the natural agents are not so active.

During a rainfall the textural pores are filled with water and as the rain-water percolates down essentially through the structural pores the aggregates then absorb additional amounts of water and swell.

The swelling, however, is a fairly slow process and only proceeds as long as percolating water is present, that is in general during the rainfall, provided the permeability of the soil is good. When sufficiently softened the aggregates are pressed together by the weight of the soil and the textural pore-volume is decreased. This process is called soil-settling, and it is essentially this process that densifies the surface soil, giving it a poor structure.

The other soil-densifying factor, elutriation, is of importance only during heavy rainfalls. The rain-drops then strike the aggregates on the soil surface and soil material is suspended in the rain-water, subsequently settling either on the surface, if the soil cannot absorb the water at the same rate as it falls, or under the surface, filling up the structural pores.

Soil-settling.

In an investigation of the two soil-densifying processes, soil-settling and elutriation, they should if possible be studied isolated from each other, as determinations of the alterations to which the volume-weight of the soil is subjected give the effect of them both. Soil-settling as a separate process is, however, easily measurable and such investigations have been carried out *inter alia* at Rothamsted.

In one of the Rothamsted monographs, »The physical properties of the soil» (9), Keen has published an investigation on the settling of a clay soil which had been treated by rotary cultivation and had consequently got a very loose and mellow structure. The settling-curve (Fig. 1) gives the settling of a seven-inch-deep surface soil during a period of 65 days and shows a fast settling in the beginning and after 30 days an asymtotic approach of 0. The soil surface had then settled more than 2 inches. The curve has a smooth course and seems to be independent of the rainfalls during the period, which, however, are not stated.

If already after 30 days a cultivated soil has reached the limit of settling, the settling-factor ought to be eliminated after this time and a subsequent soil consolidation can then be ascribed to the sedimentation in the structural pores of material suspended in the gravitational water.

Considering this I have earlier made a series of determinations of the volume-weight at different depths in order to obtain a quantitative estimate of the verti-

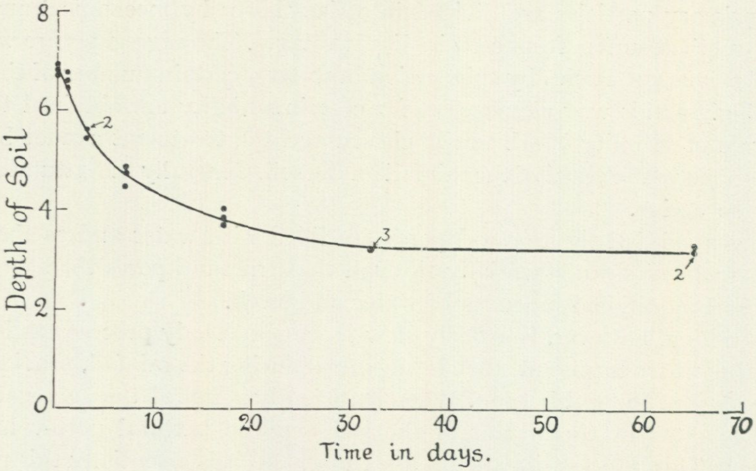

Fig. 1. Consolidation with time of tilth on rotary-cultivated soil. Reprinted from Rothamsted Monographs.

cal transportation of soil material. During these studies I have found that this process plays but a limited part in the consolidation of the soil, which must essentially be ascribed to the settling process. Generally the deepest layers of the surface soil were found to have the greatest volume-weight. Evidently the soil-weight presses together the swollen and softened aggregates and the greater the pressure the more are they pressed together, so that theoretically the deeper layers settled more than the top-soil.

In order to verify this theory I have measured the soil-settling layer by layer in the surface soil. These investigations were carried out in the autumn of 1941 at Klagstorp, in the district of Kåkind in Västergötland. The soil at Klagstorp is known to elutriate easily, as is true of the silt loam in general in that district.

Geologically, the loam is an ice-lake clay with a variable clay content at different levels. At the more clayish levels it displays brown or reddish brown layers — winter layers — alternating with layers of a light and strongly silty texture — summer layers. Curiously enough the summer layers are sometimes absent and there are only winter layers which easily split along the bedding planes when the clay dries. In connection with the land elevation and the draining of the sediments an intensive soil-flow (solifluction) has occurred, traces of which are often discovered in ditch-digging in the shape of layers set up edgewise even in fields that are now plain. Flowing and dispersion are characteristic features of the type of soil to which silt loams belong.

Table 1 shows the results of a mechanical analysis of two soil samples, A and B, the settling of which has been measured, and of two subsoil samples from different depths at A. The subsoil at B was of the same kind as at A.

The grain-distribution shows no decided maximum in any size-group. The samples display no great difference in mechanical composition, all belonging to the silty clay loams. It is remarkable that there is no difference as regards clay

Table 1. Mechanical analysis of surface soil from A and B and of subsoil from A.

Fraction mm	Surface soil %		Subsoil from A %	
	A	B	24—29 cm	29—34 cm
20—6	1.9	—	—	—
6—2	4.0	1.2	6.3	2.1
2—0.6	2.9	3.0	4.4	3.1
0.6—0.2	12.3	17.6	13.5	11.9
0.2—0.06	13.3	20.4	9.3	6.7
0.06—0.02	16.7	13.3	20.2	26.8
0.02—0.006	16.2	12.8	18.6	17.8
0.006—0.002	10.6	8.9	5.6	4.3
<0.002	22.1	22.8	22.1	27.3
Ignition loss	5.0	5.3	2.5	2.5
Hygroscopicity (weight per cent)	4.6	4.5	4.2	3.7
Organic matter	3.0	3.3	0	0

content between surface soil and subsoil. It might be expected that the clay content of the surface soil would have decreased due to elutriation, but that is evidently not the case. The transportation of soil material that undoubtedly occurs from the surface soil to the subsoil does not consist of a separation of clay materials but includes the whole material, as has earlier been shown, *inter alia* by American scientists. The transportation is performed »bodily».

Upon treating the soil samples with Tamm's reagent preparatory to mechanical analysis, the samples prove to contain fairly large quantities of sesquioxides. The soil has accordingly a reddish colour. Material from the reddish ferric-oxide-rich Visingsö sandstone, deposited in the Vättern-depression to the east, has probably been mixed with the sediment, which has resulted in a higher sesquioxide content in the soil than is otherwise common. Some concretionary aggregates of sesquioxides are also to be found. Air-dried samples of soil, left in water for 24 hours, dispersed completely into primary particles. But the soil having been moistened before submersion, the aggregates had a much higher stability.

The experiment was arranged as follows: The surface soil was removed from a piece of land 0.5 m in diameter, so that the surface of the subsoil was laid bare. The depth of the surface soil was the same as the plough-depth. The earth dug up was mixed and visible parts of plants were removed before the earth was replaced layer by layer in the hole. In the centre of the hole a brass net, 5 cm in diameter and with a slender rod soldered to its centre, was placed on the surface of the subsoil. The rod was long enough to reach over the soil surface and was encased in a glass tube, so that it was movable in the earth without friction. Part of the earth dug up was then replaced and planed to a bed of uniform thickness. On this bed four wire nets were placed with rods protected by glass tubes, as described above. A total of four layers with four measuring-points each were arranged as outlined. The measuring-points were placed according to a fixed plan, so that all the nets were as far as possible from each other (fig. 2). They were numbered according to the number of the quadrant in which they were placed, an index being added to indicate the order of the layer on which they were resting. E. g. measuring-point I_3 indicates that the point is situated in the first quadrant and on the third soil-layer counted from the surface.

All measurements were referred to the rod in the centre resting on the subsoil surface. This was made a fixed point, as any elevation or settling of the surface of the subsoil must influence the various layers of the surface soil to the same degree.

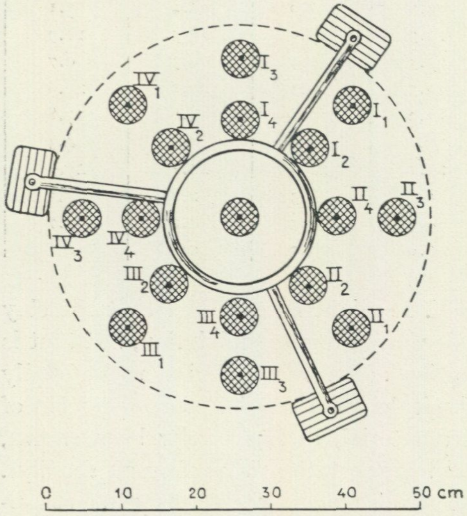

Fig. 2. The position of the measuring-points (cross-ruled circles) and the plane-ground ring. The Roman figures denote the number of the quadrant and the index figure added shows the order of the corresponding soil-layer. 1 : 10.

The measurements were made from the surface of a steel-rule resting on a plane-ground steel-ring supported by three removable feet supplied with setscrews and reaching so far, that the feet could be placed on wooden blocks on firm soil outside the area. The steel-ring was levelled with the aid of the setscrews. Special measuring rods of known length were used to measure the distance from the surface of a plane-ground steel-rule placed over the ring to the end of the rods placed in the soil. The measuring rod was inserted through holes bored in the rule suited to the thickness of the rod so that it obtained a vertical position. A stop-cylinder placed over the measuring rod and resting upon the surface of the rule determined the length to be measured, which was then done with a nonius with an exactness of 0.01 cm.

The length of the rods embedded in the soil being known, the exact position of the nets can be measured and the exact depth of the soil on which rests the net in question can be ascertained.

Table 2 shows the position of the various measuring-points above the subsoil surface for the two stations A and B.

The table also shows the thickness of each layer, which is the difference between the average depths of two consecutive levels. These figures are used when calculating the settling percentage of the different layers. At the two stations the corresponding layers have approximately the same thickness. The thickness of layer 3 is about double that of the others.

The measurements were made in Sept. 1941, generally every two days, and were continued to the end of the month. In contradistinction to August, September was very dry with only two rainy periods with in all but 16 mm rain. A final reading was made in the middle of October after three

Table 2. Depth of surface soil under each measuring-point, cm.

Layer No.	Station A.						Station B.					
	Measuring-point				Average	Layer thickness	Measuring-point				Average	Layer thickness
	I	II	III	IV			I	II	III	IV		
1	24.9	24.1	23.0	24.4	24.1	6.1	24.0	24.0	25.0	24.5	24.4	6.4
2	18.3	17.6	17.3	18.6	18.0	4.6	17.8	17.4	18.1	18.7	18.0	4.1
3	13.5	13.4	13.2	13.6	13.4	9.4	14.2	13.1	13.3	15.0	13.9	9.4
4	4.0	3.8	4.1	4.0	4.0	4.0	4.7	3.9	4.1	5.1	4.5	4.5

days of rain, in all 17.9 mm. This last reading was made by Mr. ERIK VÄRINGER.

Close to the two stations a small piece of ground, now a stubble-field after the oat harvest, was dug in the same way as at the stations. From these places samples of soil were taken to determine the moisture content in different layers of the surface soil, it being assumed to be very much the same here as at the respective stations.

The stations were in different fields; station A in a field which in the previous year had been a fallow and then sown with winter-wheat, which, however, had been destroyed during the cold spring. After harrowing, the field had been sown with oats. The field selected for station B had in the previous year yielded spring-corn too. Though the soil is mainly of the same kind in the two places the surface soil at A was considerably denser and harder than at B. The dug soil at A was therefore cloddier than at B, where it was more crumbly. A determination of the weight of soil per unit (100 c.c.) of the undug soil yielded the figures in Table 3. They are means of nine parallels.

Table 3. Weight of soil in gr per 100 c.c. of non-dug soil at A and B.

Depth cm	A	B
0 — 2.5	119±1.2	121±1.4
2.5— 5.0	124±1.2	121±1.2
5.0— 7.5	135±3.3	123±1.4
7.5—10.0	141±1.5	125±1.4

The apparent volume-weight of the soil at A increases considerably with the depth while the weight of the soil at B is almost constant.

For the dug up ground the corresponding mean weights for the whole layer of surface soil were 117±1.8 at A and 106±1.1 at B. These figures will also give the approximate soil weights at the measuring-points when the measurements were started. The digging mellowed the soil to a high degree, more at B than at A.

Before giving an account of the settling, a few words will be said of the climatic conditions just before and during the experiments as well as the variations in the humidity of the soil, which conditions have proved to be decisive as regards soil-settling.

In August the long summer drought was broken by an unusually rainy period with rain almost every day till the last day of the month, when a total of 135 mm had fallen. At the beginning of September the rainy period was over, and the only rainy period in September was between the 6th and 15th. After some small showers on the 6th, 7th, 9th and 10th, when in all 2.4 mm had fallen, a shower on the afternoon of Sept. 11th yielded 5.0 mm. On the following days, the 12th and 13th, only small showers fell, in all 2.0 mm, and the rainy period ceased on the 14th, the weather that day being misty with repeated showers. However, only 6.5 mm fell during the day.

After this last rain dry weather reigned until October 12th when it was succeeded by rain. During three days, October 12th—15th, 17.9 mm fell.

Table 4. Weight-percentage of water at A and B.

