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PHYSICAL SOIL DEGRADATION IN THE NETHERLANDS

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CONTENTS

1. INTRODUCTION

Soils used in agriculture are subjected to a wide variety of human activities. Soil tillage and soil improvement operations may loose the soil, while soil wetting due to rainfall, and farming operations as sowing, spraying, weed control and harvesting but also grazing cattle may compact the soil. Compaction may also be caused by land levelling, grading and heavy loading from earthmoving machinery in land consolidation schemes.

All these activities go with stresses in the soil. To withstand these stresses the soil reacts in some way. When this reaction is an elastic one soil density and structure will be temporarily changed only over the time that the stress is exerted. When this reaction is a plastic one, soil density or structure is definitly changed. The latter will be the case after soil tillage, soil compaction and drainage installation.

The processes occurring when the soil structure is deteriorated by the impact of raindrops are more complicated. Due to energy dissipation, not only stresses are exerted at the soil surface, but also a transportation of soil particles occurs in consequence of splashing raindrops. The latter process may result in a surface seal, impeding the infiltration of rain.

In agriculture soils function as a substrate for crops. Given the boundary conditions for crop growth: rainfall, sunshine, temperature, wind velocities, air humidity, initial depth of water table, maximum rooting depth, only depending upon physiology of the plant, available nutrients, the theoretical maximum crop yield will be obtained when the yield cannot be increased by changing soil density or structure. This means with regard to crop yield, that an optimum density and structure of the soil layer above the deepest groundwater table must exist.

Physical soil degradation may then be defined as that change in soil density or structure of the relevant soil layer emanated from external influences, which decreases crop yield. However, this definition does not need to be unique, because in agriculture crop yield is not the one target. The main objective is to earn an income and that simply is the difference between costs and benefits of farming. Therefore a second function of the soil in agriculture must be considered too.

This function is the trafficability of the soil. Generally it can be said that the denser and the drier a soil the higher the bearing capacity. This means that a loose soil has to be drier than a dense soil for reaching a certain bearing capacity value. Under the weather conditions prevailing in the Netherlands a dense soil has a larger number of days per year that the bearing capacity exceeds some value than a loose soil. Assuming that compactions may not occur, the costs of field operations which must be performed within a certain span is higher on a loose than on a dense soil.

Therefore a complex relationship between costs (of soil tillage, harvesting, land levelling, etc.) and soil density must exist and a such one that within some boundaries the cost increases when the soil density decreases and reversely. Within a certain range also an opposite relation can be assumed to exist between crop yield and soil density.

With reference to the maximum benefit an optimum soil density will exist, depending upon the level of mechanisation. In a period of increasing labour costs it may be profitable to invest in machinery with higher capacity. Assuming compaction may not occur, the average bearing capacity can be too low, however. In that case a limited compaction and decrease in crop yield may be acceptable. This compaction occurring by external stresses, may be considered as a physical soil degradation, when the latter is defined as a change in soil density and structure which exceeds that value necessary to obtain the maximum benefit. With regard to the maximum profit one can only define a physical soil degradation if the reference soil structure and density is known and the reference mechanization level is accepted.

To evaluate whether there will exist a probable soil degradation when changing a mechanization level, the impact of this change on both soil density and structure has to be investigated. But at the same time one has to investigated the effect, duration and costs of soil loosening because these costs may be lower than the losses as result of an additional soil compaction.

In this paper an outline will be given of the extent to which soil degradation may occur. For a better understanding of the consequence of soil degradation and its control some results of investigations on soil degradation in the Netherlands will be presented and recommendations for further research will be formulated.

2. DEVELOPMENT IN AGRICULTURE

2.1. Land use in the Netherlands

In the Netherlands about 2.1 million hectares are used for agriculture. Of this area 61% is used for grassland and 39% for arable land. On the various soil types these percentages may vary as is shown in Table 1.

Table 1. Land use in the Netherlands in 1976 (after BUSZ, 1979, and VAN DAM, 1979)

Soil type	Total area ★ 1000 ha	Percentage of this area used as	
		grassland	arable land
Clay	808	55	45
Sand	954	65	35
Peat	249	75	25
Loam	62	35	65
Total	2073	61	39

From 1900 large areas of land are lost for agriculture by urbanization (new towns, roads, harbours, industries, etc.). However the total area of agricultural land is not changed much due to the reclamation of new polders in the IJssel Lake (VAN DAM, 1979). From 1950 the area

Table 2. Livestock in the Netherlands (x 1000)

	1900	1921	1940	1960	1970	1975
Cows	1656	2063	2,690	3,507	4,314	4,956
Pigs	747	1519	1,288	2,955	5,533	7,279
Sheep	771	668	574	456	575	760
Chickens	4300	9700	34,900	42,400	55,400	68,053
Horses	295	364	326	187	46	19

of arable land is decreased with about 7%, while the area grassland increased. The growth of livestock since 1900 is considerably as can be read from Table 2.

In the number of cows store cattle is included. The number of cows per ha grassland was 3.9 in 1975 while the number of dairy cows was 1.8 per ha. In some regions with sandy soils dairy farms with a very high cattle density per ha (3 to 4 dairy cows per ha) are found. There silage maize is grown as an additional fodder. The area with this crop amounted to 6400 ha in 1970 and 126,000 ha in 1979 (COOLMAN, 1980). On these maize cropped sandy soils cow and pig slurry is distributed during winter and spring. As in some cases storage capacity of slurry is lacking (on 13% of the dairy farms with 70 to 160 dairy cows, VOERMANS, 1976) or is insufficient, it is inevitable that the slurry is distributed under bad soil conditions.

Table 3. Crop yield (average) in 1000 kg per year, and area of that crop in 1000 ha (after VAN DAM, 1979)

	Period							
	1901/1910		1931/1940		1961/1970		1975	
	area	yield	area	yield	area	yield	area	yield
Wheat	58	2.2	129	3.0	144	4.4	108	4.9
Oats	142	2.1	144	2.4	97	3.8	34	4.6
Barley	32	2.6	36	3.0	103	3.8	84	4.0
Rye	218	1.7	210	2.2	87	3.0	18	3.5
Potatoes	135	12.0	110	20.0	87	31.5	78	33.0
Sugar beets	45	30.5	43	37.5	90	45.0	137	43.4

In a number of cases intensifying the dairy farming goes with stock keeping housed during all the year. Foraging has to be performed over the whole growing season, even under unfavourable soil condition. Moreover, irrigation on these farms is indispensable to guarantee a continuous grass production. Frequent irrigation decreases the bearing capacity of the sod.

The change in the area of different crops since 1900 is shown in Table 3. It can be seen from that table that the area of sugar beets is steadily increased, while the area potatoes shows a tendency to decrease. This implies that the area where harvesting is done under bad soil conditions increases. Moreover there exists an increasing tendency to distribute slurry over land where sugar beets will be grown. This operation has to be done before sowing date, that means before half April.

2.2. Farm size and mechanization

The number of farms decreases continuously. In the period 1959-1965 this number changed from 175,878 to 152,716, a decrease of 2.3% per year (PROMPERS, 1969). In 1975 the number of farms was 124,510 and in 1978 102,446 (COOLMAN, 1980). A farm size distribution is shown in Table 4.

Table 4. Number of holdings in the Netherlands (after COOLMAN, 1980)

Area	1975	1978
<5 ha	12,793	13,731
5-10	36,613	19,773
10-15	29,169	36,134
15-20	19,190	-
20-30	16,120	18,232
30-50	8,611	11,170
>50	2,014	3,406
Total	124,510	102,446

As the average farm size increases, mechanization has been intensified, which is reflected by the increase in the number of tractors. In 1975 about 158,000 tractors were used in agriculture and 160,000 in 1980. It can be expected that this number will decrease to 152,000 in 1985 and 137,000 in 1990 (CRUCQ, 1980). The engine power of the tractors will increase more and more, however. Table 5 shows the types of tractors used on the different soil types and farms of different sizes.

