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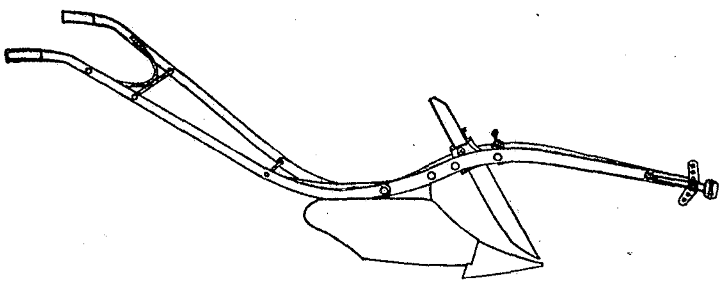

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WORKING GROUP ON SOIL COMPACTION BY VEHICLES WITH HIGH AXLE LOAD.
REPORT OF MEETING IN UPPSALA 1980.

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WORKING GROUP ON SOIL COMPACTION BY VEHICLES WITH HIGH AXLE LOAD. REPORT OF MEETING IN UPPSALA 1980.

Abstract.

An international working group was founded at a meeting in Uppsala, Sweden, in 1980. The primary aim is to start an international series of field experiments on crop response to subsoil compaction by vehicles with high axle load, and its persistence. The objective of the experiments is to form a basis for recommendations for upper limits of field application of axle load. The report contains summaries of research activities on soil compaction in the participating countries, and results of discussions about the need for new experiments, and about the experimental outline.

PREFACE

Field experiments with soil compaction by vehicles with high axle load were started in Sweden in 1976-1978 (see page 40) aiming at forming a basis for recommendations concerning maximum axle loads for vehicles trafficing arable fields. 26 ton vehicles (10 tons on a single front axle, and 16 tons on a rear tandem axle unit) were used.

The initial results show that high axle load may cause significant adverse effects on the crops, at least on some types of soils. Therefore it seems necessary to make a thorough investigation of the problem. Because the market for farm machinery is becoming increasingly international it is desirable to carry out an investigation of this kind, and to prepare any resulting recommendations, on an international basis. However, the effects, and hence the recommendations, may be strongly dependent on soils, crops, and climate, and international cooperation would suitably be restricted to physiographically reasonably uniform regions.

The Swedish experiments were presented at the poster session of the 1979 conference in Stuttgart-Hohenheim with the International Soil Tillage Research Organization (ISTRO). At the same time there were discussions on the formation of an international working-group on soil compaction by vehicles with high axle load, and on starting an international series of experiments. During these discussions, Northwestern Europe and similar areas in North-America were suggested as one suitable region.

For the possible start of an international cooperative work scientists from several countries in the region mentioned met in Uppsala, Sweden, on September 2-4, 1980. During the first part of the meeting a review was made of the research work on soil compaction carried out or in progress in the participating countries. The conclusion was that new experiments concerning the effects on soils and crops of traffic with very heavy vehicles were needed (see page 56). Therefore the participants decided to form a working-group and to try to initiate such experiments in their respective countries. During the second part of the meeting the joint experimentation was thoroughly discussed (aim, experimental outline, variables, measurements, applicability of results).

Available information shows that the higher the axle load the deeper in the soil the compaction effects penetrate and the longer they persist. At the highest axle loads in current use the compaction effects may penetrate deep into the subsoil. Compaction at the 40 cm level or deeper may persist for decades, even in areas with deep annual freezing. Tillage to alleviate the compaction becomes more difficult and expensive the deeper the compaction penetrates. In areas where compaction of deep subsoil layers normally gives significant adverse effects on the crops, it therefore seems advisable to restrict the axle loads to avoid such compaction.

The objective of the joint experiments is to form a basis for recommendations for upper limits of field application of axle load. For this purpose the experiments must be designed to reveal the depth and persistence of the compaction, and the crop response. In the end the compaction effects on different soils must be weighed against the technical benefits of using the high axle loads. This weighing must be made in close cooperation with agricultural engineers, farmers, and machinery manufacturers.

The farm machinery is very expensive and the axle loads used may have a large influence on the costs as well as the performance of the machinery. Therefore it is of great economic importance that the choice of axle load is based on knowledge rather than on belief or opinions in fashion. For some situations the final result of the experimentation may be that there is no need for axle load restrictions within the range of loads which is of interest from technical viewpoints. However, even a result in that direction will be of great importance, and justifies the experimentation.