Depth cm	Dug ground										Undug ground	
	A					B					A	B
	3/9	10/9	12/9	15/9	21/9	5/9	11/9	12/9	15/9	21/9	19/9 $n = 9$	22/9 $n = 9$
0 — 2.5 . . .	22.8	21.7	23.5	25.2	18.0	20.5	21.8	23.4	23.9	19.5	23.2±0.14	22.6±0.35
2.5— 5.0 . . .	24.1	22.6	25.1	26.4	21.7	22.9	23.2	25.4	25.6	21.7	23.6±0.21	22.4±0.26
5.0— 7.5 . . .	25.6	23.1	25.8	26.3	22.8	23.7	23.9	26.1	26.3	22.9	23.8±0.19	22.8±0.15
7.5—10.0 . . .	25.1	23.5	25.8	27.3	22.9	24.1	23.6	26.1	27.3	23.1	23.9±0.14	22.9±0.13
10.0—12.5 . . .	25.6	24.5	26.6	26.6	23.2	24.4	24.0	25.5	26.7	24.1		
12.5—15.0 . . .	25.9	27.3	24.4	27.3	22.2	24.4	25.1	24.7	27.4	23.7		
15.0—17.5 . . .	25.4	23.6	23.2	26.8	24.9	24.6	24.5	24.9	28.5	23.6		
17.5—20.0 . . .	25.9	23.8	23.8	26.4	24.5	24.5	25.1	24.1	27.4	22.9		

Table 4 is intended to give a picture of the moisture content of the different layers of the soil during the period. The figures are, however, only single values and determined in a volume of 196.6 c.c. Dug in this way a soil must be very heterogeneous; also as regards humidity the figures give a general idea only.

When dug on Sept. 1 after the continuous rainy weather the soil at A must have had a moisture content equal to its field capacity. The percentages shown in the table for A on Sept. 3 are in the deeper layers somewhat less than 26 per cent. The field capacity is undoubtedly somewhat higher. Owing to evaporation during the digging and the following days the moisture content must have decreased somewhat. The readings of Sept. 10 disclose a decrease in the moisture content, which is evident also in the deeper layers. This loss of moisture evidently occurred before the beginning of the rainy period, thus before the 6th or 7th, the evaporation then being compensated by rain.

The next reading at A was made on Sept. 12, the day after a rain of 5.0 mm. The figures in this column show that 5.0 mm of rain was not enough to moisten the whole surface soil. The rain scarcely penetrated deeper than 15 cm, under which level the moisture content is the same after the rain as before. In the thoroughly moistened layers the moisture content has increased to about 26 per cent. After the rain and by the time the reading was made the upper layers have dried somewhat.

The figures of Sept. 15, the day after a rainfall of 6.5 mm or together with the rain of the two previous days 8.5 mm, show that the quantity was nearly sufficient to moisten the whole layer of surface soil. An increase in the moisture content above that obtained on Sept. 12 in the layers then moistened can now be established. The field capacity is apparently not a constant, but varies with the duration of the rain, with the moisture content of the subsoil or more exactly with its capillary potential. The decreasing water-content of the bottom-layers indicates that these layers, especially that under the 20 cm-level, have not reached their full capacity.

At the last reading on Sept. 21 dry weather had prevailed for 6 days and meanwhile the soil had dried a little, the drying also this time including the deeper layers, which must be ascribed to capillary absorption by the subsoil.

The moisture content of the soil before and after the rain of 17.9 mm in October was not determined, my field-work having to be accomplished by the end of September. But it may be assumed that also after that rain the whole surface soil was moistened. As is well-known, evaporation decreases as autumn advances and it is quite possible that the rain really was sufficient to moisten the whole layer. Considering the local density of the soil, we may calculate that the rain was enough to increase the moisture content of the surface soil by an average of 8 per cent.

Regarding the contemporary moisture conditions at B the variations correspond to those at A, and it is thus only necessary to state that no drying was here observed in the deeper layers during the first period from the beginning of the experiment to the time when the rain set in. On the contrary, it is quite possible that the bottom layer nearest the subsoil absorbed some water from the latter, as the soil, which had not been dug until Sept. 4, had dried somewhat, especially in the upper layers. After replacing the dug soil, when the brass nets, etc., had been installed, relatively dry earth thus lay on top of the moist subsoil and there is a possibility that water was absorbed from the latter. This process is, however, not definitely reflected in the figures of the moisture content, but the possibility is mentioned in order to afford an explanation of the fact that the settling measurements here indicate a swelling of the soil in the deepest layer. It is remarkable that the evaporation in a fairly short time is mirrored even down to 10 cm, which accentuates the good capillary conductivity of the soil.

As it was of interest to know to what extent the digging of a soil preserves the moisture in the soil, examinations were made of undug ground at corresponding levels, though not deeper than 1 dm (*cf.* Table 4 »Undug ground»). Comparing these figures with those from dug ground and from the reading of Sept. 21 we cannot find the digging, i. e. the mellowing of the soil, to have preserved the moisture, but rather the contrary, at least to a depth of 5 cm.

Table 5. The settling and elevation (—) of the different measuring-points in mm. Station A.

Date	I_1	II_1	III_1	IV_1	M_1	I_2	II_2	III_2	IV_2	M_2	I_3	II_3	III_4	IV_3	M_3	I_4	II_4	III_4	IV_4	M_4
Sept.																				
1	—1.2	—2.2	—3.2	—1.0	—1.9	—2.1	—1.4	—1.3	—1.5	—1.6	—1.2	—0.3	—1.1	—1.9	—1.1	—0.3	—2.4	—0.2	—1.2	—1.0
4	0.6	0.8	1.4	0.0	0.7	0.4	0.1	0.6	0.4	0.3	0.3	0.6	0.9	0.9	0.7	0.1	0.0	0.3	0.2	0.2
5	0.9	0.1	—	—	—	0.7	0.4	0.9	0.8	0.7	0.8	0.9	0.6	1.1	0.9	—0.1	0.3	—0.6	—0.1	—0.1
7	1.1	0.8	—0.2	—0.1	0.4	0.7	0.5	0.9	1.0	0.8	0.7	0.9	0.7	0.8	0.8	—0.4	—0.2	0.5	0.1	0.0
9	1.2	1.3	—0.4	0.3	0.6	0.9	0.7	0.9	1.2	0.9	1.1	0.8	0.6	0.9	0.9	0.2	—0.4	0.1	0.1	0.0
10	1.2	0.6	—0.1	0.8	0.6	1.1	0.6	1.2	1.1	1.0	1.1	0.8	0.8	1.3	1.0	0.0	—0.2	0.4	0.4	0.2
12	1.9	0.3	2.9	1.5	2.3	1.4	1.8	3.3	1.6	2.0	0.7	0.9	3.3	1.5	1.6	0.1	—0.1	1.0	0.6	0.4
13	2.2	3.3	2.8	1.5	2.5	1.7	1.9	3.3	1.6	2.1	1.4	1.2	3.4	1.6	1.9	0.0	—0.1	0.7	0.4	0.3
15	8.7	10.8	9.4	9.7	9.6	9.9	9.3	10.7	9.8	9.9	8.3	6.8	9.9	10.1	8.8	0.4	0.6	2.2	1.7	1.2
16	9.0	10.1	9.6	10.1	9.7	9.3	9.1	10.7	10.0	9.8	8.3	7.0	9.7	9.7	8.7	0.3	0.9	2.2	1.7	1.3
18	9.3	10.5	10.0	10.2	10.0	9.5	9.5	11.1	10.3	10.1	8.5	7.0	10.2	10.1	9.0	0.6	1.0	2.2	2.0	1.5
20	9.5	10.7	10.1	10.2	10.1	9.8	9.5	10.9	10.4	10.2	8.1	7.3	10.1	10.0	8.9	0.2	0.9	2.2	1.7	1.3
23	9.9	11.0	10.7	10.7	10.6	10.0	9.7	11.5	11.0	10.6	8.9	7.5	10.5	10.8	9.4	0.4	1.2	2.6	1.9	1.5
25	10.1	11.0	10.6	10.8	10.6	10.1	9.8	11.4	11.0	10.6	9.2	7.7	10.2	10.5	9.4	0.4	1.1	2.3	2.0	1.5
27	9.9	11.0	10.9	10.7	10.6	9.9	9.8	11.4	11.0	10.5	9.2	7.6	10.4	10.6	9.5	0.5	1.9	2.3	2.0	1.7
30	9.7	11.0	10.8	10.7	10.6	10.0	10.1	10.9	10.9	10.5	8.4	7.5	10.3	10.5	9.2	0.2	1.0	2.4	1.8	1.4
Oct.																				
16	10.7	12.0	11.5	11.6	11.5	9.8	10.7	10.9	10.9	10.6	9.6	8.8	10.8	10.7	10.0	0.6	1.3	2.3	1.8	1.5

Table 6. The settling and elevation (—) of the different measuring-points in mm. Station B.

Date	I_1	II_1	III_1	IV_1	M_1	I_2	II_2	III_2	IV_2	M_2	I_3	II_3	III_3	IV_3	M_3	I_4	II_4	III_4	IV_4	M_4
Sept.																				
5	1.0	0.3	0.3	0.7	0.6	0.5	0.7	0.3	0.4	0.5	0.0	0.7	0.2	0.0	0.2	0.3	0.6	1.0	0.1	0.2
7	1.1	0.4	0.0	1.1	0.6	0.9	1.0	0.4	0.5	0.7	0.4	1.7	—0.2	0.3	0.6	0.4	—0.6	0.6	—0.1	0.1
9	1.3	0.1	0.2	1.1	0.7	1.1	0.7	0.1	0.6	0.6	0.6	0.7	—0.9	0.3	0.2	0.5	—1.1	—0.3	—0.2	—0.3
10	1.0	—0.1	—0.6	0.3	0.2	0.7	0.6	—0.1	0.4	—0.4	—0.7	0.2	—0.7	—0.0	—0.3	—0.2	—1.5	—0.4	—0.5	—0.7
12	1.5	0.3	—0.3	1.2	0.7	1.2	1.2	0.3	0.7	0.9	—0.3	0.8	—1.0	0.3	—0.1	—0.2	—1.4	—0.4	—0.4	—0.6
13	1.9	0.5	0.3	2.1	1.2	1.4	1.0	0.6	1.5	1.1	—0.1	0.5	—0.5	0.9	0.2	0.2	—1.8	0.0	0.3	—0.4
15	9.1	5.8	6.7	11.6	8.3	8.9	7.7	7.3	10.0	8.5	7.5	5.5	4.6	9.4	6.8	2.3	—0.7	1.3	3.6	1.6
16	9.3	5.7	6.7	11.9	8.4	9.1	8.4	7.7	11.2	9.2	7.6	5.4	4.3	9.1	6.6	2.3	—0.4	1.1	3.6	1.7
18	9.4	5.8	7.1	12.0	8.6	9.1	8.0	7.9	11.3	9.1	7.7	5.5	4.3	9.4	6.8	2.3	—0.5	1.2	3.5	1.6
20	10.0	6.6	7.8	12.7	9.3	9.5	8.4	8.4	11.8	9.5	8.1	5.7	4.9	9.7	7.1	2.6	—0.2	1.6	4.2	2.1
23	9.8	6.6	7.9	12.8	9.3	9.6	8.5	8.4	11.8	9.6	8.1	5.6	4.7	9.9	7.1	2.6	—0.3	1.5	3.9	1.9
25	10.6	4.0	7.0	10.9	8.1	9.9	8.1	8.1	11.6	9.4	8.7	5.6	4.0	9.7	7.0	2.9	—0.2	1.7	3.8	2.1
27	10.4	5.4	7.9	11.3	8.8	9.9	8.9	8.4	11.9	9.8	8.2	6.1	5.0	9.7	7.3	2.6	—0.1	1.8	4.0	2.1
30	10.2	5.5	7.8	10.9	8.6	9.9	8.7	8.9	11.7	9.8	8.1	5.9	4.9	9.6	7.1	2.3	—0.2	2.0	4.0	2.0
Oct.																				
16	10.4	6.9	7.9	12.1	9.3	10.3	10.1	9.5	12.3	10.6	8.0	6.5	6.4	10.4	7.8	2.6	—0.4	2.3	3.8	2.1

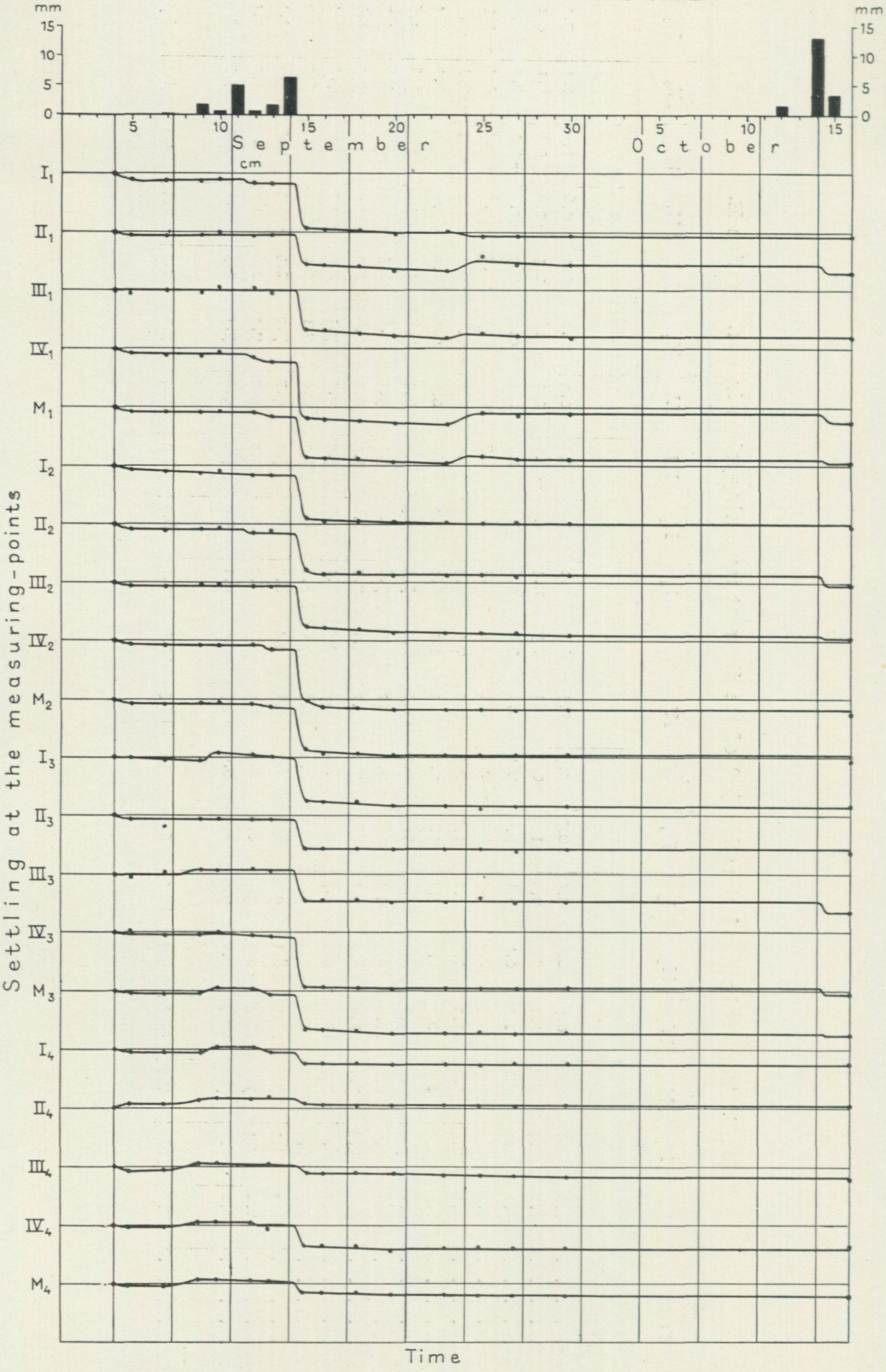

Fig. 3. Graphic reproduction of Tab. 5. The piles at the top denote the size of the rainfalls. For the depth of the soil under each measuring-point see Table 2. The paper is cross-ruled in cm.