Table 5. Tractors used in 1975 on holdings of different size on sandy soils (A), loess soils (B) and clay soils (C) (data after VAN DER HAM, 1978, and PREUTER, 1978)

Area arable land per holding (ha)	Percentage of holdings with tractors having engine power											
	50 hp			50-70 hp			70-100 hp			100 hp		
	A	B	C	A	B	C	A	B	C	A	B	C
15-20	79	90	92	34	28	8	1	3	8	-	-	-
20-30	73	81	98	46	54	51	5	16	21	1	-	-
30-40	81	89	69	63	82	66	11	14	24	0	-	-
40-50	83	86	95	64	76	86	20	33	27	-	-	-
50-75	85	82	88	65	64	81	44	45	75	1	-	-
>75	77	100	89	91	100	89	68	67	44	18	-	-

From Table 5 it can be derived that the number of tractors per farm is 1.14 on farms with 15-20 ha, 1.9 on farms with 40-50 ha and 2.48 on farms with more than 75 ha. It can also be concluded that the engine power per tractor is lower on large than on small farms. This does not mean that on small farms no tractors are used with high engine power.

On small farms potatoes, sugar beets and silage maize are mostly harvested by contractors, who use machinery with a high capacity. These machines operate at relative low costs per ha. Sugar beet harvesting goes with the lowest costs when using a six row machine on a large area (TANIS, 1975). In combination with these harvesting machines wagons with a high loading capacity (3 to 10 tonnes) are used. From about 1975 the engine power of tractors is strongly increasing as is pointed out by COOLMAN (1980).

The distribution of cow and pig slurry requires slurry tankers. In 1975 such tankers were available on 79% of dairy farms with more than 70 to 160 cows (VOERMANS, 1979). The load capacity of the tankers can be up to 15 tonnes. The wheel loads vary from 2.5 to 7.5 tonnes. In 1975 about 20,750 tankers were available while this number was 25,000 in 1980 (COOLMAN, 1980).

On dairy farms wagons are used for foraging. These have load capacities up to 10 tonnes. Most of the transportation machinery is equipped with relative small tires, with an inflation pressure of about 3 bar.

2.3. Land consolidation

In the Netherlands land consolidation schemes are performed to improve water control and drainage, to increase the area of the parcels by filling up ditches and to level the land. About 40,000 ha is annually invested in the consolidation programme. This involves earth moving on a very wide scale with heavy equipment. Depending on the extent of earth moving 13 to 35% of the soil surface is touched by wheels or tracks. The number of passages over the same spot is very high and sometimes more than 80 times (BOELS, 1980).

3. SOIL DEGRADATION IN THE NETHERLANDS

3.1. Extent and type of soil degradation

Some developments in agriculture result in probable soil degradation. A growing livestock is coupled with an increasing need for distribution of slurry also when the soil conditions are unfavourable. This spraying is carried out with heavy loaded slurry tankers. Especially on arable soils where silage maize is grown, soil compaction may arise. In a crop rotation of about once per three years, an area of about 500,000 ha sandy soils may be compacted, not only due to distribution of slurry but also due to harvest operations with the usual heavy equipment.

Harvesting potatoes and sugar beets about 50 to 80% of the entire soil surface is touched by wheels of the harvest and transportation machines (LUMKES, 1976). It is estimated that at least 10% of the area of sugar beets is harvested under bad soil conditions, causing deterioration of the structure of the arable layer and probably compaction of the subsoil. This implies at a crop rotation of once per four years a soil degradation over an area of about 55,000 ha within a span of four years.

In land consolidation operations a mean area of about 8000 ha per year is frequently touched by wheels and tracks of heavy earth moving equipment. On a part of this area soil compaction extends to the subsoil. The latter occurs annually over an area of about 1000 ha.

From Table 3 it can be read that our crop yields are fairly good. Nevertheless they are far beyond the theoretical maximum attainable under the weather conditions prevailing in the Netherlands. VERHAEGH (1979) reports a yield of 8.5 tonnes winter wheat per ha and WIEBING (1979) 85 tonnes (starch) potatoes per ha. These yields approximate the theoretical maximum yields and could only be obtained by optimizing soil tillage, plant nutrition, water supply and pest control, while as early as possible must be planted or sown at the right moment. Frost injury was prevented by sprinkling irrigation.

ZACHARIASSE (1974) proved that in practice a number of failures is regularly made, causing a reduction of crop yields. One of the failures is that soil tillage is carried out under sub-optimum soil conditions. This goes with deterioration of soil structure and compaction of the top soil. It may be assumed that over an area of about 10 to 20% of the arable land (80,000 to 100,000 ha) these failures are made. On comparable farms with an area of about 33 ha all the failures together caused differences in annual returns up to 50,000 guilders in 1968 and up to 110,000 guilders in 1969. These returns are measured as 'net revenue', i.e. gross returns minus all fixed and variable costs, excluding those for the farmers managerial and risc-bearing functions.

3.2. Compaction characteristics

Compaction can be considered as an increase in bulk density, resulting from external forces, acting on the soil, due to human activity. The degree of compaction can be defined accordingly to SCHOTHORST (1963) as a relative density:

$$\rho_r = \frac{\rho - \rho_{min}}{\rho_{max} - \rho_{min}}$$

where ρ_r = relative density
ρ = actual bulk density (kg.m^{-3})
ρ_{min} = minimum bulk density (kg.m^{-3})
ρ_{max} = maximum bulk density (kg.m^{-3})

The minimum bulk density is that density, which is just in equilibrium with each degree of saturation. The maximum dry bulk density is that density which is obtained at some prescribed state of stress. An example is given for sandy soils with different organic matter content in Fig. 1.

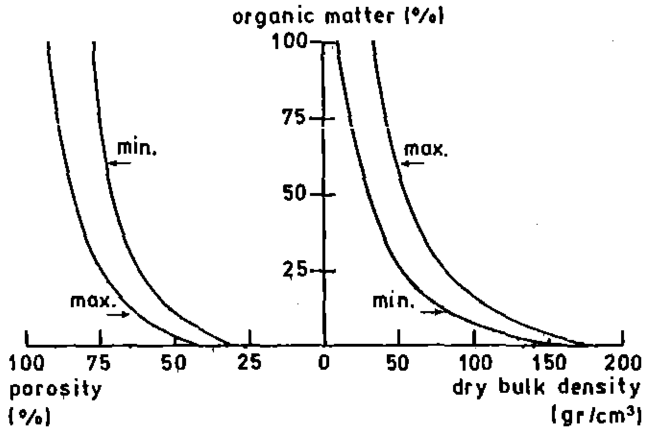


Fig. 1. Minimum and maximum porosity and bulk density of natural sandy soils with different organic matter content (after SCHOTHORST, 1963b)

Soil properties as bearing capacity and penetration resistance are related to the (relative) density. Based on the relationship between penetration resistance and density, the penetrometer is often