It must be stressed here that the axle load limits recommended will, naturally, be influenced by the wheel equipment used. Furthermore, restrictions of the axle loads do not necessarily imply restrictions of the total weights of the vehicles. However, when the weights increase over certain limits the number of axles and wheels also must be increased. This may strongly influence the design of the vehicles.

It is my hope that the meeting will result in starting field experiments with soil compaction by vehicles with high axle load in several countries.

Some of the material presented at the meeting, as well as the results of the discussions, are summarized in the present report in order to disseminate information about the problem, to initiate a broader discussion about it, and to promote the experimental work.

Uppsala, October 1980

Inge Håkansson

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LITERATURE REVUES CONCERNING PLANT RESPONSE TO SUBSOIL COMPACTION

RESEARCH ON PLANT RESPONSE TO SUBSOIL COMPACTION BY VEHICLES IN NORTH AMERICA - A BRIEF LITERATURE REVIEW

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There has been extensive research on modification of subsoil compaction and plant response in the United States and Canada (Unger, 1979, and Barnes et. al., 1971). However, essentially all of this research has been done on soils having a naturally high density in the subsoil or having a distinct plow pan or hard pan, and very little research has been done on the specific problem of crop response to subsoil compaction caused by high axle loads on the surface of soils that are not naturally excessively dense.

Furthermore, little effort has been made to differentiate between subsoil and surface soil (tilled layer) compaction effects. With respect to the objectives of the International Working Group on soil compaction under high axle loads, it is desireable to know the extent and duration of compaction in the subsoil caused by the large heavy farm machinery in current use. Attention is directed to the subsoil because any compaction in the tilled layer is theoretically more easily managed with ordinary equipment and practices.

Axle loads of about 3 tons applied on surface of loamy sand to sand soil in eastern Canada increased the bulk density to a depth of about 50 cm (Raghavan et.al, 1976). Axle loads up to about 4.5 tons applied on the surface of a silty clay loam in Minnesota did not significantly increase bulk density below a depth of 30 cm, but did increase penetrometer resistance to a depth of 45 cm (Voorhees et.al., 1978).

Persistence of compaction in absence of deep frost penetration such as in southern United States is well documented (Barnes et.al., 1971). Elder (1958) reported persistence of compaction at a depth of 40 cm for at least 5 years in a Houston black clay, a soil that is annually subjected to shrinking and swelling. More recent research in Minnesota has shown subsoil compaction to persist for at least 10 years in clay loam soil annually subjected to freezing temperatures to a depth of at least 100 cm (Blake et.al., 1976). Even soil structural units subjected to annual tillage and weathering remained dense after being subjected to wheel traffic (Voorhees et.al., 1978).

A silt loam soil in Minnesota was subjected to a compactive effort of about 10 kg/cm^2 at a depth of 20 cm with the surface soil remaining uncompacted. Bulk density was increased by 7% at a depth of 25 cm and deeper. Corn yields were reduced by 3-4% (Adams et.al., 1960). When the surface soil was also compacted, the yields were further reduced, showing the importance of separating surface and subsoil compaction.

All of the above compactive forces were within the range of current axle loads of U.S. farm equipment. Combines, when fully loaded will have axle loads in excess of 12 tons and estimated soil-tire contact pressures of 10 kg/cm^2. Farm trucks will also have excessively high axle loads. Public road restrictions in the U.S. are currently 9-10 tons/axle.

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RESEARCH ON PLANT RESPONSE TO SUBSOIL COMPACTION BY VEHICLES IN NORTH-WESTERN EUROPE - A BRIEF LITERATURE REVIEW

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In northwestern Europe there has been a lot of research on the subsoil structure, but only a few papers with direct relevance to the theme of the meeting will be mentioned here.

Gliemeroth (1948) reports about traffic with very heavy military track vehicles over the experimental fields at Göttingen during World War II. No heavy traffic had previously occurred on the field - not even with heavy horses. The traffic increased the bulk density to a depth of 80 cm, adversely influenced the rooting of the sugar-beet crop the year after the compaction,and reduced the yield more than 50 per cent.

In two experiments on sandy loam soils in the Netherlands (van Ouwerkerk 1968) the layer 18-40 cm was artificially compacted. After the compaction soil cores were taken out several times during a period of 3 1/2 and 6 1/2 years respectively and some soil physical properties were studied. The compaction was found to be unchanged throughout the period studied.

