Soil structure and plant growth

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Summary

One of the aims of soil tillage is to bring the soil in a physical condition favourable for plant growth. A knowledge of soil cultivation requirements depends on questions regarding the most favourable soil structure. These questions however, are not solved very easily, because of the complexity of soil structure, the variety of soils and the different ways in which the various crops react during the different phases of growth.

The influence of the structure of the top soil on growth and yield of several crops was studied, especially on clayey soils. Soil structure was characterized by visual estimation and by measurements of pore space and air content at pF 2.

For a period of 30 years an average yield increase of 25 % was obtained by improving the structure of a heavy clay soil. The highest yield was obtained when the visual structure index was at least 5½, corresponding to an air content at pF 2 of at least 15 vol. %. In one year early summer was rather dry and a more compact soil structure (visual structure index 4) gave the better plant growth.

On a silt soil a favourable influence of good soil structure on yield was found. Depending on crop and weather, a pore space of 48—50 vol. %, corresponding to an air content at pF 2 of 14—17 vol. %, was required to obtain the highest yield. In one year however, an unfavourable influence of a higher pore space on the yield was obtained. This phenomenon could be explained by a rapid depletion of soil nitrogen in the early stages of growth.

There are indications that the most favourable air content at pF 2 in sand soils (used here as an index for soil structure) is about 20—25 vol. %. At higher air contents the yield decreases through water deficiency. At lower air contents at pF 2 the mechanical resistance of the sand soil seems to be limiting root growth.

The relation observed between visually estimated aggregate size and porosity on one side and visual estimation of soil structure on the other gave the possibility to convert the results for clayey soils to data more suitable for soil tillage purposes. On a heavy clay soil, a visual estimation of 5½—6 corresponds to a structure characterised by rather dense clods, with mean diameter 0,5—1 cm, or to a structure characterised by porous aggregates of 5—10 cm.

Introduction

One of the aims of soil tillage is to bring the soil in such a physical condition, that good plant growth is possible. Before the question how to cultivate our soils can be answered, we must be informed about the most favourable state of soil structure for plant growth. This problem however, cannot be solved easily, since:

a. soil structure is a complex factor; several aspects such as pore space, air content, moisture content, stability, aggregation and soil temperature can be distinguished, all these aspects may have an influence on plant growth;

b. during the growth of the crop different phases can be distinguished and during each, there may not be the same demands upon soil structure;

c. there is a great variation in crops and it is probable that every crop has its own requirements with respect to soil structure;
d. there is a great variety of soils with differences in mechanical composition, fertility and moisture characteristic and possibly every soil type requires a special spatial arrangement.

The problem of soil structure and plant growth has been studied during the last ten years by the Institute for Soil Fertility on some experimental fields with differences in soil structure. This study will be discussed here briefly.

Methods

The influence of the structure of the top soil on growth and yields of several crops was mainly studied. This was done on a heavy clay and a silt soil during a number of years and more incidentally on sand soils.

Differences in soil structure on the heavy clay soil (60 % particles $< 16\,\mu$) were obtained by liming. This experimental field has been laid out about 30 years ago and yields have been determined every year. Soil structure has been evaluated only during the last five years. This has mostly been done by visual estimation (PEERLKAMP, 4). This method mainly judges the porosity of the soil and the size and form of the aggregates; these aspects are combined in the structure index St, ranging from 1—10. A low value indicates a poor, dense, soil structure, a high value a favourable, loose crumbly, soil. Pore space and air content at pF 2 (KUIPERS, 3) were measured a few times only, however sufficiently frequent to obtain the relation with the visually estimated structure index. This enabled conversion of one set of data into the other.

On a silt soil (15 % particles $< 16\,\mu$), differences in soil structure were obtained by the application of several soil conditioners. This experimental field was laid out in 1953. The crops were cereals, peas and root crops and the yield was determined every year. Sometimes the condition of the crop was judged. The structure of this silt soil was always characterised by pore space and air content at pF 2 measurements and in addition a few times by the visually estimated structure.