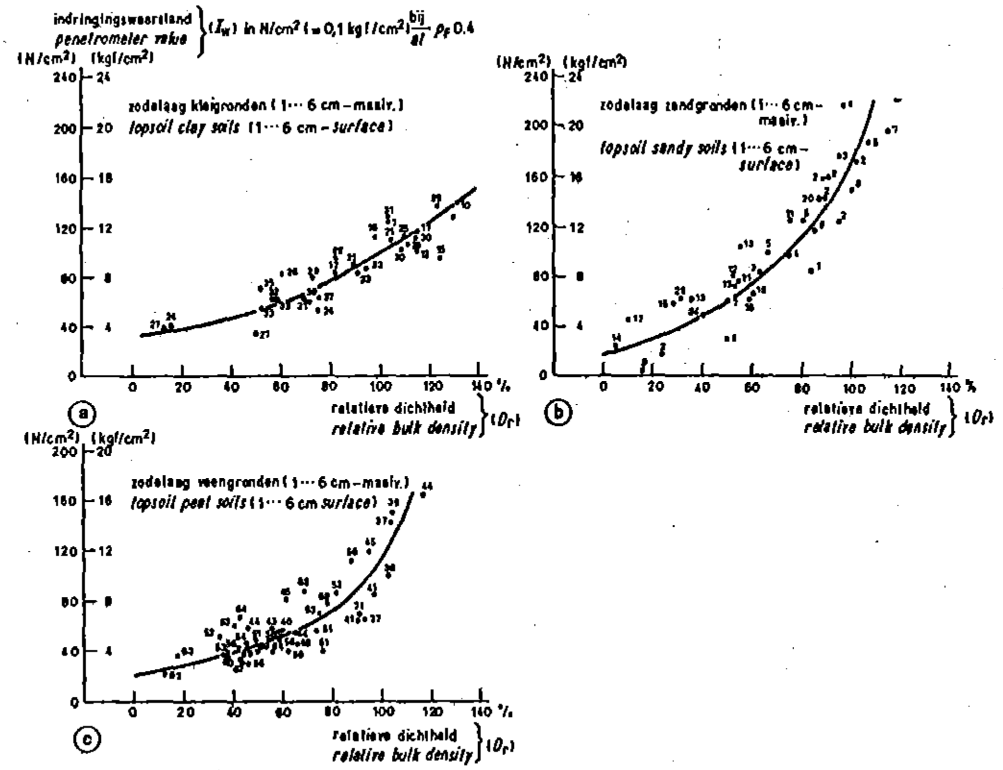
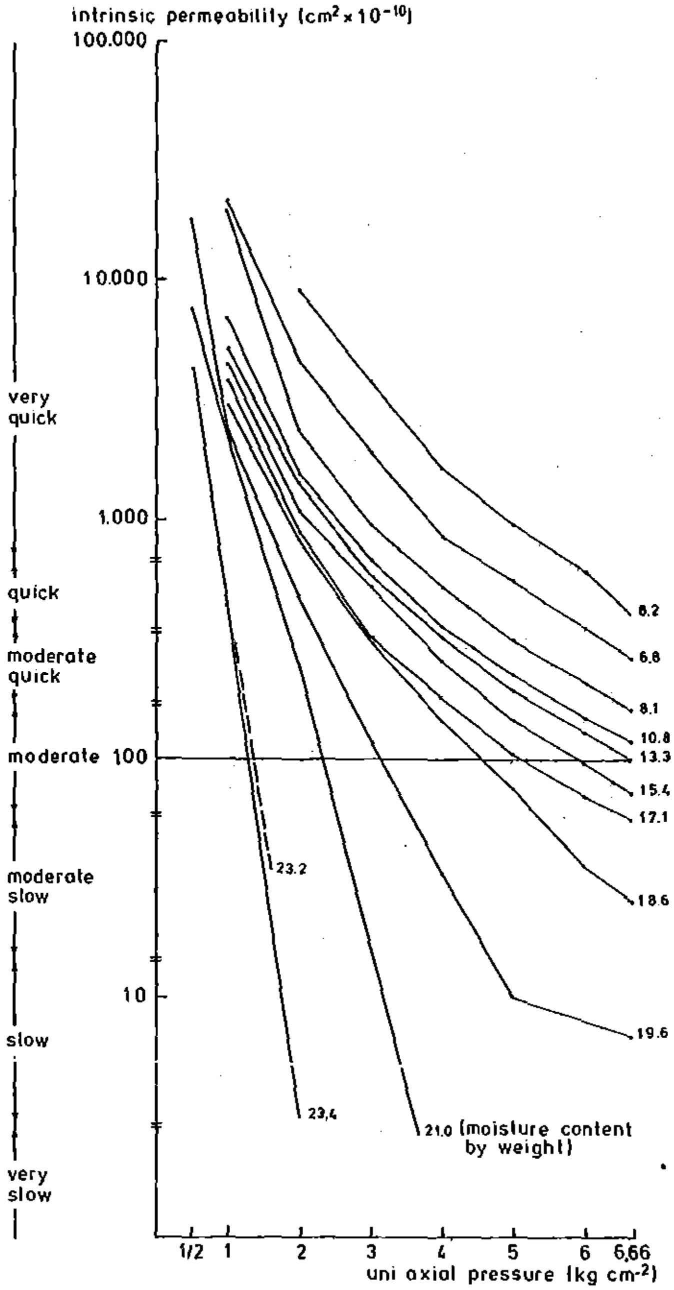


Fig. 2. The relation between penetrometer value and relative density for (a) clay, (b) sand and (c) peat soils. The numbers at the plotted points indicate the weight percentage of organic matter (after SCHOTHORST, 1968)

used as a measuring device to obtain qualitative or relative information about soil density. The measurements must be carried out under defined moisture conditions of the soil, as the latter is mostly a predominant factor. A relationship between penetration resistance and relative density at a suction of 3.5 mbar of a top layer in grassland is shown in Fig. 2. From this figure it can be concluded that these relationships are not unique, but depend upon the type of soil.

A quite different method of characterizing soil density is developed by HAVINGA and PERDOK (1969). This method consists of determination of the relationship between the uni axial pressure at different moisture contents and the resulting air permeability. Such a relationship is

Fig. 3. Intrinsic air permeability versus uni axial pressure at different moisture content of a loamy sand (after HAVINGA and PERDOK, 1969)



shown in Fig. 3. A combination of axial pressures and air permeability limits is used to derive the soil water content maximally acceptable for tillage (PERDOK, 1976).

3.3. Density profiles of some soil types

A frequent traffic occurs over the soil in agriculture. During harvest about 50% and more of the area comes into contact with wheels.

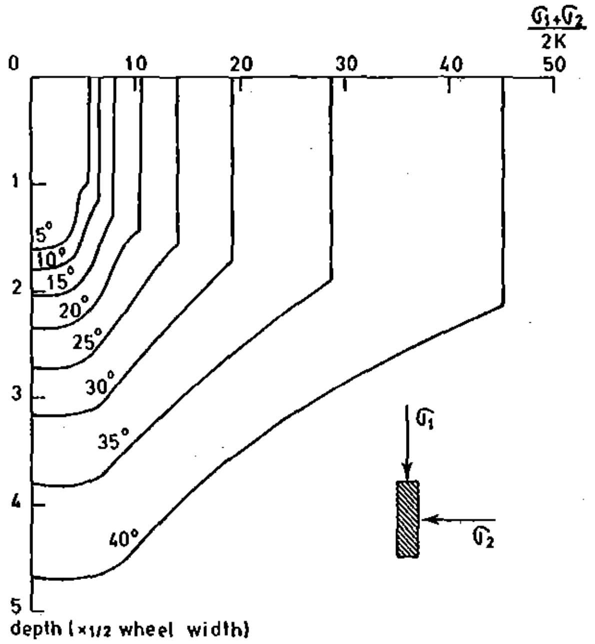


Fig. 4. Relationship between reduced hydrostatic pressure and reduced depth for different values of the friction angle (K-cohesion)

(LUMKES, 1976). Doing this implies that over a sequence of years with varying moisture conditions the bulk density profiles will come in an equilibrium with the stresses, acting on soil during field operations.

If it is assumed that loading of the soil with wheels is identical to a strip load with a uniform load distribution in the soil - strip interface assuming plastic equilibrium and neglecting the weight of the soil the stress distribution in the soil can be calculated accordingly to PRANDTL (1921). In this connection the soil behaviour must be assumed to be perfectly plastic.

From the stress distribution along the enveloping slipline a relationship between depth and maximum 'hydrostatic' pressure is derived and shown in Fig. 4. The maximum pressure in the interface wheel - soil is then calculated with:

$$P_{max} = \frac{K}{tg\ \delta} \{e^{\pi\ tg\ \delta} \frac{1 + \sin\delta}{1 - \sin\delta} - 1\}$$

where P = maximum pressure under wheel

K = cohesion

δ = friction angle

The cohesion is related to soil water pressure, assuming δ is independent of the moisture content, as:

$$K = K_o - \psi.\chi.\mathrm{tg}\ \delta$$

where K_o = cohesion at $\psi = 0$

ψ = soil water pressure (negative in unsaturated soil)

χ = relative contact area water - solids

The friction angle δ depends upon the bulk density in such a way that the higher the bulk density the higher the friction angle.