Eriksson (1976) studied a field with clay soil where intensive traffic with heavy military vehicles had occurred during av 30 year period. Analyses of several soil physical properties showed compaction effects to a depth of nearly 1 m. The effects were very pronounced to a depth of 50 cm.

Danfors (1974) measured the vertical strain at several depths in the subsoil when vehicles of different axle loads moved over the measuring plots. The depth to which a certain strain occurred increased with increased axle load. At an axle load of 8 tons and higher the strains were considerable even at depths deeper than 50 cm When having used so heavy loads it was also possible to reveal remaining compaction effects two years after the traffic to a depth of 50 cm or more.

Håkansson (1979) reports about a study on a clay soil where one part of a field had intensive traffic with vehicles weighing up to 30 tons nine years earlier. Compaction was still observed especially in the 45-50 cm horizon.

Håkansson (1979) also reports about nine field experiments with heavy traffic started in 1976-1978 using a 26 ton vehicle, 10 tons on a single front axle and 16 tons on a rear tandem axle unit. Measurements two years after the traffic showed compaction effects to a depth of about 50 cm. The crop yield effects were considerable during the first years. They will be studied for a period of about ten years.

Heinonen (1979) discusses the concept of "normal bulk density" in the soil. The "normal bulk density" should be a function of the composition of the soil and of several environmental factors and is the equilibrium bulk density towards which the soil goes if the environmental factors stay unchanged. At incresed traffic intensity the "normal bulk density" of course will increase. This concept may be regarded when the subsoil compaction and their durability is studied.

Hartge (1979) presents another approach. In some situations it seems to be possible, by soil mechanical investigations and calculations, to reveal to which extent and depth the soil is "overconsolidated" by vehicular traffic.

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RESEARCH ACTIVITIES IN THE PARTICIPATING COUNTRIES CONCERNING SOIL COMPACTION

SOIL COMPACTION RESEARCH IN MINNESOTA

By Ward B. Voorhees, North Central Soil Conservation Research Center, USDA-AR-NCR, Morris, Minnestoa 56267

Current soil compaction research in Minnesota was started in 1973 and is concerned mainly with compaction in the tilled surface layer, about 0-25 cm depth. The field experiments are conducted on a clay loam soil typical for the corn-soybean areas of Iowa and Minnesota. Normal field-sized tractors are used with total weight ranging from 3,700 to 7,300 kg. In these studies, all wheel traffic is controlled to occur only between the rows, except in the tillage energy study where the entire soil surface is covered by wheel traffic.

Several soil parameters are measured to determine depth, intensity, and persistance of compaction. These measurements show that normal wheel traffic can cause compaction to a depth of at least 30 cm. This compaction has agricultural significance in three areas: 1) energy, 2) erosion, and 3) plant response.

1. Energy: Compared to the control treatment having no wheel traffic, the draft on a moldboard plow was increased by 25, 36, and 43% respectively when the soil was previously compacted by 1, 3, and 5 passes of a 7,300 kg tractor. The depth of the tillage was about 30 cm. Calculated fuel consumption was 3.3, 3.6, and 3.7 l/ha for respectively 1, 3, and 5 passes compared with 2.7 l/ha on the control.

   The greatest relative increase in the tillage energy requirements was caused by the first pass of the tractor wheel. This data would seem to favor the use of 4-wheel drive tractors instead of 2-wheel drive with duals.

2. Erosion: Soil erosion, by both water and wind, are serious problems in Minnesota and much of the United States. With row crops, such as corn and soybeans, the soil is often intensively tilled in the spring prior to planting. Canopy cover does not occur until some weeks later. During this period, the soil is bare and unprotected from rather intense rainstorms that commonly occur, and erosion can mean the loss of soil, fertilizer, and seed. Field experiments show that with a 6-row planter, wheel tracks from the tractor will cover about 22% of the total field surface area. However, 34% of the water runoff and 49% of the soil loss comes from these wheel tracks.

   When the field is tilled in the autumn after the crop is harvested, the wheel-tracked compacted soil often is very cloddy and rough. This can be beneficial because this type of soil surface can retain more autumn precipitation and is stable enough to persist over winter, thus giving some protection against spring erosion.