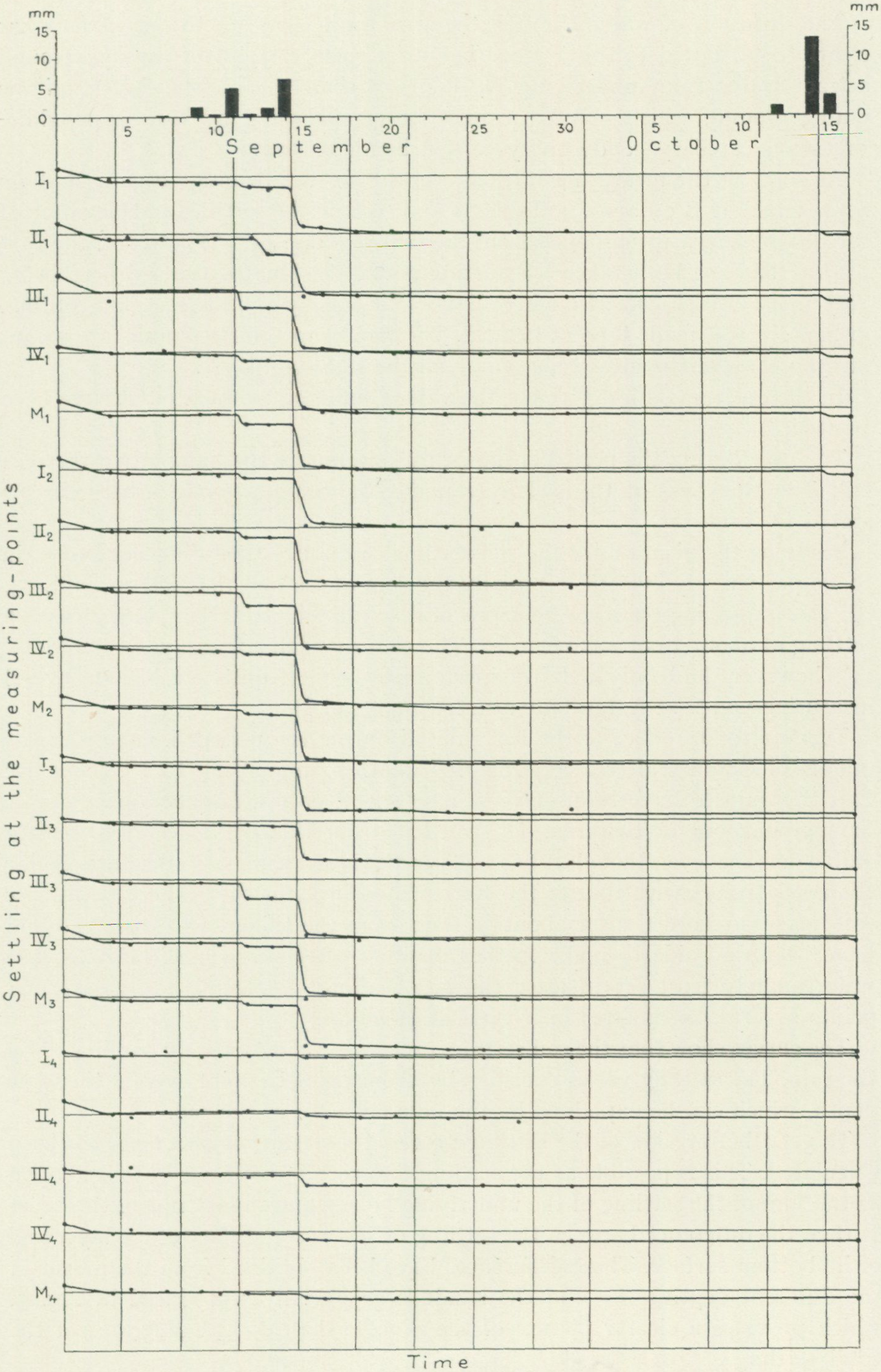

Fig. 4. Graphic reproduction of Tab. 6. For legend see Fig. 3.

The diffusion of water through the structural pores up to the surface has clearly contributed to the drying. The drier surface layers of the dug ground attract water from underlying layers more than the moister layers of the undug ground, which, maybe, cannot be compensated by the supposed decrease in capillary conductivity caused by mellowing.

As soon as the measuring-stations were ready the readings began, at A on Sept. 1 and at B on Sept. 4. Tables 5 and 6 show the settling and elevation of the different measuring-points from the first reading. For A, however, the first reading has not been taken as starting-point, this due to the soil here being very moist, which caused an irregular settling, 0—3 mm. The second reading, of Sept. 3, was made 0-point instead. The figures in the M-columns are means of the values of the measuring-points on the same soil-layer.

In the diagrams, Figs. 3 and 4, the values obtained for each point have been plotted.

The rain during the period is shown by columns at the dates when the rain fell. The thickness of the soil-layer under the respective measuring-points is stated in Table 2.

Studying the diagrams of the soil-settling, we notice the influence of the rain to be particularly evident, especially the rain of 6.5 mm that fell on Sept. 14. All the measuring-points were more or less influenced and in many cases a settling of about 1 cm was recorded. The rain that fell a few days earlier (Sept. 11), however, had only a fairly insignificant effect, quite visible at several measuring-points at A, but only at a few points at B.

Turning to the effect of the last rainfall during the period, i. e. that of the middle of October after a month's dry weather, amounting to 18.9 mm, we find this rain to have been of very little effect, only a few measuring-points having sunk one or two mm. The soil once consolidated, it seems to remain stable and this even though it has not yet attained its densest structure. So far the result agrees with that of the Rothamsted investigation, where no further settling was recorded after about 30 days from the tillage. Of course it would have been desirable to make further readings after subsequent rainfalls, but unfortunately frost set in after the last reading, displacing the measuring-points several centimetres in a vertical direction.

The curves show that the soil-settling process is almost entirely dominated by the rain. The settling varies considerably from point to point even at the same depth, which can be explained by the heterogeneity of the soil.

To get a better view of the settling process the settling of each layer has been calculated. This is possible as the settling of a certain level can be looked upon as the sum of the settling of the underlying layers, and the settling of this layer is then the difference between the settling of the upper surface of the layer and of its bottom surface. These differences have been obtained from the means of the different depth-series and the result is graphically reproduced in Fig. 5, which provides a clearer picture of the process than do the diagrams of the total settling.

It should be observed, however, that although the settling can be deter-

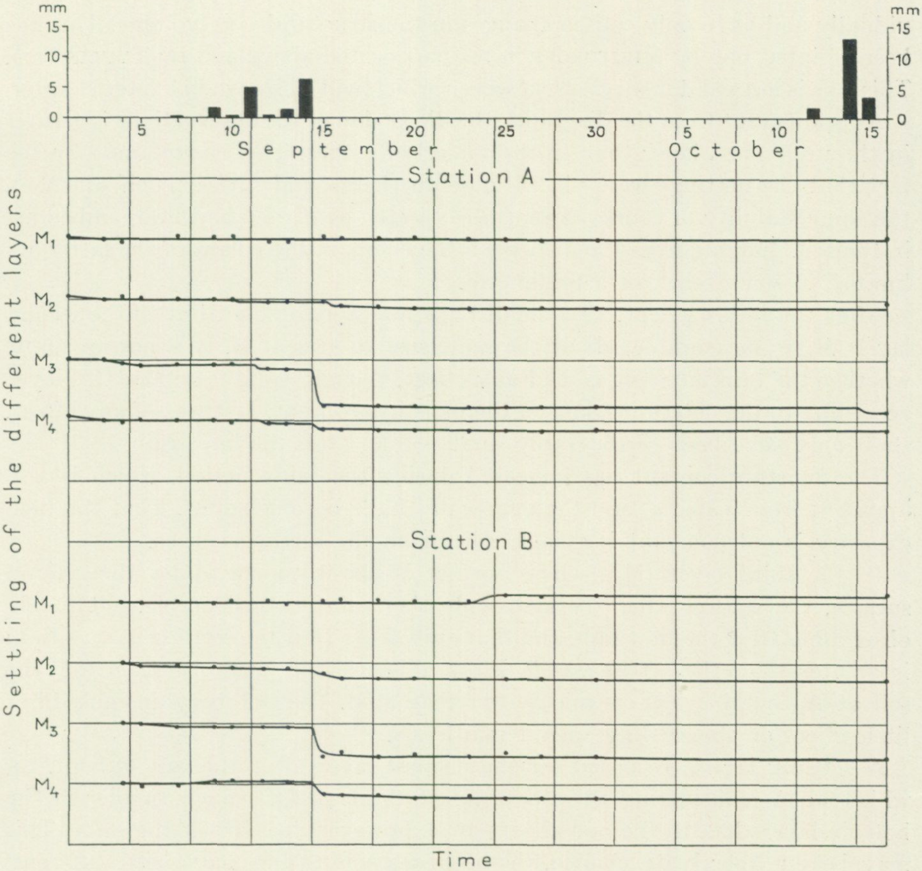

Fig. 5. Settling of the different layers. For depht and thicknes of the layers see Table 2.

mined with great accuracy at each measuring-point, the settling of a certain layer calculated from the mean for only 4 points of observation is nevertheless impaired by a certain error on account of the heterogeneity of the soil, which is also demonstrated by the different values for the settling obtained at the individual points in spite of their lying on the same layer.

First of all the surprising fact is disclosed that the surface layer at A as well as B, has been influenced neither by the dry weather nor by the rain. At B the surface layer shows a sudden rising on Sept. 25 in the middle of a dry period, no reasonable cause being known of. The two measuring-points concerned (see fig. 4) have been dislocated in some way or other, perhaps by worms.

Shrinkage and swelling of the soil, caused by variations in the moisture content, which may have amounted to 10 per cent in the superficial layers, have not produced any change in the external volume. The volume-changes of the soil have instead been internal. The aggregates have swollen and shrunk individually and have only caused changes in the structural pore-volume. This has been pointed out by NIKIFOROFF in his paper cited above and by TYULIN (17). This rule is not valid in all cases, however, which will be shown in a later chapter.

As is apparent from the diagrams, the dispersion of the observations is greater in the uppermost layer than in the underlying ones. This is explained by the fact that the nettings were placed loose on the ground surface itself, and then the same stability of course cannot be expected as if they had been embedded in the soil. Judging from the dispersion the errors in the means of the latter are limited to some tenth of a millimetre.

After the rain on Sept. 14 a small but quite apparent settling of the second layer (M_2) is measurable, about the same size at A as at B. It is not apparent whether the rain on Sept. 11 had any effect, though it did penetrate this layer according to the determinations of the moisture content. If it was of any effect, that must have been considerably smaller than after the later rain.

The moisture content has increased during the rainy period, which is also apparent from Table 4, and the aggregates have become softer. That the field capacity is not constant is evident also from the settling curves.

In the third layer (M_3), whose surface is about 10 cm under the ground surface, the settling after the last September rain is considerable, but barely observable after the first rain, and that only at A. That the settling at A (6 mm) is greater than the settling at B (4.5 mm) is probably due to the fact that the soil at A contains less organic matter than at B. The October rain caused but little effect on the settling, only 1 mm for A.

A settling is also recorded for the deepest layer after the rain of Sept. 14, which at A, considering the thickness of the layers, is much smaller in the bottom-layer than in the one above; at B, however, it is about the same. This may be due merely to chance, the original packing may have been different, but it is also possible that the rain, which, as an estimate shows, was not more than necessary for saturation of the surface soil, was too scarce at A to compensate the capillary movement of water downwards in the subsoil, which at A may have been somewhat drier than at B.

The October rain had no influence on the stability of the bottom-layers. On the whole this rain was of very little effect, only a small settling being observed in the layers nearest above the bottom-layers (M_3). The soil, however, is far from its densest packing. Once thoroughly moistened and then slightly dried out the soil structure is hardly influenced by a subsequent rainfall. After the first rainy period the aggregates have increased considerably in stability. Thus, it seems as if the first rainfall after the tilling is of the greatest importance for the settling. If the rain had been of a longer duration, the aggregates would have had time to swell more, the field capacity would have increased, the aggregates would have been softer and consequently the settling greater and observable also in higher layers than was now the case.