From Fig. 4 it can be seen that the depth to which stresses acting on the soil depends upon the width of the loaded strip i.e. the width of the wheel. Moreover it can be concluded that the density profile must have such a shape that over a certain depth the bulk density is constant and then decreases till the bulk density comes in an equilibrium state with the overburden pressure ($\simeq \{\gamma.z - \psi.\chi\}$).

Density profile can be estimated if the relationships are known between ρ and δ and between δ and K_o. Moreover it must be known which load P_{max} in combination with the width of the equivalent strip and a certain soil water pressure, determines the density profile. These investigations are started (on a laboratory scale), but up to now data are lacking to predict density profiles under field situations.

However, the presented theory may be used to explain the density profiles presented in Fig. 5. The bulk density profiles are selected

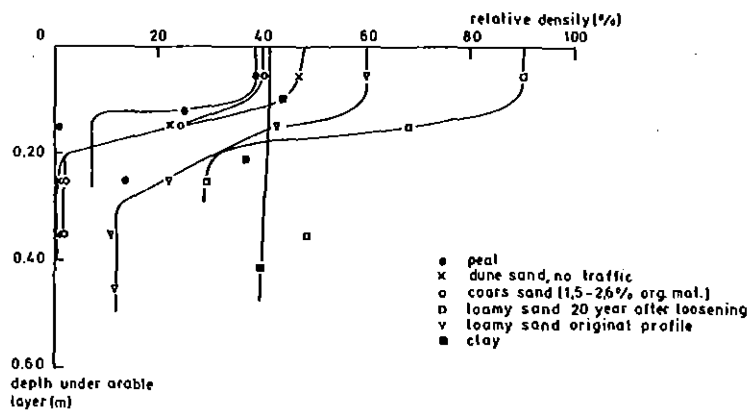


Fig. 5. Density profiles of some soil types

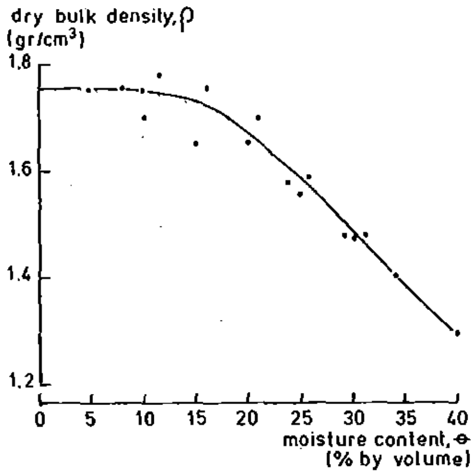


Fig. 6. Bulk density versus moisture content for a clay soil (after BEEKMAN et al., 1977)

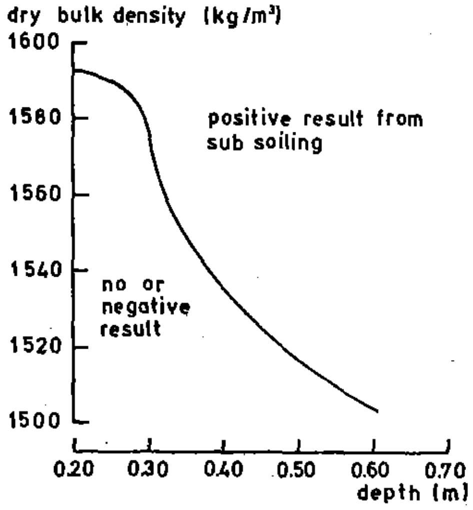


Fig. 7. Critical dry bulk density profile at which soil loosening has a long term effect on sandy and loamy soils (after HAVINGA, 1975)

in such a way that they are only a result of human activities. It must be noticed that other processes have also influence on the bulk density. Drying and wetting of clay soils result in shrinking and swelling respectively. On such soils it is difficult to determine the influence of farm traffic, because the moisture condition has a great influence as is shown in Fig. 6.

The density profile of the dune sand comes from an experimental plot where about 20 years ago the dense soil was loosened. Pine trees were planted and there has been no traffic up to now. The present density of the top layer is a result of drying.

The strength of the soil is not only determined by the bulk density but also by some cementing of the soil skeleton. When these cemented soils are loosened it is observed that the bulk density found some time after this operation may be higher than the initial bulk density (BOELS and HAVINGA, 1974a). From soil loosening experiments on both sandy soils with less than 2.5% organic matter and loamy sands with less than 3% organic matter, HAVINGA (1975) derived critical bulk density values. If a soil has a bulk density at some depth, higher than the critical density, the soil can be loosened with a probability of 90% that this operation has a long term effect (Fig. 7). The critical bulk density profile gives in fact some equilibrium state between bulk density and some average loading by farm machinery on non-cemented soils. This means also that soil loosening on soils with densities less than the critical value, has to be repeated to keep the soil in a loose state.

From Fig. 5 it can be concluded that under the arable layer a soil layer occurs with a rather high density. Analyzing the causes of the bad harvest conditions of potatoes and sugar beets in the very wet autumn 1974, BOELS and WIND (1975) found on 40% of 93 parcels on loamy sand and sandy loam a very dense layer below the ploughing sheet. DE KREIJ (1975) measured density profiles with a penetrometer (cone area 1 cm^2, top angle 60^o) on 500 parcels distributed over various soil types. Some results of this investigation are shown in Table 6.

Table 6. Groundwater table depth (cm), average penetration resistance I_w ($kg.cm^2$) and percentage of parcels with I_w > 25 $kg.cm^2$ directly under the arable layer (after DE KREIJ, 1975)

Soil type	Groundwater table depth		Average I_w		% parcels with I_w > 25 kg/cm^2	
	winter	summer	no silt	silty	no silt	silty
Black earth soil	>0.40	>1.20	16.5	17.3	0	5
"	0.4-0.8	>1.20	18.2	21.0	9	26
"	>0.8	>1.20	18.9	22.8	3	29
Brown earth soil	>0.8	>1.20	25.6	26.6	44	44
Vague soil*	>0.8	>1.20	25.6	26.6	45	70

*sandy soil with top soil with 1-2% organic matter, overlying a 0.2 to 0.4 m thick yellow brown sandy layer

Compared with penetration resistance of soils which were not compacted by field operations, all the objects investigated appeared to be compacted. This compaction was the highest in the brown earth soils and podsolic soils. A penetration resistance higher than 30 kg/cm^2 is assumed to represent a bulk density which impedes completely root penetration.

3.4. Field experiments on soil compaction

A number of field experiments on soil compaction due to offroad traffic are carried out. DE HAAN and WIND (1966) investigated density profile occurring after levelling deeply ploughed soils and DE HAAN and VAN DER VALK (1970) the growth of flower bulbs on differently packed sandy soils. BOELS and HAVINGA (1974b) studied the relationship between soil moisture conditions during levelling and compaction and between compaction and crop growth. BOONE et al. (1978) and VAN LOON and BOUMA (1978) investigated the influence of farm operations on compaction and the influence of different types of compaction on root growth and yield of potatoes. In this context it should be noticed that the pressure exerted by tracked vehicles on the soil is comparable with the pressure exerted by a number of rigid wheels in the same rut, as is pointed out by BEKKER (1962). Vibrations may cause compaction. To obtain compaction of dry loose sand without any overburden pressure, the accelleration during vibration has to be at least 1 g (g = accelleration due to gravity). At an overburden pressure of 0.7 bar this accelleration must be 1.8 g and at least 2.3 g at an overburden pressure of 1.75 bar. The maximum accellerations of bulldozers amounts to 1.05 g in vertical and 0.93 g in horizontal directions (HUIBERS, 1976). So it is not likely that vibrations generated by bulldozers have any influence on the compaction of moist sand and loamy sand.