3. Plant Response: Crop yield is perhaps the most important aspect of soil compaction and is also the most difficult to predict because of its strong dependence on climatic factors. Years with near-normal precipitation resulted in a 25% yield decrease of wheat due to soil compaction. In 1976, a record drought year, wheat yields were increased by 53% with moderate soil compaction.

   These yield response were closely related to seed-soil contact and water supply and emphasizes the importance of seed bed preparation.

   Root crops, suchas potato and sugar beets, may be more consistently affected by soil compaction. On a clay loam soil, potato yields were always decreased by inter-row compaction, with an average decrease of 25%. In addition, soil clod production was doubled by the interrow wheel traffic. Depth of sugar beet rooting was about 1.5 meters in non-compacted soil compared to only 45 cm in compacted soil.

   Corn and soybean yields were significantly affected by inter-row compaction but generally in a positive manner. Seven years of data show a consistent positive effect of compaction for soybeans growing in a soil deficient in phosphorus content. The average yield increase was 11%. When plots were fertilized with phosphorus, the yield response was more variable but average 6% higher when there was wheel traffic between the rows.

   Corn yields were similar to soybean with a 26% average yield increase from compaction at low soil phosphorus levels, and 9% yield increase at high phosphorus levels. Corn yields were more variable than soybeans.

   These positive effects from interrow compaction are probably due to increased phosphorus uptake from the tilled layer when interrow compaction causes a higher root length density in the row, and from increased water uptake when interrow compaction encourages downward root growth into the subsoil rather than lateral root growth.

Submitted to Working Group on Soil Compaction by Vehicles with High Axle Load, Uppsala, September 1980

A NOTE CONCERNING WORK ON COMPACTION UNDER AGRICULTURAL VEHICLES IN SCOTLAND

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1. INTRODUCTION

Work on compaction at the Scottish Institute of Agricultural Engineering has been primarily concerned with the way in which soils respond to different types of wheels (Soane *et al.*, 1981a; 1981b). Little attention has been given to the effects of such compaction on subsequent plant growth. In planning such work it was felt that the techniques for measuring and expressing compaction under wheels were often unsatisfactory and not appropriate for replicated field experiments in which it is desirable to complete all soil testing operations very quickly if the results are to be unaffected by changing weather conditions.

2. TECHNIQUES

The techniques which have received particular attention are:

(a) gamma-ray transmission techniques for the measurement of changes in dry bulk density (Soane, 1976; Soane and Henshall, 1979)

(b) an electronic recording penetrometer for measurement of changes in cone resistance (Anderson *et al.*, 1980)

(c) a soil test vehicle on which instruments and operators can be carried to facilitate rapid testing without disturbance to the soil prior to passage of the test wheel (Soane, 1974).

We regard it to be of particular importance to make as full an examination of the changes resulting from the passage of the wheel as is possible with the resources and time available. In addition to measurements of changes in bulk density and soil strength it is desirable to measure changes in the permeability to air and water and the depth and width of ruts produced by the wheels under test.

Techniques for the quantitative expression of the changes of soil properties resulting from the passage of wheels are still evolving. Measurements made only in the midline of the wheel track may be misleading when comparing wheels of different widths and will give little indication of the overall compaction effects in a field when a limited part of the total area has been covered by wheels. We therefore distinguish between the maximum intensity of compaction occurring at some particular depth below the midline and the total compaction response indicated by the cross sectional area of the wheel rut or by the integrated change of bulk density in a cross section below the wheel track. Both these parameters of compaction are important in assessing the likely implications of wheel traffic on crop growth.

3. THE CLIMATE

The climate of Scotland shows several features which tend to enhance the risks of serious compaction from wheel traffic. In certain respects the climate characteristics are similar to those encountered in other parts of NW Europe and in Northern USA and Eastern Canada where compaction problems have also been widely experienced.

Spring seedbed preparations are frequently delayed by excess soil water until March or even early April when a difficult choice has to be taken between suffering a yield loss from delayed planting or risking a poor seedbed by putting wheeled equipment on too early. However, unlike those parts of Europe having a more continental type of climate, lengthy periods of wet weather may follow spring sowing operations in Scotland.

At this Institute the average monthly potential evapotranspiration exceeds rainfall in only one month of the year and then by only a small margin (June, 25 mm). Nearer the eastern coast average accumulated soil water deficits may exceed 75 mm but only exceed 100 mm in very limited areas.

Operations during the summer months such as silage harvesting will often take place when soil water deficits are very low and soil strength is insufficient to resist the applied wheel loads without compaction.