It is remarkable that this very instable soil, when left untouched for a time, increased its stability to such an extent that the fairly heavy October rain had no noticeable effect. The present observations give but little indication where to seek an explanation. The fact that the soil had already been subjected to a settling process can scarcely in itself have had a stabilizing effect, for in this experiment the soil displayed a settling even as a result of the rain on Sept. 11, which, however, was followed by another and greater effect on Sept. 14. The soil had not been dried out in the meantime and here there is a difference compared with the conditions in October.

It has long since been proved that a plastic clay increases its stability with time from the moment of stirring. This increase lessens with time in a logarithmic regression (5) and it is conceivable that the cohesive forces between the aggregates increase in the same way with time. But it would scarcely appear probable that the effect is of such a size that it was of practical importance in this case. It is more likely that during the drying process the aggregates grow together and form a firm skeleton resulting in increased stability.

During the drought of about a month, when the earth lost some of its moisture, shrinkage must have taken place (cf. Table 4). However, during the latter part of the observation period the curves, even those representing the deeper layers, all go horizontally, in spite of the shrinkage. The shrinkage must thus have been exclusively an internal shrinkage of the aggregates, not manifested externally. The nature of the slight settling that can be observed in most of the curves and that lasted a few days after the pronounced settling on Sept. 14 will be discussed later.

Immediately after the experiment being started pronounced settling occurred in the deepest layers at station A, being especially great in the bottom layer considering its small thickness. Here the earth was saturated with water at the outset, as already stated, and the aggregates were not able to resist the pressure of the soil above. At B the soil was drier and no or only a slight settling took place. Strange to say, the bottom layer here shows an elevation which is difficult to explain. Assuming a swelling of the deepest layer to be the cause, which is the most likely explanation, it is difficult to understand why it has not been possible to demonstrate any swelling caused by the rain.

In order to get a still clearer picture of the relation of the soil-settling to the depth, the settling caused by the rain of Sept. 14 has been presented in fig. 6. To the left the settling of the various measuring-points has been plotted against their height above the subsoil and the continuous lines denote the approximate settling at different depths. On the basis of these lines the settling of the various layers has been obtained from the differences between the size of the settling of the top and bottom surfaces of the respective layers, expressed in per cent of the thickness of the respective layers. The broken lines to the right denote the settling of the various layers in per cent.

At A the settling increases proportionally to the depth from 9 cm below the ground surface to a maximum and then decreases. At 9 cm the soil-pressure has reached the point where the rigidity of the softened aggregates has not been sufficient to resist the pressure and the aggregates have therefore been pressed together. As the depth and thus the soil-pressure increases the compression likewise increases.

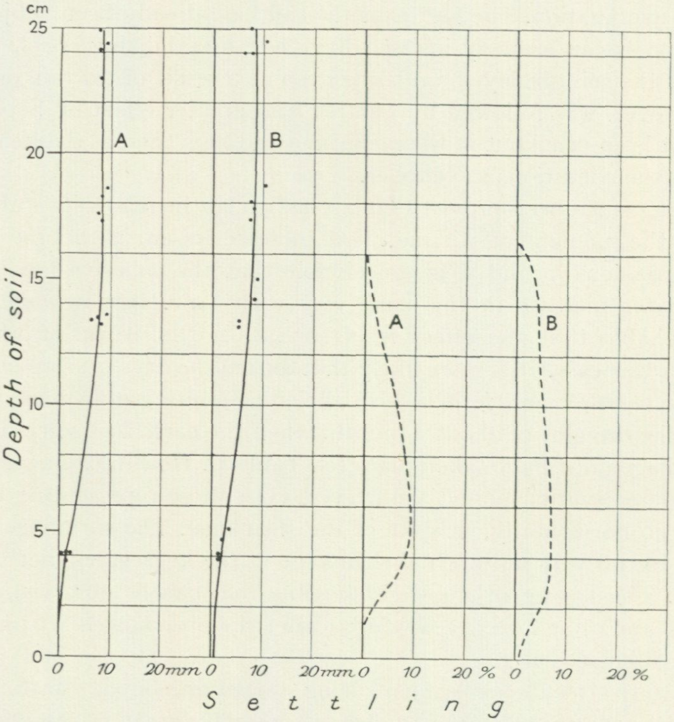

Fig. 6. The curves to the left illustrate the settling at Stations A and B in relation to the depth of the soil after the rainfall of Sept. 14th. To the right these curves are differentiated and the settling is expressed in per cent of the thickness of the resp. layers.

At B the settling begins a little higher, at 8 cm, and then increases to a maximum slower than at A. The decrease in the settling in the deepest layers at both stations is thought to be due to the rain not being sufficient to saturate the whole layer of surface soil. With more rain the soil would probably have shown increasing settling towards the bottom. The soil at B is also slightly richer in humus (cf. Table 1), and consequently has a higher water-capacity and a more stable structure, and therefore the maximum settling is not so great as at A.

It may thus be considered established that it is the deeper layers of the surface soil that first of all are exposed to compression when it has rained. This also agrees with my earlier experience regarding the density of the different layers, and with practical experience. A frequent complaint is that the soil is »hard at the bottom».

Only under very special circumstances can conditions be the reverse. If the whole surface soil has a mellow and stable structure and subsequent tilling breaks the connection between the aggregates in the upper layers only, rain will produce settling only in the tilled layer, which may cause a greater density than that present before the tilling of that layer.

Another very common case may occur during the thawing of the frozen ground. Frost, like tilling, has a mellowing effect upon the structure. If rain falls during the early stages of the thaw, i. e. while the upper layer of the surface soil is thawing, but is followed by dry weather during the later stages, the soil grows dense and hard in the surface layer but mellow at the bottom.

Earlier investigations of the effect of tilling on the structural porosity have proved that the more intensely the soil is cultivated and the more it is pulverized by the implements, the denser will the soil become under the influence of rain, a fact long well-known in practice.

The relatively considerable settling at B demonstrated by the curve above the 10 cm-level can in view of this fact be attributed to the higher degree of disaggregation lent the soil at B by the digging. It has already been emphasized that the soil at B was drier and better crumbled and the aggregates smaller. The water-absorbing surface has consequently become greater. Furthermore the smaller size of the aggregates shortens the distance the water has to travel from the surface to the centre of the aggregates. Small aggregates will consequently swell quicker than big ones and thus more rapidly grow so soft that they are compressed by the existing soil-pressure. Furthermore, small aggregates must be easier to compress than large ones, and this is perhaps the simple explanation of the greater settling of soils of a fine structure. The greater the capillary conductivity of the soil, the less the rigidity of the aggregates and the faster the rigidity decreases as the moisture content increases (low plasticity), the greater will the soil-setting be under the same conditions otherwise.

These qualities are especially predominant in the silt loams. When it rains they easily loose their structure and when they subsequently dry they form a dense and hard mass. Soil-elutriation contributes to a certain degree, the soil material suspended in the gravitational water then settling in and filling the structural pores. The quantitative rôle of this process is not demonstrated clearly by this investigation, which is intended to be a study of the settling-process apart from soil-elutriation. In any case the soil-settling seems to be the more important one of the two densifying factors.

Comparison between the settling of surface soil and subsoil.

The investigations described above were continued also the following summer in the hope of more rain falling than during the previous period of observations. Certain questions also required further elucidation, e.g. the influence of the humus on soil-settling and the part played by elutriation of soil as a densifying factor.

Since the previous measurements were made the apparatus has been readjusted (the grinding of the plane surfaces has been improved) and the errors in measuring are consequently smaller. The long lists of figures obtained in the observations are not being published. The values observed can be seen from the diagrams.

It is a well-known practical experience that an increase in the thickness of the surface soil layer, when subsoil is ploughed up, can produce very detrimental results, which may be felt for a number of years. The damaging effect of the subsoil being ploughed into the layer of surface soil is not only that the concentration of the manures in the surface soil layer decreases but also that the soil becomes more difficult to till, it loses its mellow structure more easily. To study this two parallel series of measurements were started on the surface soil and on the subsoil.

On the site of Station A of the previous year the surface soil was dug up down to the subsoil, as before, and was mixed, whereupon the nets with their rods were placed in the soil on top of the various layers.

The field was now lying fallow after grass. The grass sown the previous year had turned out a failure due to the severe drought and the field had to be ploughed up after an early harvest. The small quantities of grass-stubble and roots remaining were removed.

At another spot not far away the surface soil was removed and in the denuded subsoil there was dug a hole the depth of which corresponded to the thickness of the surface soil layer, which is about 25 cm. Lumps of subsoil were crushed to pieces not larger than a nut so that its structure reminded as far as possible of that of the surface soil. As in the case of the surface soil, the nets were embedded in the subsoil when replaced. The depths of the measuring-points at the two stations are shown in Table 7 below.

When this investigation was started the moisture content of the surface soil was not so great as at the outset the previous year. The moisture content was, however, slightly above the *omslag*-point. Likewise the subsoil was drier than the time before. The rain that had fallen earlier during the summer had

Table 7. Depth of soil under the measuring-points, cm.

Layer No.	Surface soil. Experiment 1				Subsoil. Experiment 2			
	Measuring-point				Measuring-point			
	I	II	III	IV	I	II	III	IV
1	25.5	24.5	25.1	25.2	25.8	26.7	26.0	—
2	21.4	20.6	21.1	20.5	19.9	19.4	19.1	19.3
3	17.3	16.4	19.1	16.3	16.5	16.4	15.7	15.9
4	7.1	7.2	7.0	6.4	5.3	5.0	5.3	5.1

not been sufficient to moisten the dried out subsoil. The surface soil became better disintegrated now, too, and became mellower.

The measurements were started on Aug. 22nd and were continued until Oct. 1st, when a pause was made until Nov. 3rd. On the latter date a new measurement was made after some very heavy rains which fell the last few days of October. During the early part of the period dry weather reigned, except for a few small solitary showers, but on Sept. 15th a week of rains set in, a total of 56.9 mm falling during that period. The reader is referred to the diagrams for detailed data of the rainfalls.

The settling effect of the rain on the surface soil and on the mellowed subsoil is apparent from figs. 7 and 9. If we first study the course of the settling curves for the surface soil (fig. 7), we find that to begin with they were rectilinear, the rain of Aug. 30th (4.4 mm) only having produced settling at a few measuring-points and that not exceeding 1 mm. The rain of Sept. 8th, 7.7 mm, had a somewhat greater effect, and the settling of the bottom layer averaged a little less than 1 mm, which is merely reflected at the higher measuring-points without any settling of the higher layers having occurred.

But during the subsequent rainy period the settling is considerable. Already on Sept. 18th, after 3 days of rain, when a total of 24.9 mm had fallen, the total settling of the whole surface soil layer amounted to almost 2 cm. After a rainfall of 3.5 mm on Sept. 18th a new reading was made which disclosed continued settling. Before the reading was completed (2 measuring-points remained) a heavy shower yielded 6.9 mm in half an hour. As soon as the rain had stopped the readings were renewed. In the short time the soil had settled 2—3 mm, *i. e.* the settling is almost instantaneous and may be looked upon as a sudden collapse when the aggregates have been sufficiently softened.

On the 21st 13.8 mm fell and the reading the day after, when another 6.4 mm had fallen, disclosed a renewed settling, which amounted to about 0.5 cm for the whole surface soil layer. The slight sinking to the following day's figure may be regarded as an elastic after-effect of the previous settling. This will be discussed later.

During the rainy period the settling successively decreased after the same quantities of rain in spite of the rigidity of the aggregates certainly decreasing

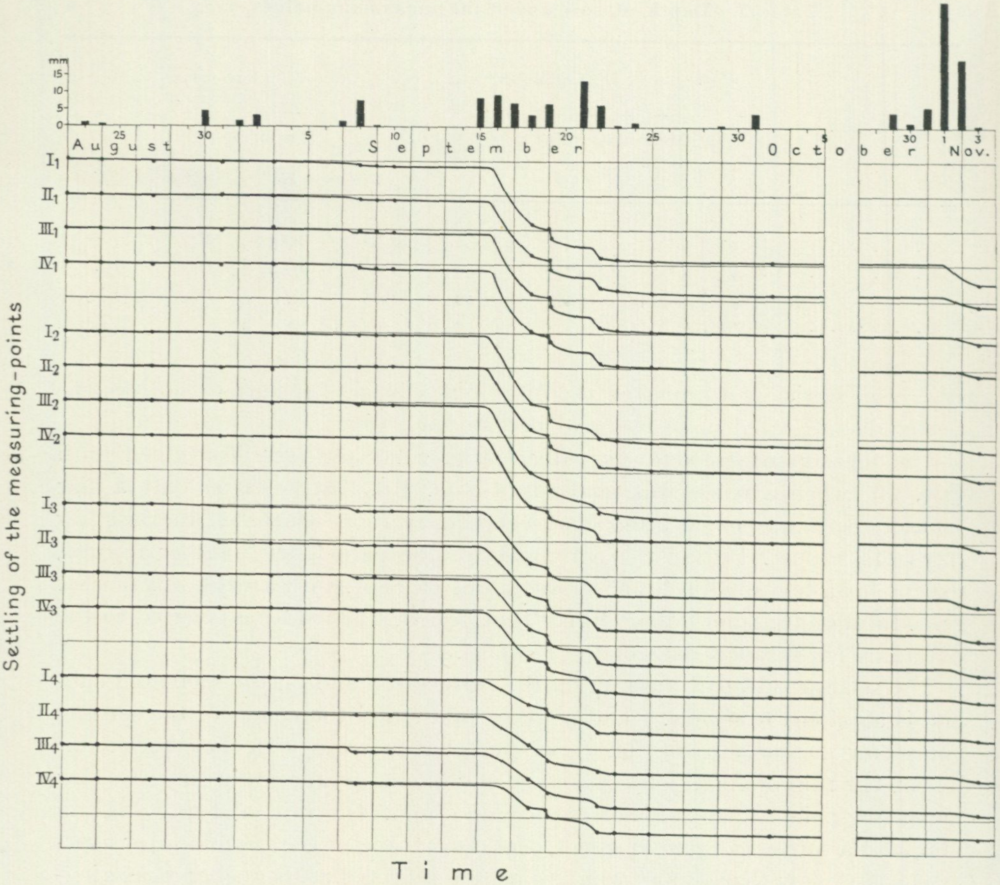

Fig. 7. Settling of the surface soil (Experiment 1) at various depths. For depth of soil under each measuring-point see Table 7.

as the moisture content increases. The stability of the soil naturally increases as the closeness of texture increases and furthermore the decrease in the rigidity of the aggregates produced by the increased moisture content, which is very rapid in the beginning, counting from the *omslag*-point, will grow slower and slower as the moisture content increases. This is an especially characteristic trait of the group of soils to which the soil now considered belongs (7).