The results of DE HAAN and WIND (Fig. 8) and of DE HAAN and VAN DER VALK (Fig. 9) reflect the influence of rut depth on the stresses, acting in the soil - wheel interface. This means that the additional rut depth at each subsequent passage is decreasing, causing higher stresses in the soiltrack interface. The measurements shown in Fig. 8 are carried out in the rut. The sharp decrease of the penetration resistance can be made reasonable with the theory of plastic equilibrium. Below the track a soil wedge penetrates into the soil, causing failure along some sliplines. The enveloping slipline starts at the top of

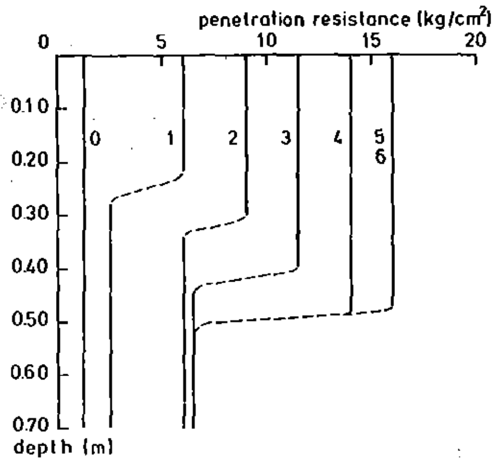


Fig. 8. Penetration resistance in the ruts on a deeply ploughed sandy soil, after 0, .., 6 passages of a bulldozer (Cat. D6) (after DE HAAN and WIND, 1966)

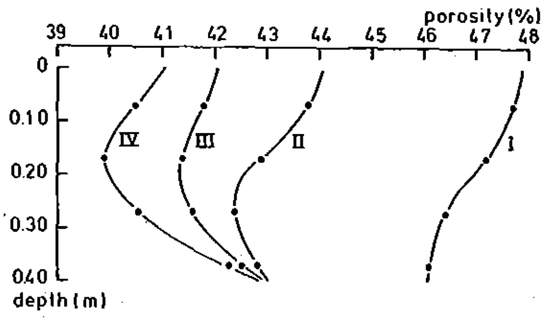


Fig. 9. Soil compaction by a bulldozer (Cat. D4) on a sandy soil. I. initial porosity, II. after 1 passage, III. after 3 passages, IV. after 5 passages (after DE HAAN and VAN DER VALK, 1970)

the wedge and ends at the soil surface. The form of this slipline may be discribed with some log-spiral. The increasing penetration resistance below the yield zone may be caused by a non-ideal plastic behaviour of the soil. As the 'hydrostatic' soil pressure is constant in the soil wedge under the track, the friction angle of the soil given in Fig. 8 can be estimated. The width of the tracks of the Cat. D6 is about 0.75 m. The reduced depth at which the penetration resistance is constant, in this case about 1.3 (= 0.48/0.37), is equal to the reduced maximum height of the soil wedge. From Fig. 4 it can be derived that the friction angle is about 15^{o}.

Fig. 9 gives density profiles found after complete touching of the area by a specified number of passages. The maximum depth at which compaction occurs is about 0.4 m. The width of the track of a Cat. D4 is about 0.33 m. So the reduced maximum compaction depth is about 2.4 (= 0.4/0.17) and a friction angle of about 26^{o} can be derived from Fig. 4.

Fig. 10 demonstrates that additional compaction occurs over greater depths when wider wheels are used as normally in agriculture. It con-

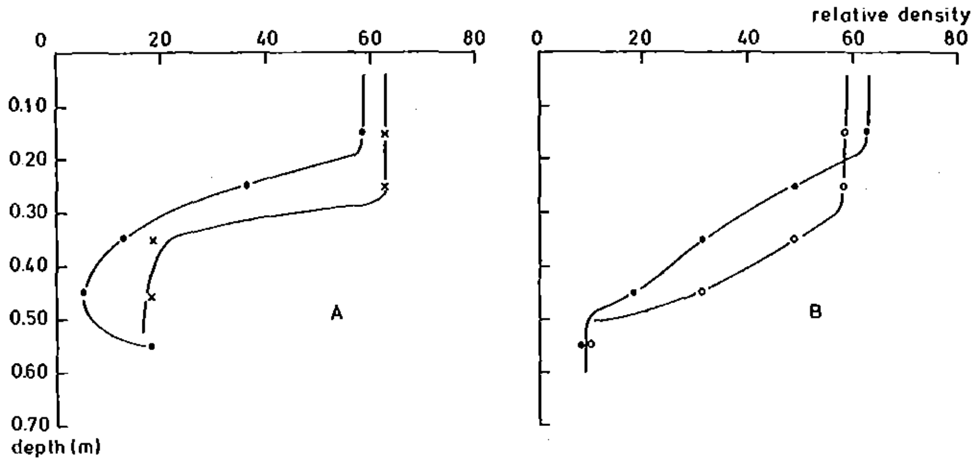


Fig. 10. Density profiles on a loamy sand after 8 passages of a bulldozer (Cat. D6). A. moisture content of the top soil 19%, B. moisture content of the top soil 23% (after BOELS and HAVINGA, 1974)

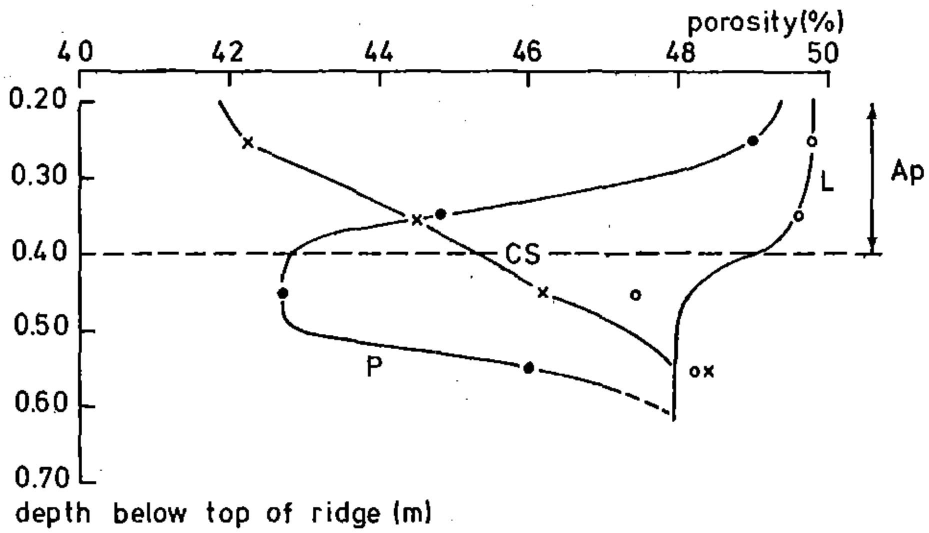


Fig. 11. Porosity after different treatments of a loamy sand soil. L. loose, not compacted, CS. strongly compacted, P. plough pan , strongly compacted below the arable layer (after BOONE et al., 1978)

cerns arable land both uncompacted and compacted by 8 passages of a track of a Cat. D6 and a soil moisture content of the arable layer of 19% (situation A) and 23% (situation B). The rut depth of the track was 0.02 on plot A and 0.08 m on plot B. This implies that the soil pressure was higher on the soil with the lower moisture content, but the soil strength is higher than on the plot with a higher moisture content.