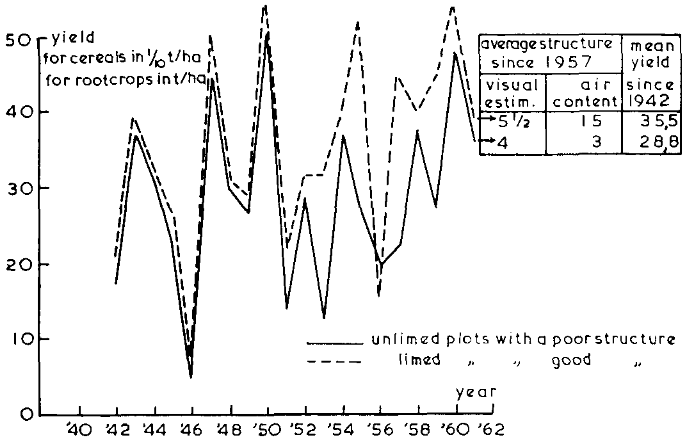
The results on the heavy clay soil

FIG. 1 shows the yields, obtained during a period of twenty years on plots with a good and a poor soil structure and the mean result of the visual structure estimations during the last five years.

On the plots with a favourable soil structure, which during the period 1957—1962 had an average structure index, St, 5½, yields were larger nearly every year than on the plots with a structure index of 4. The mean yields for the whole 20 years period were 3550, resp. 2880 units/ha (a unit for cereals equals 100 kg/ha, for root crops 1000 kg/ha) which is a difference of 25 %. Thus a clear influence of the structure of the top soil on plant growth was found on this heavy clay soil.

An investigation with soil conditoners on this field and a statistical analysis showed, that the pH-increase brought about by liming only had a minor influence on crop yield. Therefore crop response is mainly attributed to soil structure differences. This view is also supported by the fact, that the yield differences vary strongly in the course of the years.

FIG. 1. Yields on a heavy clay soil on plots with a good and a poor soil structure (period 1942—1961)

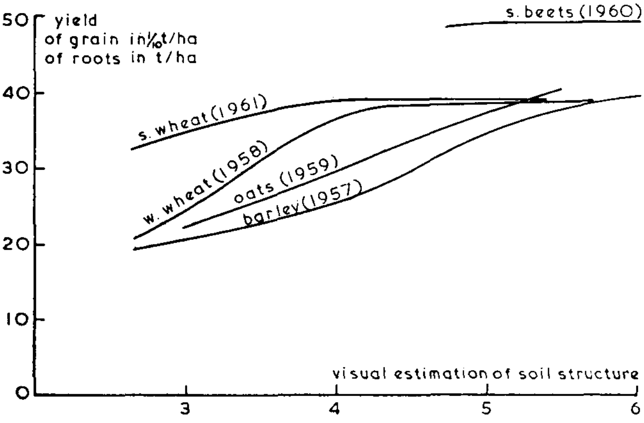


The influence of soil structure on crop yield is given for a number of years in FIG. 2.

In 1957 and 1959 a decrease in yield occurred when the structure index dropped below 5½. In 1958 and 1961 however, a decrease in yield occurred only if the structure index dropped below 4. This variable influence is mainly attributed to weather conditions. The early summer in the latter years was much dryer than in 1957 and 1959. Under such dry circumstances even a rather dense soil contains a sufficient quantity of air. To be ensured every year of the highest yields, a structure index of 5½ or more is necessary. This means that the soil should have an air content at pF 2 about 15 vol. %, distributed regularly throughout the soil.

From this example it appears that the influence of soil structure on plant growth may depend strongly on weather conditions.

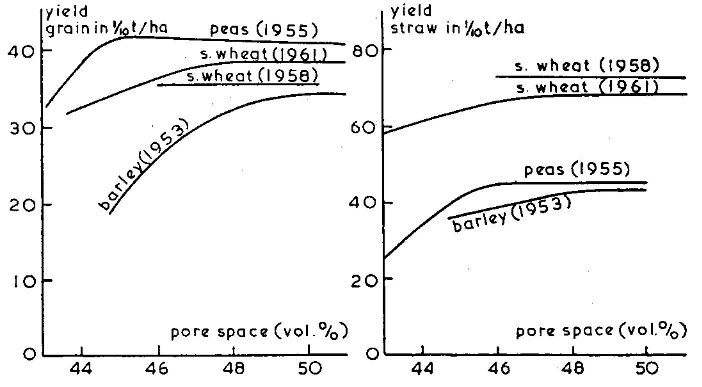
FIG. 2. Influence of the visually estimated structure of a heavy clay soil on crop yield



Results on the silt soil

The relations between soil structure, characterised by pore space, and the yields of cereals and peas are given in FIG. 3.