The total settling during the rainy period amounted to about 3 cm. The year before, the settling amounted to only about 1 cm. Certainly the difference in the rainfall was considerable, 56.9 mm as compared with 8.5 mm the year before, but the moisture content of the soil was about the same, approximately 27 per cent, so one might have expected the same settling for the two years. That this was not the case is probably mainly due to the fact that during the present year the soil was more porous from the beginning. The soil-weight was less, about 110 g per 100 c. c. as compared with 117 g the year before. But another cause is also imaginable. When the stations were arranged the soil surface was smoothed to the same level as the surrounding ground that had not been spaded. When the spaded ground settled 2—3 cm a depression resulted in the ground surface, and it is very likely that after heavy rainfalls some of the water from the surrounding ground, which did not get time to sink into the ground, ran down into the depression. This is also indicated by certain anomalies in the settling process, which will be further discussed later.

The last reading was made a month later, on Nov. 3rd, after a rainy period lasting five days during which there fell 69 mm of rain. During the interval a total of 19.2 mm of rain had fallen, distributed over 12 days, mainly during the later part of the period. It is probable that the soil was moister at the beginning of the last rainy period than at the beginning of the preceding one, and that the last rainfall produced a greater moisture content in the soil than the first one. At the station in question there now remained some water on the surface. In this case the heavy rain brought about a further settling, but it did not amount to more than about 2.5 mm for the whole surface soil layer. One of the points on the surface, however, displayed a settling of as much as 5 mm. The stabilization that may be expected to be produced by the drying of moistened soil, when the aggregates are united to a solid system, was not quite sufficient to compensate the softening resulting from the increased moisture content. Such a consolidation occurred, what more, already after the rain of Aug. 30th, but the structure was then too loose to be able to withstand the effect of the subsequent rainfall.

It is of interest to study the course of the settling of the various layers of the surface soil during the different periods of rain. Fig. 8 demonstrates the settling in relation to the height above the surface of the subsoil during four different periods. From the surface of the subsoil (the fixed point), which is 25.1 cm below the mean surface of the ground, the height of the measuring-points above the fixed point, i. e. the thickness of the layers of surface soil, has been set off on the y-axis, and the settling observed has been set off on the x-axis. The continuous curves illustrate the mean settling at the various depths during the periods stated. The disperison of the points of observations around these curves certainly appears to be unexpectedly small, but this is of course due to the thorough mixing and crushing of the clods when arranging the station. In soil cultivated in the usual manner the heterogeneity is of course much greater.

During the period Aug. 22—Sept. 10 (Curve A, fig. 8) the total settling was not quite 1 mm, which figure was valid even for the deepest layer, about 7 cm above the surface of the subsoil or 18 cm below the soil-surface. The soil above that level was not influenced by the rainfall. Only the bottom layer could not withstand the soil-pressure.

The heavy rainfalls of the second period resulted in a considerable settling. Curve B illustrates the settling after the rain of the first three days, Curve C the settling for the whole period. The points of observation lie in groups fairly

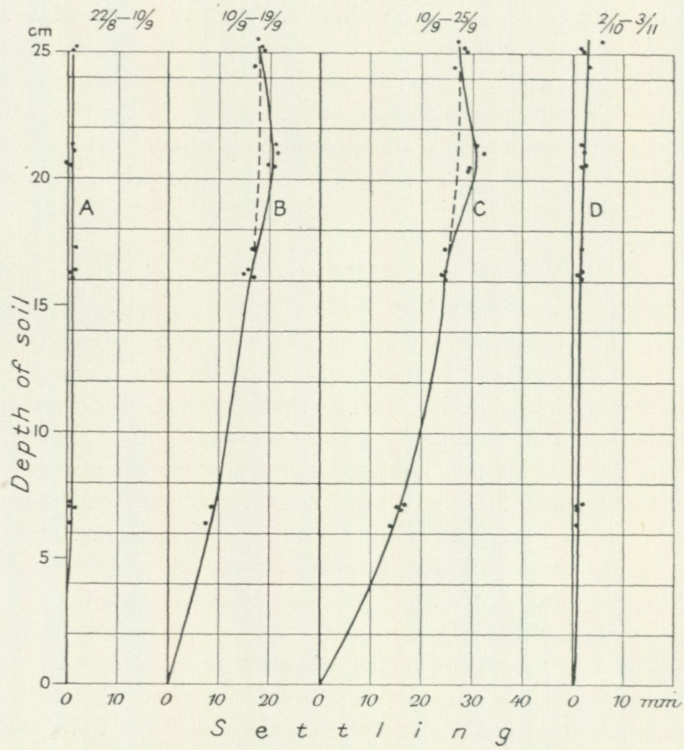

Fig. 8. Settling of the surface-soil (Experiment 1) in relation to depth of soil during the rainy periods indicated at the top of the figure.

close to each other and it can thus not be accidental that the second group counting from the surface, lying about 4 cm below the soil-surface, lies fairly far from a normal curve, which has been denoted by a broken line for the layer in question. The observations disclose a settling that is 3—4 mm too large, which implies that the layer just below the surface layer was abnormally packed. A statistical analysis of the observation material has demonstrated that the difference is statistically sure.

The observation points of the surface group tell of a smaller settling than for the group below. This can only mean that to a depth of 4 cm the surface layer has swollen, not only sufficiently to neutralize any settling that may have occurred, which, however, probably was slight in this superficial and small layer, but also sufficiently to increase the thickness of the layer by about 3 mm. In this case the swelling is not solely of an internal nature, expressing itself in a decrease in the structural pore-volume, but it is mainly external, causing an increase in the total soil-volume. Such an exception from the rule governing a loose soil might be explained by assuming that the structural pores of the surface layer were partly filled by elutriation, and then an increased moisture content would necessarily produce an external swelling, this especially in view of the fact that the soil-pressure is practically nil in the surface layer.

To explain the abnormal conditions both as regards the swelling of the surface layer and the packing of the layer next in order we may assume that as a result of free water remaining on the surface after a heavy rainfall at this locality, the layers just below the surface got a fairly high moisture content. The upper layers are so to speak supersaturated and the rigidity of the aggregates is strongly decreased, which results in a packing of the layers rich in moisture that are subjected to pressure. A corresponding phenomenon is observed when free water collects on the plough-sole in the lower layer of the surface soil, which is then supersaturated with water. As, furthermore, the weight of the whole of the remaining surface soil layer rests upon that layer, it is especially strongly compressed.

During heavy rains, when the soil cannot absorb the rain as quickly as it falls, free water is collected on the surface in the small depressions always present and the layers just under the surface layer will at those places become extra dense, which, however, is not caused by elutriation. The layer in question is at normal sowing depth and if the heavy rain comes just after the sowing, the air cannot penetrate to the sprout. This is the danger of giving the seed-bed to fine a tilth. This danger may also be said to be present, though to a smaller degree, without free water necessarily remaining on the surface, and that is when the rain falls so heavily that it does not run down to the lower layers fast enough to prevent the aggregates from being too greatly softened for the existing pressure.

Curve C illustrates the settling at the end of the rainy period and from its beginning (Sept. 10—25). Compared with Curve B it is considerably displaced towards the right, but this displacement mainly depends on a strong settling of the bottom layer, amounting to as much as 7 mm, during this later part of the period. The lower part of the curve is strongly bent. The packing of the overlying layers decreases successively upwards and is rather slight in spite of the heavy rains. The packing of the layer immediately above the bottom layer is 2 mm; of the layer immediately under the surface layer it is 1 mm. The thickness of the surface layer is unchanged.

It is of interest to estimate the soil-weight per 100 c. c. and the structural pore-volume in the various layers of the surface soil at the end of the first rainy period. This can be done with the aid of the values for the packing of the various layers demonstrated by Curve C, to which must be added the small settling figures obtained at the beginning of the rainy period (Curve A).

The original soil-weight may be assumed to have been approximately the same as that of a sample from a neighbouring plot, which had been spaded in a similar manner. The value there was 110 g per 100 c. c. The moisture content at the end of the rainy period may be assumed to have been 27.5 weight per cent, obtained from the same neighbouring plot. The moisture content is assumed to be the same in the various layers. The specific gravity of the soil-substance has been established to be 2.588. The result is shown in Table 8. The first line in the table shows the settling of the various layers, obtained from Curve C. For the surface layer, where swelling occurred, that is denoted by a minus sign. From these values the soil-weight per 100 c. c. has been calculated and is shown in the second line. For the surface layer the value is fictitious, as elutriation occurred there. In the last line the air volume, i. e. the structural pore-volume, has been calculated after the volume of the soil-substance and that of the original water being subtracted from the total volume.

Table 8. Calculated soil-weight per 100 c. c. and structural pore-volume.

Depth below surface cm	0—4	4—8	3—15	15—20	20—25
Settling mm	—3.0	5.0	5.5	7.8	12.5
Soil-weight g/100 c. c.	(101)	125	118	129	144
Air volume %	(33.2)	17.3	21.8	14.6	4.5

It is remarkable that a soil of this type, of so unstable a structure and in spite of a long rainy period, could retain its original porosity so well. And nevertheless the moisture content increased by several per cent over the *omslag*-point, which was determined to be at 18.3 per cent, the aggregates thus having swollen considerably. It is only the bottom layer, where the aggregates could not resist the load, that was greatly compressed. After the rainy period the deepest and most compressed layer has an air volume calculated to be not more than 4.5 percent. The question then arises whether it is worth while ploughing such a soil to a depth exceeding 20 cm. Very little seems to be gained in the way of mellowing the soil. In the experiment the soil certainly had a fine tilth and was consequently not of a very stable structure, but undoubtedly the soil is frequently, especially when the frozen ground thaws in spring, exposed to far severer conditions than those reigning during the investigation.

Also the subsequent very heavy rainfall at the end of October and the beginning of November, when a total of 57 mm came down in 2 days, had but little effect. The diagram in fig. 7 and still better Curve D in fig. 8, showing the settling between Oct. 2nd and Nov. 3rd, demonstrate that the total settling was only about 2.5 mm. The settling curve is almost a straight line, i. e. the settling was the same in the various layers in spite of the difference in depth. The more compressed a layer is the greater is its rigidity when the rain comes.

The subsoil, which is practically without humus, behaved quite differently, displaying a far greater sensitivity to rain, which is apparent from the diagram, fig. 9. Even the second reading disclosed that solitary measuring-points had settled, a settling that in the bottom layer in some cases amounted to as much as 2 mm. The slight amount of rain that had fallen in the meantime can of course not have had any influence, and the settling must have been caused by some originally labile aggregates sinking together.

The rainfall of Aug. 30th, which may have had some influence on the surface soil, produced no effect on the subsoil, but the rain amounting to 7.7 mm

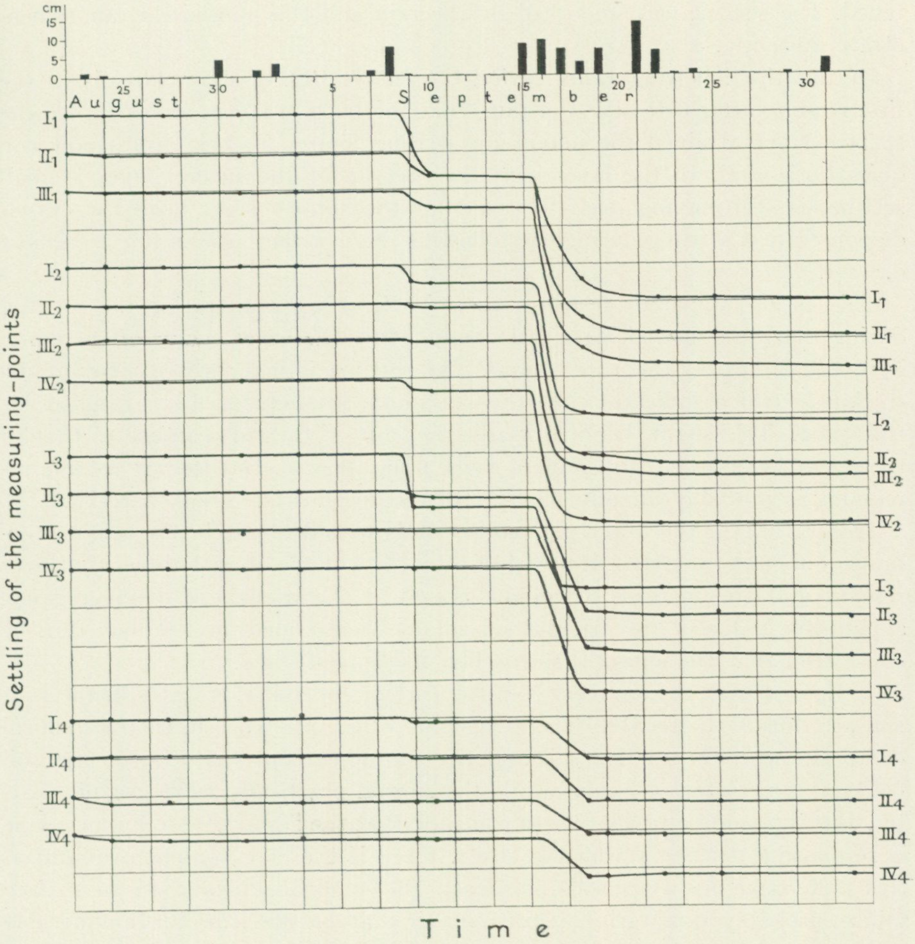

Fig. 9. Settling of the subsoil (Experiment 2) at various depths. For depth of soil under each measuring-point see Table 7.

that fell a few days later brought about a much larger settling in the subsoil than in the surface soil. Just as in the case of the surface soil, the rain was not sufficient to moisten the bottom layer, which is practically intact, but the other layers display a fairly considerable settling, which in the case of a couple of measuring-points in the same quadrant amounted to about 15 mm.