The compaction patterns shown in Fig. 11 were obtained by different treatments of the soil. It concerns a soil recently reclaimed in the Flevopolder and therefore still hardly compacted by agricultural use. The treatments carried out after ploughing to a depth of 0.20 m are: loose, not compacted (reference), L; strongly compacted, achieved by driving four times over the entire soil with a heavy tractor (5.6 tonnes, inflation pressure 1.5 bar), CS; strongly compacted subsoil, achieved by removal of the arable layer and repeated driving over the exposed subsoil with a heavy tractor and a loaded wagon after which the top soil was redeposited, P. The latter treatment caused a plough pan and a porosity profile with the same shape as the density profiles shown in Fig. 5. Driving over the top soil as is done in the treatment CS, results in a porosity profile almost equal to treatment P. In this case there is a slight compaction of the subsoil. These findings imply that one should not drive with the tractor wheel in the open furrow during ploughing.

3.5. Soil physical properties

Soil can be characterized with a wide variety of physical properties. However, only those properties have to be determined which are relevant to the subject under investigation. In determining the influence of compaction on crop growth or on moisture regime, the moisture retention curve and the unsaturated hydraulic conductivity has to be known at different bulk densities. Figs. 12 and 13 give some retention and unsaturated hydraulic conductivity curves of two differently compacted soils, measured with an evaporation method (BOELS, 1978b). Up to now a theory is lacking to predict the change in the mentioned soil characteristics due to a change in bulk density. Moreover if the bulk density changes, the soil structure changes too. This behaviour influences also the soil properties. BOELS (1979) determined the influence of soil deformation caused by a drainage plough on the saturated hydraulic conductivity. From these experiments appeared that the saturated hydraulic conductivity of a loamy sand was not influenced by deformation, while the saturated hydraulic conductivity of silt loam and silty clay loam decreased sharply after some deformation.

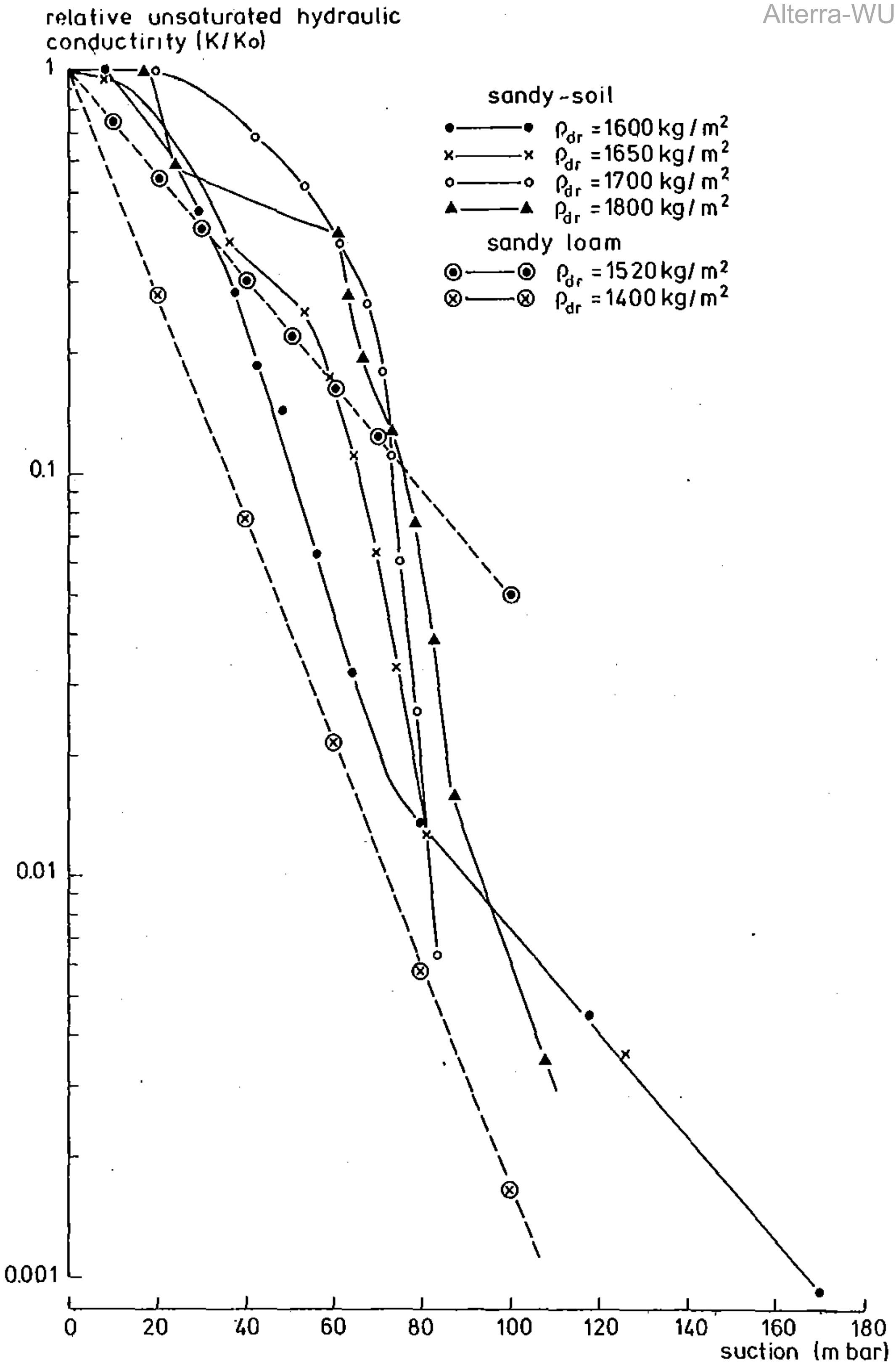


Fig. 12. Unsaturated hydraulic conductivity of a sandy soil (after ROSSI-PISA, 1978) and a sandy loam (after BOELS and VAN HEMMEN, 1975) at different bulk densities

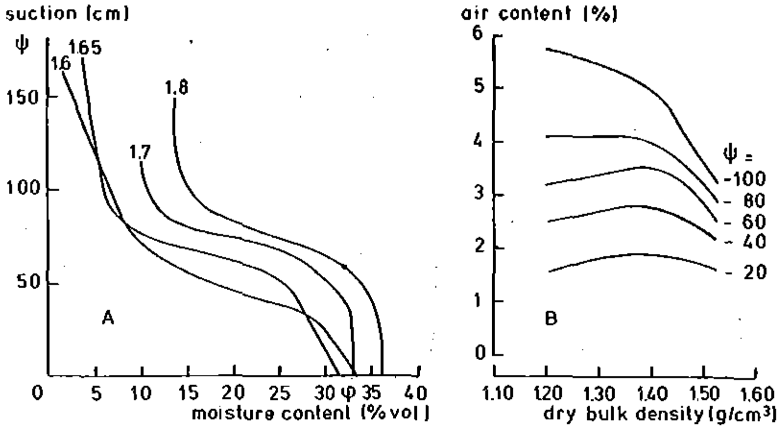


Fig. 13. Soil moisture retention curves. A. sandy soil (after ROSSI-PISA, 1978), B. sandy loam (after BOELS and VAN HEMMEN, 1975)

3.6. Compaction and plant growth

Soil compaction alters not only the pore volume, but also the pore size distribution. For a favourable root development a sufficient number of pores with a minimum diameter of 200 μm is required (WIERSUM, 1957). Root development is also correlated with the total pore volume. HIDDING and VAN DEN BERG (1961) concluded that the porosity of at least 40% is necessary for root formation in sandy soils. SCHUURMAN and KNOT (1974) confirm these results but observed that roots can penetrate a dense sand layer over a distance of a few centimeters.

Water and nutrient uptake is closely related to the rooting depth as is shown in Table 7.

If the thickness of a compacted layer (see Fig. 10) under an arable layer is not too high, roots can penetrate this layer. However, an increase in thickness inhibits root penetration.

Fig. 14 shows the relationship between rooting depth and increase in the thickness of the plough pan. The latter variable is expressed as a lowering of the surface.