FIG. 3. Influence of total pore space on the yields of cereals and peas on a silt soil



Low yields were obtained on plots with a poor structure (small pore volume). Similarly to the heavy clay soil, the level of soil structure required to obtain a good yield changed here from year to year. In 1953 and 1961 yields decreased when pore space dropped below 48—49 vol. %. In 1955 and 1958 however, a good yield was still obtained on a soil with a pore space of 45—46 vol. %. This phenomenon can be explained in the following way. In 1955, when peas were grown, the first part of the growing period was rainy; the soil was continuously at about pF 2 and therefore rather wet. In this period soil aeration affected plant growth strongly and the best growth was obtained on plots with the highest pore space. Half way through the summer however, the weather became very dry and all the available water was taken up within a short time. The rooting zone in this soil is rather shallow, only little water could be extracted from the deeper layers and the plants on plots having a good soil structure lacked water. Periodic sampling showed that on these plots wilting point was reached sooner than on the plots with a poor structure. This can be explained by stronger evaporation by the greater mass of leaves. Therefore the plants on the well structured plots suffered more from lack of water than those on plots with a poorer soil structure, consequently seed setting and development lagged behind and yield did not come up to expectations.

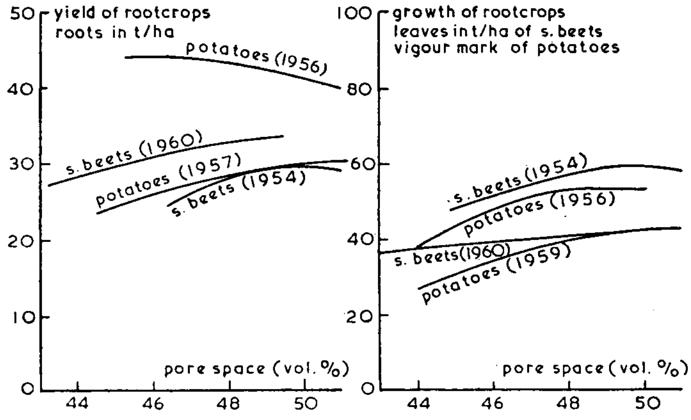
In this case the influence of soil structure on plant growth was affected by the weather conditions which appeared to have a critical influence on water availability.

The relations between soil structure and yields of potatoes and sugar beets on the silt soil are given in FIG. 4.

A favourable influence of soil structure on the yield was found in three out of four years. The highest yields were obtained on a soil with a pore space of about 50 vol. %. In 1956 a lower yield was obtained when pore space exceeded 47 vol. %, despite the fact that half way through the growing season the plots with the highest pore space had the better growth.

This may be explained in the following way. Crop growth on the plots with a high

FIG. 4. Influence of pore space on the yields of potatoes and sugar beets on a silt soil

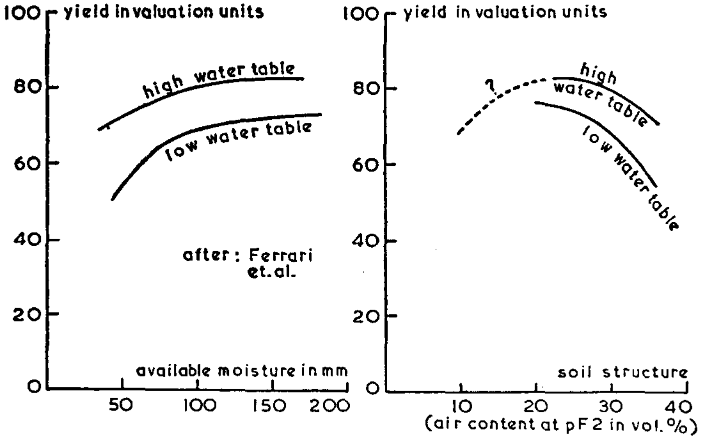


pore space was very good during the first part of the growing season. The bigger mass of leaves and stems obtained, indicate, that nitrogen uptake will have been relatively high. This topic was specially studied on this experimental field. Determinations of the soil nitrogen content showed, that in the later period during which tuber growth occurred, a smaller quantity of nitrogen was available on the well structured plots. This accounts for the fact that the yield of tubers did not come up to expectations. On the plots with a poor soil structure however, the first growth was more gradual and consequently nitrogen uptake not so rapid, so that in the period of tuber growth more nitrogen was available.
On the average the best result was obtained on plots with a pore space of 49 vol. %. corresponding to an air content at pF 2 of about 16 vol. % and a visual structure index of about 6.