In fig. 10 the settling is, as before, put in relation to the height above the untouched surface of the subsoil, and the settling curve demonstrates that here the settling increases towards the surface, i. e. quite the contrary to what is the case with regard to the surface soil. The aggregates in the subsoil are so unstable that they have not even been able to withstand their own weight, and as the surface layer got the largest moisture content, it was most greatly compressed. The uneven settling indicates that the soil was unevenly moistened. The surface was smoothed by the rain and this caused the rain to penetrate unevenly.

During the following rainy period the curves (fig. 9) show, already in the first reading after three days of rain, that the bottom layers almost up to the surface layer attained the maximum settling figure, for the curves now run quite horizontal. In the layer next in order under the surface layer a small settling is still making itself felt, and for the surface layer itself the curves demonstrate a settling during the following days of rain, amounting to almost 0.5 cm.

This is also apparent from Curve B in fig. 10 demonstrating the settling during the whole period Sept. 3rd—Sept. 25th. The lower course of the curve is rectilinear up to the 10 cm level. The settling is here proportional to the thickness, which indicates that the maximum settling has been reached for this part. The slight bend towards the top of the curve indicates that in the upper layers there still remain a few mm, about 9. But the air volume remaining is probably already partly replaced by elutriated soil material.

The settling in the lower part corresponds to a decrease in the original volume of about 21 per cent. If we add to this the volume of air-bubbles that may remain and the increase in volume caused by the swelling of the aggregates, a plausible value of the original air volume is obtained, and it may thus be considered that the subsoil has reached its densest state.

Compared with the aggregates in the surface soil the aggregates of the subsoil are thus very unstable. There exists no other difference in the mechanical composition of the surface soil and the subsoil, except that the surface soil contains 3 per cent of humus while the subsoil practically lacks organic matter. But it would be premature to conclude that the admixture of humus alone is responsible for the stabilizing effect. Even if the clay content is quantitatively the same in surface soil and subsoil, the colloidal substance in the surface soil is probably qualitatively different to that of the subsoil. Innumerable hygroscopic determinations of surface soil and subsoil carried out in Sweden have demonstrated that the mineralogic part in the surface soil has a considerably lower hygroscopicity than in the subsoil, although a mechanical analysis may disclose the same clay content for the two soils. Exceptions from this rule are only encountered in low damp areas where the surface soil has a high humus content. EKSTRÖM, who has mentioned this condition, draws attention to the well-known fact that as a result of strong and repeated drying (the heat of the sun's rays) colloidal gels contract and become partly irreversible, and through this change the gels lose part of their hygroscopicity (3). It is also possible, of course, that as a result of chemical weathering the colloidal clay substance in the surface soil layer is transformed into substances with a lower hygroscopicity, e. g. by kaolin-weathering.

Generally speaking the soils that rapidly lose rigidity when the moisture content increases should be those most exposed to packing after a rainfall. The group of soils called silty loams and silty clay loams is characterized by the fact that the cohesion of the soils rapidly decreases as the moisture con-

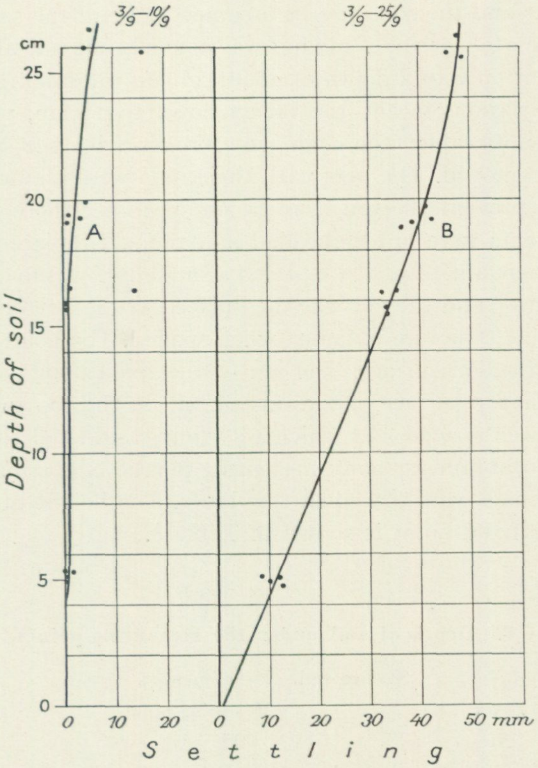

Fig. 10. Settling of the subsoil (Experiment 2) in relation to depth of soil during the two periods indicated at the top of the fig.

tent increases in the range above the *omslag*-point. They very easily acquire a dense structure, and when exposed to drying they consequently form a hard and dense mass which is difficult to break when tilling.

The influence of elutriation on the density of the soil.

In field conditions it is hardly possible to make a direct determination of the quantity of soil-material that during rain is transported from the surface to lower layers. It will be very difficult to produce a device with the aid of which the transport of material through a certain layer can be measured. The method used here is an indirect one. If we postulate that soil condensation is brought about by settling, causing the aggregates to be more tightly compressed, and by a transport of material, when the pores are filled with elutriated material, then it is possible, when the increase in the weight of the soil substance per volume unit has been directly determined and the increase in weight of the layers has been calculated on the basis of the settling curve, to state the part played by elutriation in the increase in weight.

These experiments were carried out in the immediate neighbourhood of the previous stations and the soil may be assumed to be of the same kind. A plot sufficiently large also for the sampling was spaded, but not all the way down to the subsoil but only to a depth of about 20 cm, my intention merely being to study the variations in the top layers down to 10 cm, where elutriation should be most noticeable. The clods were broken with the spade and plants and roots were removed. The nets with their rods were planted at one end of the plot, but to prevent the soil from becoming looser there than in the rest of the plot the nets were not embedded and the soil replaced layer by layer as before, but where a net was to be placed a small hole was made in the ground to the depth desired and the net was then placed at the bottom. It thus rested on a layer with the structure obtained when spaded. The holes were then filled with soil up to the soil surface. The net of the fixed points was in this case not placed on the top surface of the subsoil but on the top surface of the soil which had not been spaded and which was thus considered to be a firm bedding. In order to obtain as many measuring-points as possible in the top 10 cm-layer all the nets were placed in this layer. The height of the measuring-points above the fixed point is shown in Table 8.

Table 8. Depth of soil under the measuring-points, cm.

Surface soil. Experiment 3.

Layer No.	Measuring-point I	II	III	IV
1	18.2	18.8	18.6	19.1
2	17.0	16.7	15.6	17.2
3	13.9	13.9	14.1	14.3
4	13.2	12.2	11.9	12.8
5	10.0	11.0	9.8	9.4

The readings were started on August 27th and were then made on the same days as at the previous stations. The result is shown in fig. 11. The course of the settling is on the whole the same as shown in fig. 7, but as was expected the total settling of the whole layer is less here, only about 2 cm as compared with 3 cm before, on account of the smaller depth of the spaded layer, 18.7 cm as compared with 25.1 cm. The settling caused by the heavy rains at the end of October and the beginning of November is here, too, surprisingly small; it is remarkable, however, that it is somewhat larger than at the first station.

As before, the settling observed at the various measuring-points has in fig. 12 been put in relation to their position above the fixed point. The settling during the various rainy periods is illustrated by Curves A—C. It will be noticed that in this case the observation points are more scattered than during the corresponding periods at the first station. The soil has not become so homogenous, which was to be expected. This should be especially true of the bottom layers, where some lumps probably escaped attention when the soil was spaded.

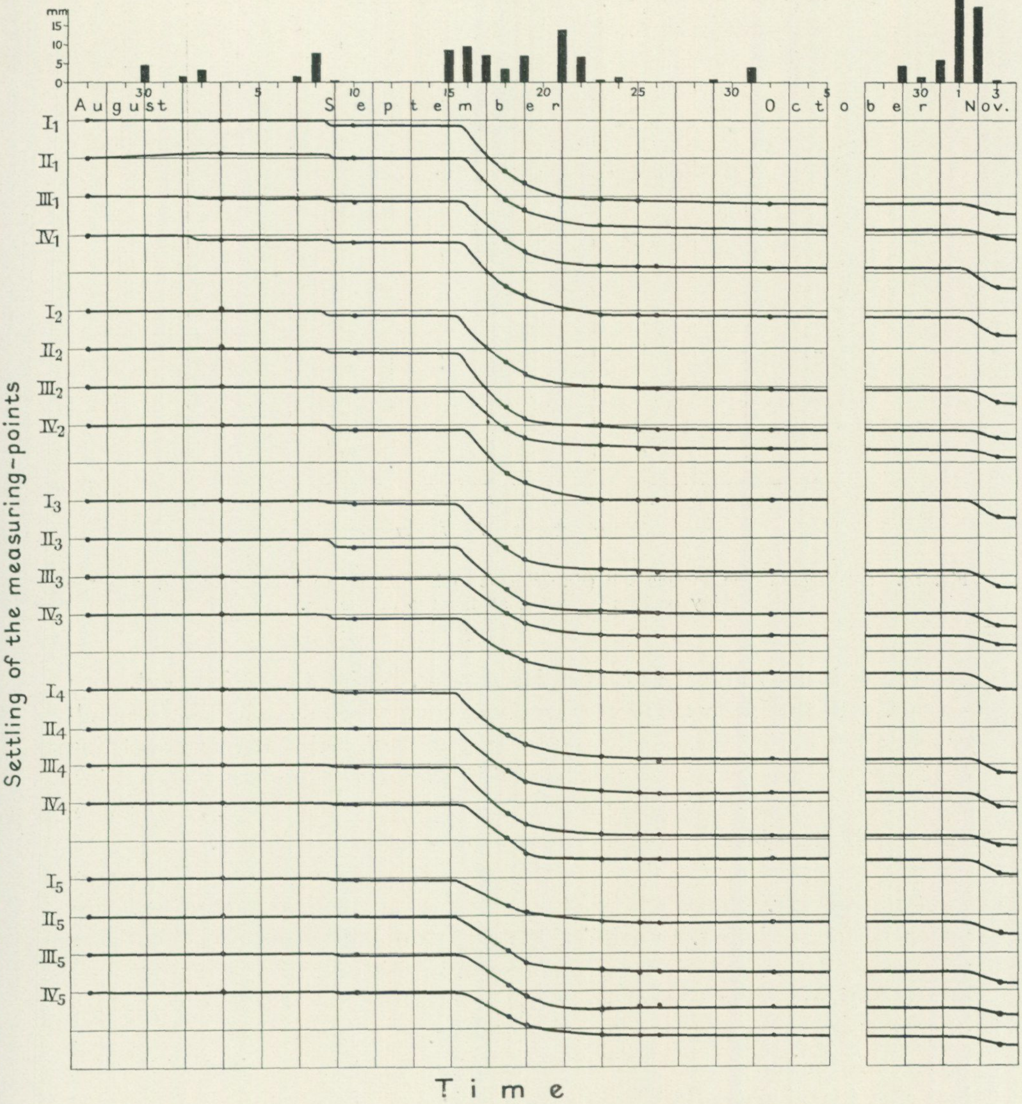

Fig. 11. Settling of the surface soil (Experiment 3) at various depths. For depth of soil under each measuring-point see Table 8.

The measuring-points that during the second period (B) display the smallest settling relatively speaking, those to the left of the curve, display the largest settling during the third period (C). The order is generally reversed. During the last rainy period the heterogeneity of the soil was smoothed out. This can be said to illustrate the well-known fact that soil of a coarser structure remains mellow longer than a soil of a finer structure. The rigidity of smaller

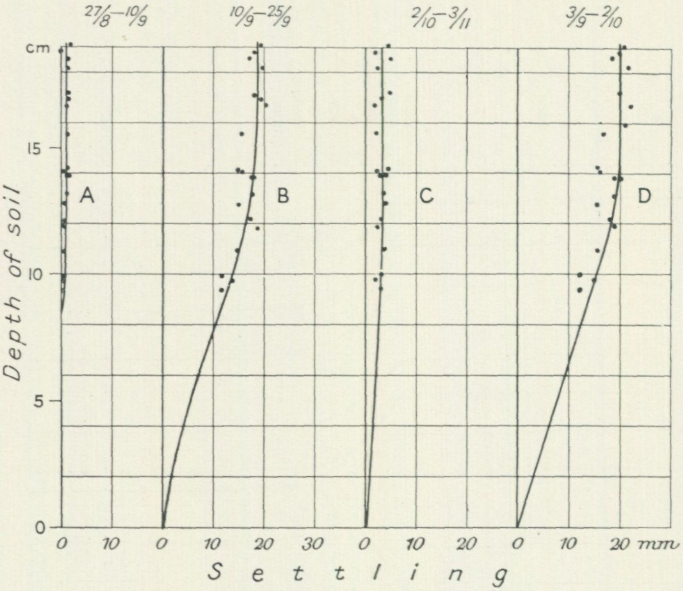

Fig. 12. Settling of the surface soil (Experiment 3) in relation to depth of soil during the rainy periods indicated at the top of the fig.

aggregates is not so great as that of larger ones. During the period Sept. 10th —Sept. 25th the larger aggregates were not compressed so much as the smaller ones, but during the very heavy rains of the last period the slight settling that then occurred was most pronounced in the case of the larger aggregates, which are comparatively richly represented in the bottom layer. It was, too, only the bottom layer (10—18.7 cm) that now settled somewhat.