Table 7. Water and nutrient uptake of oats in pot experiments. L - loose, porosity 43 to 46%, D - dense, porosity 39.9 to 40%, VD - very dense, porosity 33.9% (after SCHUURMAN et al., 1974)

Topsoil (0.25 m)	L	L	L	D	D
Subsoil	L	D	VD	D	VD
Proportional root weight(%)	100	82	50	60	45
Rooting depth (m)	0.71	0.53	0.30	0.50	0.27
Proportional water uptake(%)	100	76	28	61	22
Proportional N-uptake (%)	100	88	50	77	42
Proportional P_2O_5-uptake (%)	100	73	26	72	19
Proportional K_2O-uptake (%)	100	86	43	74	38
Proportional CaO-uptake (%)	100	93	78	72	57
Proportional dry matter production (%)	100	92	45	83	39

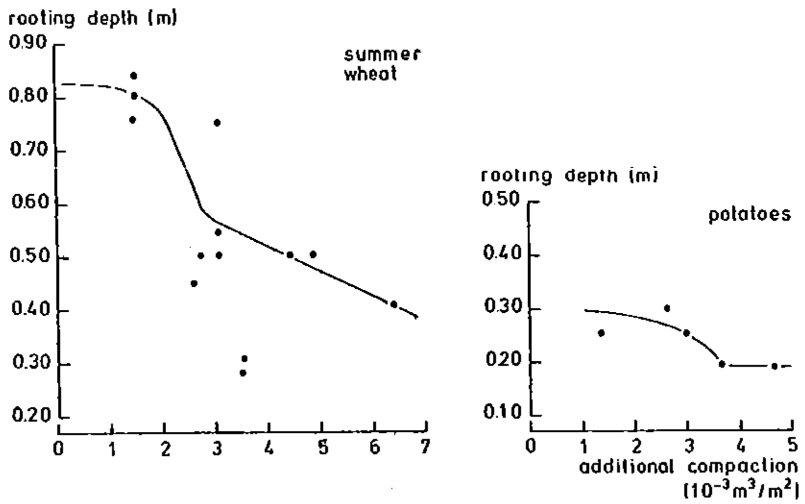
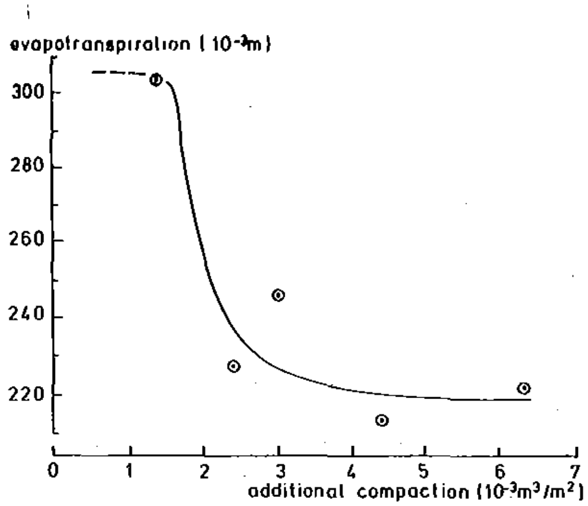


Fig. 14. Rooting depth versus additional compaction of the subsoil of a loamy sand soil

The crop yield depends largely upon the water uptake. Fig. 15 demonstrates clearly the decrease in water uptake with increasing compaction level. The nitrogen uptake did not differ systematically

Fig. 15. Evapotranspiration of summer wheat in 1975 on a loamy sand soil with additional compaction in the subsoil



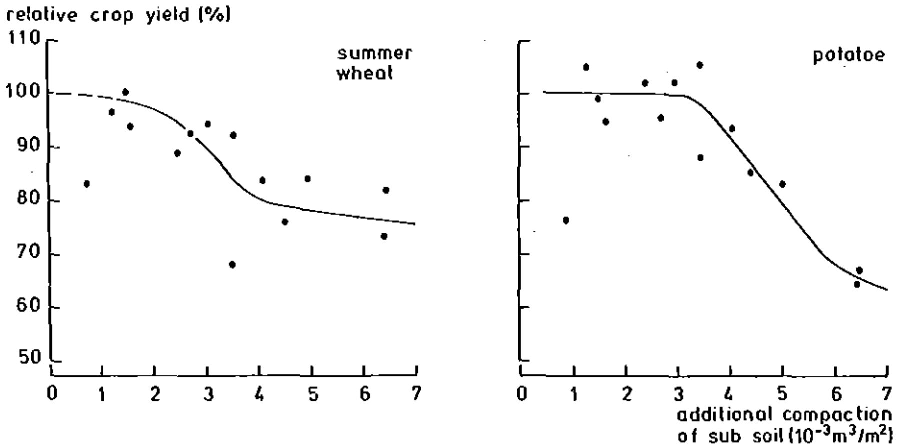


Fig. 16. Crop yield response averaged over the years 1973 through 1977 to additional compaction of the subsoil on a loamy sand

with the different evapotranspiration amounts. The average uptake was 102 kg N per ha, the maximum was 114 kg per ha and the minimum 84 kg N per ha. The relation between average crop yield and degree of compaction of the subsoil is given in Fig. 16. This relation reflects the differences in evapotranspiration of the crops.

Root development is a very complex process, depending on oxygen diffusion rate, mechanical resistance, water uptake and soil water pressure. To predict the rooting depth in compacted soils in different climates information is required about environmental conditions, causing dying of roots. Moreover the activity of micro organisms has to be known as these also consume oxygen. A preliminary model is developed

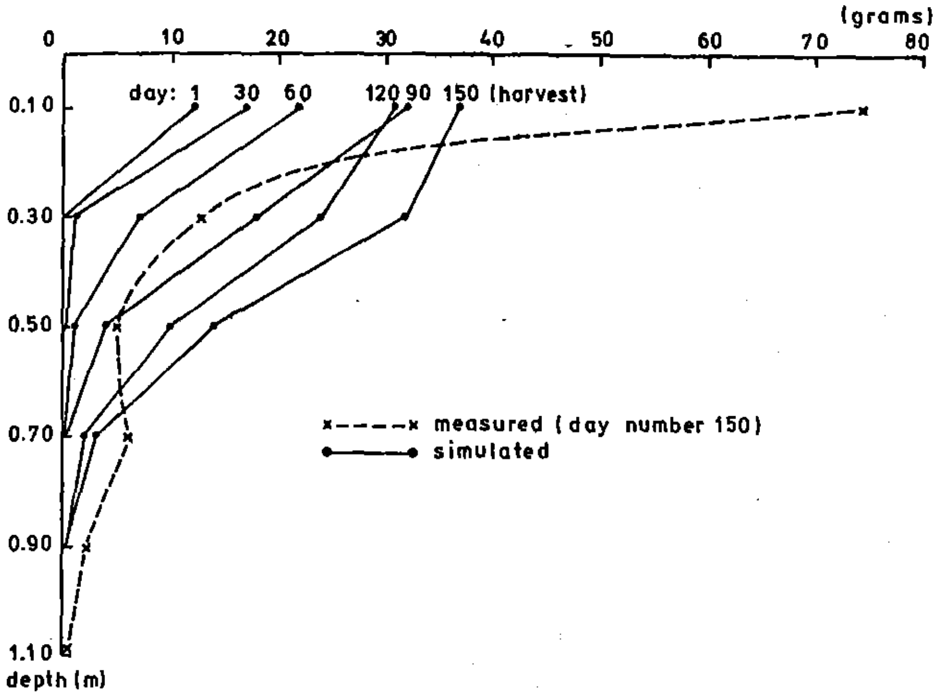


Fig. 17. Simulated distribution of roots (after VAN KEULEN, 1975)

by VAN KEULEN (1975). This model calculates crop growth, root growth, water and oxygen uptake. The model is applied to predict the root distribution of red cabbage (Brassica deracea L.: Rode Herfst). The results are shown in Fig. 17. The simulated root distribution fits not very exactly the measured one. However, a part of the difference between measured and a simulated root mass in the top layer is due to the so-called mathematical dispersion of the model. Nevertheless, the results are encouraging. More exertions are required to improve the model.