Results on sand soils

In the "Gelderse Vallei", a region with sand soils, FERRARI, V. D. SCHANS and SONNEVELD (1) found a good relation between percentage available moisture and yields of oats (FIG. 5). Furthermore, there was a relation between available water and air content at pF 2. Therefore it is possible to approximately convert the first mentioned relation into one between estimated yield and air content at pF 2, which will be used here as an index of soil structure.
Yields were highest on soils with an air content at pF 2 of 20—25 vol. % and decreased at higher air contents. It should be emphasized however, that this decrease is not due to an excess of soil air but rather to a lack of soil moisture.
This study gives no answer to the question as to what yields are obtained on soils with air content at pF 2 lower than 20—25 vol. %. Fortunately there are some other data from experimental fields serving other purposes, which provide some information. On a sand soil with an organic matter content of 15 %, good growth was found at 15 vol. % air at pF 2 and poor growth if the soil was compacted to such an extent that the air percentage became 5 vol. %. On another sand soil having

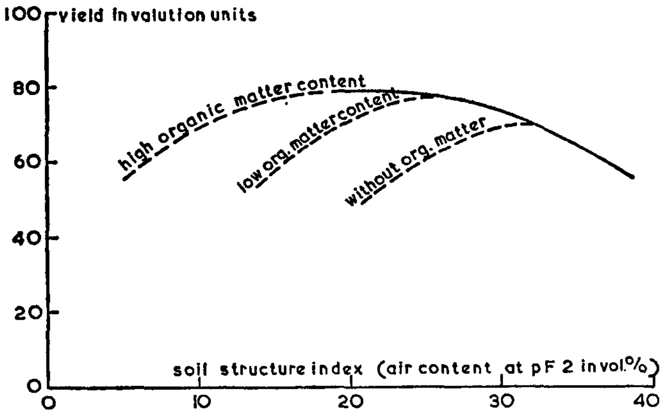
FIG. 5. Relations of available moisture and air content at pF 2 to yield on sand soils in the Gelderse Vallei



only 4 % organic matter and an air content at pF 2 of 25 vol. %, a much better growth was obtained than at 20 vol. % of air. Lastly, on sand soils without humus (generally having a pore space of about 40 vol. % and an air content at pF 2 of about 30 vol. %) plant growth always appears to be poor. HIDDING and v. D. BERG (2) showed, that a smaller pore space than 40 % on this type of soils enhances root penetration even if there is no water shortage. This is explained by the fact that the structural rigidity of the soil is great, so that a pore diameter of 50—70 microns, prevailing in this soil, is too small for the roots to penetrate (WIERSUM, 5). This means that the mechanical resistance of the soil is likely to be decisive here.

Combining the results described above, the relation between air content at pF 2, used as an index for soil structure, and relative crop yield will be approximately as is shown in FIG 6.

FIG. 6. Relation between air content at pF 2 as a soil structure index and crop yield on sand soils with different organic matter percentages



These results indicate that the air content at pF 2 required for good plant growth on a sand decreases when the organic matter content increases. As was discussed, at low organic matter contents mechanical resistance is likely to be important.

Air content required for good crop growth in relation to clay content

Converting the values for visually estimated soil structure and pore space, used respectively on the heavy and the silt soil, into air contents at pF 2, the results for the three soil types can be summarized in one figure (FIG. 7). The yields are expressed as percentages of the highest yields.

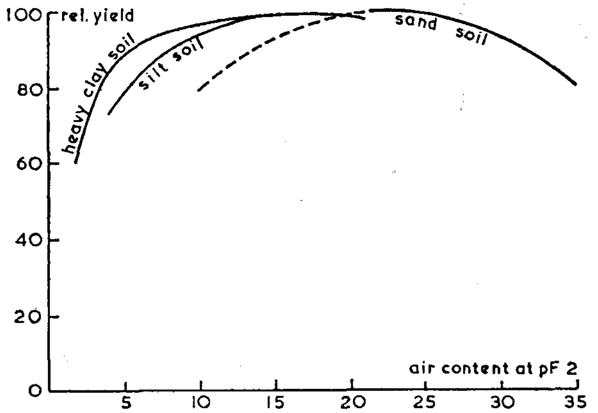


FIG. 7.
Average relation between soil structure, characterized by air content at pF 2, and yield on different soil types

The air content at pF 2 corresponding to the maximum yield appears to be highest on the sand soil and lowest on the heavy clay soil, if the soils have about the same organic matter content. The silt soil occupies an intermediate position. Therefore the optimum air content at pF 2 decreases if clay content increases. A lower mechanical resistance of the heavier soils to the penetration of plant roots may contribute to this phenomenon, in the same way as was found for the influence of the organic matter percentage on sand soils.