The settling during the first period (Curve A) appeared only in the uppermost 10 cm-layer. Contrary to what was the case at the first station the layers under 10 cm are intact. In spite of the slight rainfall the deep bottom layer was the one that was then most compressed. In this case the coarser structure at the bottom of the spaded layer could withstand the soil-pressure, which was smaller, too, than in the first experiment.

Curve B for the second period is drawn somewhat to the right of the line indicated by the mean, this being done on account of the fact that the points on the extreme left have not been considered so representative as the others, as the measuring-points by mere chance happened to be placed upon more lumpy soil.

Compared with the corresponding curve in fig. 8, the course of the lower part of this one is more rectilinear or even slightly S-shaped, i. e. the density of the lower layers did not increase to the same degree as in the first investigation, which, as mentioned above, is due to the layer of soil lying above not being so thick and, as has likewise been said above, to the lumpiness in this case increasing downwards.

The course of the upper part of the curve also differs from the corresponding part of the curve in fig. 8. The uppermost layer down to 4 cm or so displays what may be a slight decrease in volume. In the first experiment a swelling was registered in this layer. No signs of an extra packing of the layer just under the surface layer are noticeable, though such a packing was evident at the first station. As was mentioned above, free water appeared on the surface there after a heavy rainfall. The soil did not absorb the water fast enough due to elutriation in the surface layer. On the plot now considered there was no surface water.

The additional settling during the last rainy period was somewhat larger here than at the first station. It was mainly restricted to the layer under the the 10 cm level, which was more compressed than the corresponding layer in the first experiment, which further emphasizes what was said above regarding the stability of the coarser structure. *Soil of a fine structure is compressed more than soil of a coarse structure and the packing is more rapid at the beginning of a rainy period and reaches its final stage earlier than the packing of a soil of a coarse structure.*

Let us now see what were the moisture conditions of the soil during the period of investigation. This is seen in Table 9 which shows the moisture content in the upper layers of the ground down to a depth of 10 cm.

Table 9. Moisture content in per cent of the soil-weight.

Depth cm.	Aug. 26.	Sept. 4.	Sept. 24.	Sept. 28.	Oct. 3.
0 — 2.5	13.1 ± 0.6	14.2 ± 0.3	26.6 ± 0.3	23.0 ± 0.2	23.3 ± 0.2
2.5— 5.0	17.2 ± 0.4	17.5 ± 0.1	27.5 ± 0.1	23.9 ± 0.2	24.3 ± 0.3
5.0— 7.5	17.9 ± 0.3	18.2 ± 0.2	27.4 ± 0.3	24.5 ± 0.2	24.3 ± 0.2
7.5—10.0	18.5 ± 0.3	18.5 ± 0.1	27.1 ± 0.5	24.8 ± 0.2	24.5 ± 0.2

The values are averages of ninefold replicates.

The first samples were not taken until Aug. 26th, i. e. 5 days after the investigation was started, to give the differences in the moisture content caused by the spading time to be smoothed out .When the investigation was started the moisture content of the soil will have averaged a figure slightly above the *omslag*-point, i. e. the moisture content was slightly above 18.3 per cent. The soil was thus in the state of moisture when it crumbles well upon being tilled without becoming pulverous. Between the first and the second sampling a total of 9.4 mm of rain fell in three days, but these small rainfalls could not increase the moisture content farther down than to the 7.5 cm level, for the layer next in order displays the same moisture content as before. The rain compensated the evaporation and also yielded a small surplus, but it had no effect on the settling.

On Sept. 24th, two days after the rains that lasted about a week, when a total of 56.9 mm came down, the moisture content had increased to more than 27 per cent. From the 18.3 per cent at the *omslag*-point the aggregates swelled, and absorbed 9 per cent of water. It is remarkable that in spite of the persistent rain the moisture content was not higher than but about the same as the year before after the slight rainfall at that time (cf. Table 4). This must be due to the fact that when the rain fell the preceding year the subsoil must have been almost saturated, whereas this time it could absorb water during the whole period and did not reach the same stage as the year before until the end of the rainy period. *In soil with a good capillary conductivity the moisture content of the subsoil has a decisive influence on the field-capacity of the surface soil.*

However, the subsoil was apparently not yet fully saturated. This will be seen from the values of the moisture content for Sept. 28th, four days after the previous sampling. To a depth of 10 cm the surface soil had then lost so much moisture that together with the rain that had fallen in the meantime, 1.2 mm, it would imply an evaporation of 4.7 mm. But if to this be added the loss of moisture from the layers below 10 cm, the daily evaporation will be too high. The probable explanation is that the subsoil absorbed part of the moisture content of the surface soil and thus that the subsoil was not saturated and that the field-capacity would have increased still more if the rain had continued. That the subsoil was not saturated is also proved by the fact that the bottom layer had shrunk at the first station during the days following the rainy period, which must be due to the subsoil absorbing some of the moisture. During the rainy period free water could consequently not collect on the surface of the subsoil, and the strong settling displayed by the bottom layer at the first station can thus only be explained by its depth.

Between the samplings of Sept. 28th and Oct. 3rd there fell 4.0 mm, which practically compensated the loss of moisture. The evaporation during that 5-day period thus amounted to about 0.8 mm per day or, if the rainy day be excluded, about 1.0 mm per day, which is a very reasonable figure for that time of the year.

The determinations of the soil-weight per 100 c. c. carried out at the same time gave the values shown in Table 10 below, which are means of ninefold replicates. The values of the volume-weight obtained on Sept. 24th are not included, as the soil on that occasion, just after the rainy period, was so sticky that no satisfactory value could be obtained.

Table 10. Soil-weight, g per 100 c. c., in the various layers.

Depth cm.	Aug 26.	Sept. 4.	Means before rains.	Sept. 28.	Oct. 3.	Means after rains.	Difference in means.
0 — 2.5	108 ± 0.9	110 ± 1.3	109 ± 0.8	111 ± 1.5	111 ± 1.6	111 ± 1.1	2 ± 1.4
2.5— 5.0	111 ± 2.0	109 ± 1.5	110 ± 1.3	110 ± 1.3	112 ± 1.4	112 ± 0.9	2 ± 1.7
5.0— 7.5	109 ± 1.4	110 ± 1.6	110 ± 1.1	116 ± 1.1	115 ± 1.3	115 ± 0.8	5 ± 1.4
7.5—10.0	108 ± 1.5	112 ± 2.2	110 ± 1.3	117 ± 2.1	114 ± 2.1	116 ± 1.2	6 ± 1.8

The values obtained in the two samplings before the rainy period are totalled in the column »Means before rains». The moisture content was practically the same on those two occasions (cf. Table 9) and the soil displayed no settling. The case was the same in the two samplings after the rainy period. The means of these latter two determinations are also shown. The last column shows the differences between these means for the determinations before and after the rainy period.

The increase in the weight of the soil is very small, being but 2 g per 100 c. c. for the top layers and little more than the mean errors. In the bottom layers the increase is 5 and 6 g, respectively, an increase that is statistically sure. Certainly the moisture content of the soil was 6—7 per cent higher after the rainy period than it was before, and the aggregates had consequently swollen. But seeing that, as already mentioned above, swelling as well as shrinkage in a mellow soil are internal processes and do not influence the external volume, no correction need be made for the difference in moisture content when making comparisons. The swelling that actually could be established in the surface layer at the first station was undoubtedly caused by that layer having lost its mellow structure as a result of elutriation. This question will be discussed later.

If we calculate how large a settling corresponds to an increase in the soil-weight of 5 and 6 g, resp., per 100 c. c. in the two bottom layers, we obtain a settling of 1.1 mm for the layer 5.0—7.5 cm, the weight having increased 5 g, and 1.3 mm for the layer 7.5—10.0 cm with an increase of 6 g. Curve D in fig. 12 for the corresponding period discloses a settling in the same layers amounting to about 2.0 and about 4.0 mm respectively. The curve thus shows an even greater packing of these layers than that indicated by the direct determinations of the increase in the weight of the soil. The settling curve should thus be corrected somewhat so as to agree better with the increase in the weight of the soil observed. The measuring-points have evidently been too few, especially in the lower group on the 10 cm-level, to give a sufficiently positive mean of the settling of the layers. If any elutriation of clay material did occur, it must have been very slight. In the two lower layers, 5—10 cm below the surface, the settling can hardly have been less than that arrived at on the basis of the increase in weight and it is thus not very likely that any elutriation to these layers has taken place. In the surface layer, which displayed no settling, the increase of 2 g may have been caused by elutriation, but the increase is so small that it cannot be considered statistically sure.

After the rain the surface of this plot still displayed a crumbly structure. The small lumps on the surface were still present though their size had diminished somewhat owing to some material being washed away. However, no very great transport of material occurred from the surface to lower layers. Clay material suspended in rain-water was deposited on the surface itself. If the ground had been cracked, soil would probably have been washed down into the cracks. At the first station, however, the surface was quite smoothed and presumably the surface layer was there condensed by elutriation, and the conditions at this station may be said to represent those generally found in small depressions on the surface.

Swelling and shrinkage in mellow soil.

An increase in the moisture content of the soil results in a swelling which is of the same size as the water absorbed, provided that the original moisturt content of the soil is at or above the *omslag*-point. When the moisture content is below the *omslag*-point, the change in volume is considerably smaller; with this type of soil it is very insignificant. Conditions are reversed when the moisture content decreases. This is valid for soils in a compact state.

NIKIFOROFF and TYULIN consider, as has been mentioned above, that in soils of a mellow structure changes in volume are internal, *i. e.* they manifest themselves solely in changes of the structural pore-volume without influencing the external volume of the soil-mass. As I have not had access to the original works of the above scientists, I do not know what is their explanation of the phenomenon, but the cause is easily imagined. As the aggregates are united to each other at their points of contact by cohesive forces, the whole soil-mass forms a firm skeleton and the individual aggregates are so to say suspended at their points of contact. When a change of volume occurs, it must, seeing that the position of their points of contact are fixed in space, be manifested in the free parts, i. e. the parts whose surfaces border the cavities. The changes in volume of the individual aggregates can therefore not occur uniformly in all directions but preferably in the directions where there is no counter-pressure, *i. e.* in the direction of the cavities.

If the structural cavities are comparatively small or comparatively few, the changes in volume will of course also be manifested externally, and when the moisture decreases the shrinkage will be found to be greater than the swelling in the case of a corresponding increase in the moisture content, as the counter-pressure of the soil must be overcome in the latter case.

In the above reported investigations of the changes in the external volume of the soil, its settling and rising, a swelling could be definitely established in one case only, and that was at the first station, where, as already mentioned, the surface layer had swollen. In the layers that are exposed to settling after rainfalls any swelling that may occur is concealed by the settling, which is greater.

In certain cases a slight settling has been demonstrated just after the soil has been mellowed, but this settling is due to an exhaustion process in which certain labile aggregates collapse to a more stable position. In addition the curves generally reflect a small settling after the main settling process. Judging from the course of this second settling process, which is comparatively rapid in the beginning and ceases in a few days, it bears a certain resemblance to an elastic after-effect in a solid material exposed to a heavy load. The comparatively rapid decrease in the beginning is undoubtedly an elastic after-effect, as it is greater than what would correspond to a shrinkage caused by a loss of water by evaporation during the same time. It is doubtful, however, whether this effect can last for several days (6).

Between the two readings of Sept. 25th and Oct. 2nd after the long rainy period the two points of observation on the surface soil (Figs. 7 and 11) show a small sinking in each layer. In the subsoil (Fig. 10) no sinking occurred except in the surface layer, for the subsoil was densely consolidated and could not be further compressed. During the period in question dry weather reigned except on the last day, when 4 mm came down, which was sufficient to compensate evaporation. The moisture content was practically the same in the last reading as in the first, which will be seen from Table 9. No swelling caused by this rainfall could be demonstrated.

In fig. 13 the sinking observed during the 7-day period at the two stations has as before been set off in relation to the position above the fixed point. The points denote means of the sinking of various groups of measuring-points. Their mean heights are set off on the y-axis.

The two curves display certain dissimilarities. The curve for the first station (1) shows a decrease in volume in the layer just above the subsoil, amounting to quite 0.4 mm, but in the layer above, which is 10 cm thick and thus thicker than the 7-cm bottom layer, a change in volume is scarcely noticeable. In the surface layer, finally, which is 8.5 cm thick, the sinking is somewhat greater, but only about 0.3 mm.

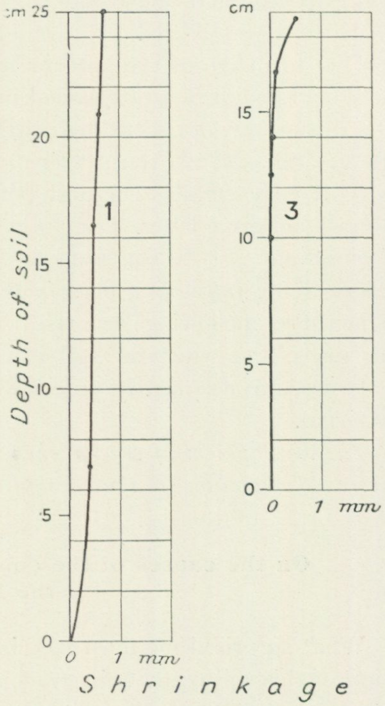

Fig. 13. Shrinkage in various layers of surface soil at measuring-stations 1 and 3. Sept. 25th—Oct. 2nd.