Compaction may not only result in a decrease of crop yield, it also affects the quality of the cash crop. VAN LOON et al. (1978) reports that potatoes grown on a loose soil (L, Fig. 12) had a net yield of 91% of the total yield. This percentage amounted to 88% on soils with a plough pan in the subsoil and 77% in the case of a compacted topsoil as in treatment CS (Fig. 12). This means that the structure of the topsoil has great influence on the quality.

Quite another effect of farm traffic is the injury to plants. LUTEN and ROOZEBOOM (1976) observed a decrease with 7% of the yield of grassland due to field operations. Grazing cattle and foraging can also damage the grass. These losses, calculated as the difference between gross yield and net yield, and expressed as a percentage of the gross yield are on poor drained sandy soils (mean of 4 years) 35% and 45% on poor drained peaty soils. These losses varied from 25% on sandy soils with a low humus content in a dry season to 55% on peat soils in a wet grazing season (SCHOTHORST, 1963a).

FEDDES and VAN WIJK (1977) mention that on peat soils the damage by grazing cattle and foraging is roughly 8% more under bad than under good drainage conditions.

3.7. Harvest costs-soil conditions

The harvesting of crops as potatoes and sugar beet have to be carried out in a season when rainfall exceeds evaporation. This means that the soil conditions grow ever worse with advancing autumn. Crop growth, especially of sugar beet, however is still going on. The average yield of sugar beets harvested on 1 September amounts to about 70% of the average maximum yield obtained at harvesting on 30 November. So it may be profitable to delay harvesting.

BUITENDIJK (1976) calculated by means of a simulation of the soil moisture conditions in the arable layer the mean number of days and time between 1 September and 30 November, with soil conditions suitable for the harvest of sugar beets. If for a large area the number of harvest machines is known, including the capacity, the number of days necessary to harvest sugar beets can be calculated. Knowing this number and the number of days and time with suitable soil conditions (expressed as a specified suction in the top layer), the date at which the harvest must start in that area can be determined. For the known harvest time the yield of sugar beets can be calculated from the relationship between crop yield and time.

The relationship between yield of sugar beets, soil conditions and number of days necessary to harvest the crop in some area, is shown in Fig. 18. This relationship holds for a probability of 80% that the total area will be harvested before 30 November.

The optimum soil conditions to perform field operations can be determined if the costs of the machinery and the cost of soil structure

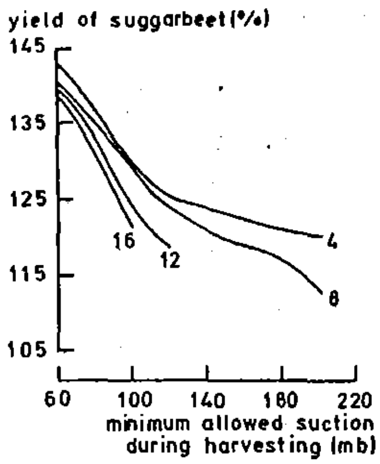


Fig. 18. Average yield of sugar beets at different suctions allowed in the arable layer during harvest, when 4, .., 16 days are required to harvest the total area on loamy sand (after BUITENDIJK, 1976)

Table 8. Maximum rut depth of earth moving equipment and relative operation costs (after BOELS, 1978a)

Maximum rut depth (m)	Number of workable days (1/9-30/11)	Relative costs (%)
0.10	30	100
0.12	40	75
0.17	50	60

damage due to unfavourable soil conditions are known. About the latter information is available. BOELS (1978a) calculated the relative costs of earthmoving if an acceptable rut depth is given. The results are shown in Table 8.

To select the worst soil conditions at which the execution of a specified field operation is still allowable, economical criteria have to be used. This means that some soil degradation may be profitable.

4. RECOMMENDATIONS FOR FURTHER RESEARCH

The boundaries of a physical soil degradation will be prescribed by economical arguments. To determine these boundaries an economical analysis is wanted and more information is needed than available at the moment. Therefore further research is required.

Firstly models have to be developed to predict soil compaction due to traffic. This demands new concepts of the behaviour of unsaturated soils under short duration loadings. It is desirable therefore to develop further the so-called critical state soil mechanics (SHOFIELD and WROTH, 1968). Furthermore theories have to be developed for a better understanding of the change of soil physical properties due to compaction and deformation. To predict the crop growth reaction on soil compaction and structure deterioration, the root growth model mentioned in this paper must be improved. At the moment it is not necessary to improve the available crop growth models.

Soil compaction and deterioration of structure are mainly caused by intensive traffic with machinery with high wheel loads and high inflation pressures (3 to 4 bar). Lowering the inflation pressures does not only reduce the maximum pressure in the soil - wheel interface, but also reduces the rut depth and the rolling resistance (KOOYMAN, 1969; PERDOK, 1976). An analysis is required to estimate which wheel equipment is most preferable in agriculture. In addition it is advisible to study how adaption of the farm system can prevent soil compaction through proper traffic control.

When it is possible to reduce the soil pressure under wheels, the problem arises how the soil can be loosened and which soils can be loosened with a long term effect. This requires to study the processes determining the ultimate density profile and the properties of soils without traffic. Only if these phenomena are known the influence of traffic on soil bulk density may be correctly evaluated.

5. SUMMARY

Physical soil degradation, defined as a change in soil structure and bulk density which decreases crop yield, is observed on all soil types except on clay soils with a clay (particles <2 μm) content higher than 35% by weight. Due to developments in agriculture physical soil degradation will continue. The growth of silage maize, 160,000 ha in 1980, requires an area of at least 500,000 ha at a crop rotation of about once per three years. On this area cow and pig slurry is distributed

with heavy tanks (5 to 15 tonnes) while the soil conditions will be unsufficient to withstand those loads without compaction or deformation.

It is estimated that about 10% of the area of sugar beets is harvested under unfavourable soil conditions. This means that within a span of four years soil structure is deteriorated over an area of about 55,000 ha, and probably some compaction of the subsoil is occurred. Performing land consolidation schemes (about 40,000 ha per year) involves earthmoving with heavy equipment. About 10 to 35% of this area is touched by wheels or tracks of the equipment. The number of passages over the same spot on this area is very high and sometimes more than 40 times.

Intensifying the dairy farming goes with keeping the stock housed during the entire year. Foraging has to be performed over the whole growing season, even under unfavourable soil conditions. Moreover irrigation on these farms is indispensable to guarantee a continuous grass production. Frequent irrigation decreases the bearing capacity of the sod. Field operations on grassland cause a decrease in grass yield of at least 7% and using heavy equipment, possibly more. In addition it must be noticed that much higher yield losses are caused by grazing cattle. These losses are on poorly drained grassland on sandy soils about 35% of the gross yield.

From experiments on soil compaction it appeared that soil compaction continues up to about 6 passages of wheels or tracks. The depth to which compaction occurs as well as the maximum bulk density increase with increasing number of passages. Density profiles reflect a certain equilibrium state between soil use and bulk density. This equilibrium density profile may be used to evaluate results of long term subsoil loosening. Long term effects of soil loosening can be expected if the actual density profile shows higher densities than the corresponding equilibrium bulk density.

Driving over arable soils with equipment which has wider wheels than normal used machines gives an increase in thickness of the 'plough pan'. This increase can be estimated with the theory of plastic equilibrium.

Crop growth response to soil compaction can be explained to a great extent from a decrease of the rooting depth and evapotranspiration.

It is shown that a small increase in thickness of the plough pan goes with a sharp decrease of rooting depth and therefore with a decrease of crop yield (about 20% on a loamy sand soil). For example the yield of potatoes is in a dry year about 35% higher on a loose soil than on a soil with a plough pan.

Harvesting sugar beets it may be profitable to accept a limited deterioration of the soil structure. This means under conditions prevailing in the Netherlands that if some structure damage is accepted, harvest time can be delayed. This implies a lengthening of the growing season and so a higher crop yield. Similar arguments hold for earth moving activities.

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