Cereal harvest rarely starts before the beginning of September and not infrequently continues into October. Except in small areas in the low lying eastern coastal districts the return to field capacity follows close to harvest or may occasionally precede it. The harvest of root crops in October and November may be undertaken on soils at or approaching field capacity with inevitable compaction, smearing and deep rutting as a result of the high stress imposed by the wheels of the machinery involved.

4. SOILS

Considerable differences have been noted among Scottish soils in their susceptibility to compaction in the subsoil. Soils derived from glacial till may show very high bulk densities in the subsoil. Values of 1800 kg/m^3 are not uncommon and may be attributable to very high stresses applied by immense thicknesses of ice during glacial periods. Such subsoils are unlikely to show additional compaction from the passage of vehicles commonly in use today.

However, soils derived from wind blown sand, silty clays of marine origin or redeposited material of fluvio-glacial origin may show bulk density values in the subsoil which differ little from those in the topsoil and thus they may be particularly at risk when subjected to heavy vehicles.

5. THE VEHICLES

The vehicles which have been used to date in our studies have been:

(a) tractors (up to 9 t)

(b) combine harvesters (up to 9 t)

(c) limespreading vehicles (up to 12 t).

However, there are many other types of vehicles where the total mass of the vehicle represents a major problem and farmers are becoming suspicious that claims for the economic advantages of increasing the size and capacity of machines may overlook the problems resulting from soil compaction.

Plans are now being made to extend the tests to heavier vehicles which are increasingly appearing in commercial agriculture. Slurry tankers, with a capacity of 13600 l and a loaded mass of 27 t are now available although the number in use is very small.

However, vehicles in the 10 t to 15 t range are encountered much more frequently.

6. TYPES OF WHEELS AND TYRES

The vehicle designer and the practical farmer have a considerable choice of types and arrangement of wheels and tyres to fit to a particular vehicle. Commercial cage wheels when fitted to a standard rubber tyre may result in little reduction in the compaction intensity under the tyre (Dickson *et al*., 1979). However, experimental cage wheels fitted with flat plate lugs designed by Dr D. Gee-Clough of NIAE can be mounted alone and preliminary work here suggests that very appreciable reductions in compaction can be obtained when such wheels are used on loose soils (Dickson *et al*., 1979; Dickson and Henshall, 1980). Such wheels have not yet been tested under commercial operating conditions.

Dual wheels may be used to reduce average contact pressures especially as partial deflation is permitted but the greatly increased contact area may give rise to an increase in total compaction (Blackwell and Dickson, 1978; Dickson *et al*., 1979) as may be the case with wide section tyres (Henshall and Dickson, 1980).

The front or non-traction wheels of vehicles are often ignored in compaction studies but Dickson (1980) has demonstrated that a considerable proportion of the total compaction resulting from the passage of a tractor is attributable to the front wheel.

7. THE PREDICTION OF COMPACTION

Because of the enormous variety of interacting conditions of weather, soil and vehicle types it is clearly necessary to be able to predict, even with only partial success, the compaction likely to result for any given set of soil and wheel characteristics. Our knowledge of the mechanisms involved is still very limited so our predictive capabilities remain weak although some progress has been made (Blackwell and Soane, 1981). An equally important step is the prediction of plant responses to the changes in soil characteristics leading eventually to an economic assessment which can act as a guide to the costs and benefits related to the problems of reducing adverse effects of compaction under vehicle wheels.

8. THE ROLE OF COMPACTION IN THE UK FARMING SCENE

There are considerable changes occurring in the UK with respect to cultivation which have important implications for soil compaction. Mouldboard ploughing is being increasingly abandoned in some areas and replaced by tine cultivation or to a lesser extent by direct drilling. As a result the mouldboard plough is used less frequently as a means of restoring favourable soil physical conditions. On the other hand subsoil cultivation has increased considerably. New designs and techniques for subsoiling (winged shares, multi-depth tines, inclined legs) have been developed and it is not uncommon for farmers to cultivate their subsoils on a regular basis say once in 4 to 5 years. It is now even suggested that subsoiling can be undertaken after preparation of the seedbed (Spoor, 1980).

Subsoil cultivation is likely to be beneficial where heavy traffic has produced unfavourable conditions for rooting below the depth of cultivation. There is considerable interest in the possible value of very intensive subsoil cultivation (Warboys et al., 1976), with or without the incorporation of plant nutrients ; in some experiments quite large increases in yield of both cereals and non-cereals have been obtained (McEwen and Johnston, 1979; Rowse and Stone, 1980).