The spatial arrangement of the particles in the soil, desired for good plant growth, depends apparently on the nature of the soil, especially on the clay and organic matter content.

Use of the obtained results for soil cultivation purposes on clayey soils

Clod-size distributions are often more convenient to characterise the effect of tillage operations than air content at pF 2. Therefore we tried to relate the optimum visual structure estimation for clayey soils (5½—6) with aggregate size. With the method of visual estimation of soil structure not only a value (St) is given as a general index for the soil structure, but the porosity of the soil and the size of aggregates or clods are also evaluated (in a range from 1 to 10). A porosity P = 1 means a dense, P = 10 a very porous soil. An M-value (indicating aggregate size) of 1 means that the soil exists of single grains and M = 10 indicates a massive soil.

Making these estimations for a great number of clayey soils, we found good relationships between the three aspects St, P and M (FIG. 8).

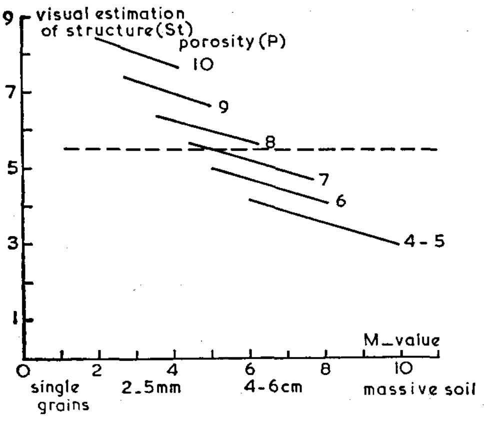


FIG. 8.
Relationship between soil structure, porosity and aggregation as estimated by visual structure evaluation

The St-values increase if the M-value decreases and if the P-value increases. This means that the visually estimated soil structure will be the better the smaller are the clods and the greater is the porosity. Furthermore, the relation between P and M is such that a low porosity mostly corresponds to big clods and a good porosity to smaller clods.

Considering now that on clayey soils a St-value of 5½—6 is required to obtain a good crop growth, it can be seen from FIG. 8 that this structural state is obtained on soils with a low porosity (6—7) if the M-value is about 3—5, which corresponds to an aggregate diameter of about 5—10 mm. On soils with a good porosity (8—9), an M-value of 6—8, corresponding to an aggregate size of about 5—10 cm will be sufficient. Thus the desired degree of crumbling, to obtain a St-value of 5½—6, depends on the porosity of the soil. A dense soil should be crumbled more intensively than a porous soil.

For sand soil it is not yet possible to convert the requirements for optimum soil structure, expressed e.g. in terms of air percentage at pF 2, into required aggregate sizes.

It is believed however that the results, mentioned above, for clay soils may be useful with respect to tillage on these soils.

LITERATURE

1. FERRARI, TH. J., R. P. H. P. V. D. SCHANS and F. SONNEVELD — Het verband tussen de opbrengst en de aan de hand van enkelvoudige profielkenmerken geschatte hoeveelheid vocht. *Landbouwk. Tijdschr.* 69 (1957) 771—775.
2. HIDDING, A. P., and C. V. D. BERG — The relation between pore volume and the formation of root systems in soils with sandy layers. Transactions Vol. 1, 7the Intern. Congress of Soil Science, Madison, Wisc., U.S.A. 1960.
3. KUIPERS, H. — Een streekonderzoek, gericht op de factoren bodemstructuur en stikstofbemesting. *V.L.O.* no. 61.9, 1955.
4. PEERLKAMP, P. K. — A visual method of soil structure evaluation. *Meded. v. d. Landbouwhogeschool en Opzoekingsstations v. d. Staat* te Gent 1959. Deel XXIV, no. 1, 216—221.
5. WIERSUM, L. K. — The relationship of the size and structural rigidity of pores to their penetration by roots. *Plant and Soil* 9.1 (1957), 75—85.