At the third station (Curve 3), where the fixed point is about 5 cm above the surface of the subsoil and the changes in the volume of the bottom layer consequently are not recorded, no decrease in volume is apparent except in the upper layers, but then the uppermost layer, which is 2 cm thick, displays a sinking of as much as 0.4 mm.

The sinking or decrease in volume is thus mainly manifested in the surface layers and most of all in the top layer, where no packing occurred earlier. The decrease in volume observed can thus not be an elastic after-effect but must be a normal shrinkage due to a loss of moisture, which consequently can occur also in mellow soil. The shrinkage does not represent the whole loss of moisture, however, which before the last rainfall of 4 mm in the surface soil will have amounted to about 10 weight per cent of water. The shrinkage of 0.4 mm recorded for the 2-cm-thick surface layer in the third experiment corresponds to a loss of moisture of but 1.8 per cent. The remaining and greater part of the loss of moisture caused internal shrinkage.

The lower layers, which displayed a very small or no decrease in volume, certainly lost less moisture than the surface layer but this alone cannot explain the great difference. Probably the aggregates in the deeper layers are united to firmer units than in the surface layer and the shrinkage becomes internal. The surface layer at the first station, which does not display any greatly increased loss of volume as compared with the layers underneath, has on occount of elutriation formed a consolidated mass and is comparable with the lower layers.

The shrinkage of the bottom layer at the first station recorded by Curve 1 is of course first of all explained by the fact that at the end of the rainy period the subsoil was not saturated with water but could absorb some from the layer above and as the bottom layer of the surface soil then became densely packed with a very small structural pore-volume, this resulted in a shrinking of the almost compact layer. *The law of the internal nature of swelling and shrinkage demonstrated by* NIKOFOROFF *and* TYULIN *is apparently valid to but a limited extent, being fully valid only in the case of a very mellow but consolidated soil.* When the mellowing decreases the external part of the change in volume increases, and when the soil reaches a compact state and a structural pore-volume is consequently practically lacking, the change in volume is entirely external.

The development of cracks when the soil dries, which is a result of an external decrease in volume, is thus a sign of poor structure.

On the causes of the comparatively stable structure during the investigations.

What surprised me most in this investigation was that in spite of the structure of this soil really being very sensitive to rain the lengthy and heavy rains produced but a small recorded settling.

Looking for instance at the third experiment, the week of rain could not increase the soil-weight per 100 c. c. in the top 10-cm layer by more than 2 g in the layer 0—5 cm, and by 5—6 g in the layer 5—10 cm (cf. Table 10). And the heavy rain at the end of October and the beginning of November caused no further increase in the density of the soil in this top 10-cm layer, at least not by settling (cf. Curve C in fig. 12). The layer underneath is the only one that was further compressed, but only about 3 mm. The mean increase in the soil-weight for the whole layer (10—18.7 cm) is thus about 4 g per 100 c. c., i. e. from about 115 g to 119 g. As when the soil is densest the soil-weight is about 150 g, the soil also in these deeper layers has retained most of its original structural pore-volume. The structure of this very unstable soil has been surprisingly stable in these experiments and nevertheless the spading was more intensive than what it is when carried out with ordinary agricultural implements. One cannot but ask oneself what can have been the cause.

It has previously been mentioned that in laboratory experiments a stabilizing effect has been produced by the secretion of bacteria which tends to unite the aggregates, and that the mycelial threads of aspergillus contribute to uniting them. The effect demonstrated has been slight, however, and I find it difficult to conceive that the bacterial and fungaceous flora should be so greatly stimulated by the spading that the effect should be demonstrable. Probably the cause must be sought for in purely physical processes.

When sampling the soil it was observed that in the first sampling, which was carried out on Aug. 26th, 4 days after the spading, the soil was still so loose that it was no easy matter to obtain samples that were not compressed when pressing down the sampling-cylinder. In the second sampling, however, on Sept. 4th, the small rainfall, which, incidentally, had not had any recorded influence on the settling, had united the aggregates to a mass of a certain rigidity, into which the cylinder could be inserted without causing any change in volume. A slight moistening of the soil followed by drying apparently has a stabilizing effect. Then came another small rainfall about Sept. 8th, followed by a few dry days, before the long rainy period commenced.

When the soil is moistened, the textural pores already being filled with water and the moisture content thus being above the *omslag*-point, water menisci are formed around the points of contact of the aggregates, so-called pore-angle-water. During a subsequent drought the curvature of these menisci is highly increased according to the well-known law of the higher capillary potential of soil when the moisture content decreases than when it increases. During a drought the aggregates are pressed closer to each other and are united to a solid mass, the soil is consolidated and the soil structure becomes more resistant to rain that it would be otherwise. This may explain the well-known fact that a heavy rain is more dangerous on recently tilled fields than if it falls later after the structure first having been stabilized by a smaller rainfall. The question should be further looked into, being of importance for instance when determining how to water the soil. From a theoretical point of view it would be advantageous to begin by using a small amount of water, followed by a thorough watering when the soil has been allowed to dry for some time.

On the Klagstorp estate, where they have great experience of how to treat this unstable soil, Director Pontén informed me that they endeavour to avoid tilling the soil when it is very dry, considering that the moist aggregates will unite better than the dry ones (moisture content below the *omslag*-point) and will therefore stand subsequent rainfalls better. We must not disregard the fact, however, that the good effect may also be due to the coarser structure of the soil when tilled in a more plastic state, i. e. when the moisture content is above the *omslag*- point, than when tilled in a drier state, when it more easily pulverizes. In the experiments here discussed the soil had a moisture content when spaded that was somewhat above the *omslag*-point, but the aggregates could not be established to have united to a solid mass before after some rain had fallen. It would be of great practical importance to have also this question further investigated.

Summary and practical application.

The method used makes it possible to study the soil's changes in volume under each measuring-point. In this respect it is superior to other methods which necessitate samples of the soil being removed intact, when, due to the great heterogeneity of the soil, especially of the surface-soil, and unavoidable errors when taking a fixed volume of soil, a large number of replicates must be taken. The method can also be used, to great advantage, when studying the changes in volume in different layers of the ground, but then a number of measuring-points must be arranged depending on the heterogeneity of the ground, for it is necessary to determine the means of the changes in volume in the various layers, in view of the fact that the measuring-points cannot be placed straight on top of each other.

The soil examined is a silty clay loam with about 3 per cent of organic matter, belonging to the group of soils that is remarkable for its unstable structure owing to the fact that as the moisture content increases, counting from the *omslag*-point, the rigidity of these soils fairly rapidly decreases.

It was therefore surprising that in spite of plenty of rain falling during the course of these experiments the settling figure was comparatively small, which has been considered to be due to the stability of the structure having been enhanced by a previous smaller rainfall followed by a drying process. This question must, however, be looked into more closely. Provided that the structure of the soil is similar at different depths, the settling will be greatest in the bottom layer owing to the greater soil-pressure prevailing there. The top layers displayed no settling.

In soil of a fine structure the settling is found to be greater than in soil of a coarse structure.

The surface soil has a more stable structure than the subsoil, which will mainly be attributable to the content of organic matter in the surface soil and possibly to some extent to a difference in the nature of the colloidal substance, due to the fact that when dried out the gels become partly irreversible, or possibly to mineralogical changes in the surface soil.

It has not been possible to demonstrate any elutriation of soil from the surface to lower layers, except in depressions where during heavy rainfalls free water can collect on the surface. Certain deviations in the shrinking and swelling of the surface layer observed during investigations in a depression prompted the assumption that soil was washed into the structural pores.

The law of the internal nature of the swelling and shrinking is valid within certain limits only. The structural pore-volume decreasing, the change in the external volume increases.

Considering the short time — scarcely more than a decade — that soil-scientists have devoted increasing interest to questions of structure, i. e. to the very problems most intimately connected with questions of cultivation and permeability, results comparable to those obtained in other branches of agriculture cannot very well be expected. Present practice in tilling and draining is still essentially based on the experience gained throughout the ages.

Conditions are, however, so variable as regards soil, climate, etc., that we often do not know what to do in the field, what measures to take. Naturally, a closer knowledge of the processes in the soil, of the factors concerned and of the way they work, would give a deeper insight into what should be the aim of the various measures and would also facilitate the choice of the procedures most suitable in different situations.

The present investigation scarcely prompts the introduction of any new methods of cultivation. Speculating how the observations made may be utilized in practice, I find that experience has already shown the way.

The investigation has proved that soil-settling increases the more finely dispersed a soil is by cultivation, e. g. by the cultivation of root-crops with repeated tilling. The smaller the aggregates the greater is the risk of the soil becoming compact. Experience also warns against too fine a tilth of a soil of this type.

It has further been observed that soil-settling mainly takes place in the deeper part of the tilth, the upper part being but little influenced. Ordinarily the soil gets »hard at the bottom» and needs mellowing. Through ploughing the heavy bottom layer is turned up to the surface and is there more accessible to mellowing processes. Ploughing has in itself no great mellowing effect on the furrow-slices and it seems very likely that its well-known good effect on the soil structure lies in the turning up of this hard bottom layer for further loosening. The bottom layer under 20 cm had acquired an almost compact structure and it is thus doubtful whether it is advantageous to plough this soil deeper.

The investigation has also shown that the aggregates in the surface soil become stabilized after rain. But that this factor plays such an essential part as indicated by the investigation was surprising at least to me. In practice we seldom have a free choice as regards the time of cultivation, and, therefore, it does not seem likely that this factor has been taken into consideration; excepting maybe in the autumn tillage. Should the surface layer for some reason or other — e. g. elutriation — be in a compact state, an extra tilling (stubble-harrowing, skim-ploughing) would be appropriate, this, however, taking place in due time before the autumn ploughing, so that the aggregates have an opportunity of stabilizing before turned down. Where stubble-harrowing is practised it is done for the special purpose of making the weed-seeds grow, and though the soil structure has not been taken into consideration the growing-time thus allowed is also good for the structure.

As to this proposition of making the autumn tillage more effective, a special investigation is, however, necessary. It is not quite clear what effect the frost may have on the mellowed but stabilized soil. It is possible that the packing of the soil when the frozen ground thaws may be denser with than without surface-mellowing before the tillage.

The same problem is encountered when considering the most convenient time for the autumn ploughing. When ploughing early in the autumn, the soil being relatively dry, the furrow-slices are more broken up than if the ploughing is done later, when the soil is more moistened and in a plastic state. But in the spring conditions may be reversed and we may find that the soil which after ploughing in the autumn was of a looser structure is now denser than the other. On the estate in question a fine structure is if possible avoided, and that in every tillage, in the spring as well as in the autumn.

The growing together of the aggregates that occurs when they dry after a rainfall and which very probably enhances the stability of the soil may possibly to a certain extent also be promoted by rolling, at least in the top layers, i. e. as far down as the rolling has any packing effect. This being the case, rolling should also help to prevent settling. On the other hand rolling will break down the lumps and crumbs on the surface, *i. e.* the topsoil will be of a finer structure, and then there is a risk of the surface layer becoming densified under the influence of heavy rainfalls.

This is another fact that practice has made use of. I have in mind the well-known fact that when filling ditches it is common practice to dig down surface soil from the ditch-edges onto the draining-tiles before the dug-up sub-soil is replaced, apparently in order to get a more permeable layer at least nearest the tiles. The efficiency of the underdrain is dependent on the permeability and stability of the filling-material and it thus seems highly necessary that special measures be taken in order to increase the stability of that material and especially in the case of such instable soils as loams.

Where the permeability of the sub-soil is small, which is a rule as regards clays, and where the water from the surface or the surface soil when running off seeks its way to the places where the drains go and then through the filling to the tiles (5), it is especially desirable that the filling consist altogether of surface soil, or that at least the filling be mixed with surface soil.

In the U. S. A. extensive experiments have been made to stabilize loose soils under roads by mixing them with several kinds of bitumen and good results have been obtained. There also seem to exist great possibilities of increasing the stability and permeability of the soil covering the draining-tiles.

Finally the effect heavy rain-falls may have on the softening of the aggregates and thus on the settling may be emphasized. If the sub-soil is not sufficiently permeable to allow the transport of the gravitational water at the same rate as it passes the surface soil, and often it is not, the water will remain on the sub-soil surface, and the period of water-absorption will perhaps be extended by several days in excess of the rainy period itself. Besides, having no capillary potential, this free water is easily absorbed by the water-drenched soil. One of the main tasks of draining is, as we know, rapidly to remove such stagnant and obstructive surface-soil water.

In clay the permeability of the sub-soil is highly variable with the seasons owing to the cracking. It decreases in the autumn when the majority of the cracks have swollen together, and in the winter, when ice fills any and all open cracks, the sub-soil often becomes impermeable. When the frozen ground thaws in the spring water has no possibility to sink down into the sub-soil;

it remains on the frozen surface and now the soil-aggregates desintegreated during the frost have a bad time. Intensive draining and permeable soil above the draining-tiles can alleviate this trouble, but it can hardly be mastered in any other way.

It has been pointed out that the water-capacity of the surface-soil is highly dependent on the moisture-content of the subsoil. As the subsoil in fallow land is moister than in land with vegetation, the surface-soil will in the former case be more moistened by the autumn rains than in the latter, and the aggregates there will be greatly softened and the soil will settle densely. By the autumn tillage the soil is therefore usually given a coarse structure with lumps and clods lying on the surface.

Furthermore, the high water-content will predispose the young plants to being uprooted by the frost, a very common phenomenon in our climate and especially in soils of the kind here in question. One tries to prevent this by intensive draining. Consequently, if the fallow is excluded from the rotation, draining need not be so intensive.

I desire to take this opportunity to thank Director S. Pontén of Klagstorp for many interesting discussions on agricultural problems.

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