Serious attempts are being made by some farmers to minimise the amount of wheel traffic over fields but in many cases the requirements for planting or harvesting the crop give little opportunity of reducing traffic below certain limits. Where the payload is light and operations are required at times of high soil water content (e.g. low volume spraying on winter cereals) mobility can be greatly increased and compaction reduced by the adoption of very low ground pressure vehicles (Cussons and Ayres, 1978). However, the continuing increase in the mass of many vehicles used for harvesting and transport of produce and farm wastes is giving rise to concern that soil compaction may be result in additional problems and costs in future crop production.

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STUDIES ON THE EFFECT OF TRAFFIC AND OF SOIL COMPACTION ON THE GROWTH OF ARABLE CROPS

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INTRODUCTION.

In the Netherlands the avarage farm size is less than 20 HA. Lack of alternatives forces the farmes towards intensive land use (LUMKES, 1976). This includes an increase of growing of root crops.(i.e. potatoes, sugar beet, onions, bulbs). Root crops are labour intensive, but with a relatively good net return. At present half or even in some arable regions three quaters of the farm acreage are covered with root crops. Potatoes (24% of the total arable area in the Netherlands) and sugar beet (17%), can be called dominating root crops (Table 1). In some regions onions, bulbs and vegatables are grown on a large scale. In mixed farm areas of the Netherlands maize for silage is the dominating arable crop. Generally it is grown for about three years or more successive on the same field or it is grown in rotation with other crops like sugar beet or potatoes.

Table 1. Percentage of the total arable land area covered by some crops in the Netherland in 1980.

crop	percentag of arable land
cereals	32
(winter wheat)	(20)
potatoes	24
sugar beet	17
maize for silage	20

Apart from the 32% of cereals in the cropping plan, the farmer has to harvest two third of his crop in autumn. This means heavy transports (crop yields, including soil tare, up to 80 tonnes/HA; 10 tonnes or more on axle load is common) in a relatively wet period on soils with a ground water table of about 1 meter and a serious claim on soil structure. After harvest often more than 50% of the soil surface is covered with wheel tracks.
In the same period and often during the whole winter, especially in the mixed farm regions on sandy soil, slurry application takes place. In other regions with intensive potato growing soil fumigation in the autumn is common. It includes an intensive rotavating of the top layer of the soil and smearing of the surface and is followed late(r) in autumn by the normal tillage. Also the harvest of vegetables for the canning industry can give serious damage to soil structure.
Production of arable crops means high investments in soil capital. Therefore it is evident that soil conditions remain as soon as possible. On the other hand it is difficult to determine what the optimal soil structure means. Must the soil only be capable to carry light types of tractors and implements, used under good conditions, without creating tracks, or must be accepted that we work under unfavourable conditions and recover the soil later on.
In fact the main question is wether we need to control the reasons of soil degradation or just the symptoms.

Soil compaction is partly an effect of traffic over the fields. It is than the result of a balance between the load on the soil at driving over the field and the counterpoise of the soil. The compaction process caused by field traffic is rather complex. However, it is clear that heavy transport under unfavourable circumstances can be disastrous for soil structure.
In the past the weight of the light agricultural tractors and machinery was not dangerous for soil structure, in 1970 the avarage tractor had a power of only 26 KW with a weight of 2100 KG, the trend was at time towards 59 KW and 3000 KG respectively. Nowadays heavy tractors of about 100 KW are rather common and the heavy machinery is also accepted. With the introduction of a 370 kW tractor with a weight of 18 tonnes, and tyres of extreme size, 20.8-42.0, in Western Europe, it is demonstrated that the number of wheels or the size of the tyre cannot keep the load acceptable low.
In Table 2 some figures on the weight of agricultural machinery are given.

Table 2. Weight of agricultural machinery.

tractor	power in KW	power in HP	weight in KG.
	26	35	2100
	59	80	3000
	92.5	125	6000
	148	200	9600
	222	300	12000
	368	500	18000
trailed potato harvester with hopper (2-wheels)			
	up to 5000 KG own weight and		10.000 KG.
	up to 5000 KG capacity of the hopper		
self propelled slurry carrier (6-wheels)			
	own weight 14 tonnes		
	capacity of the slurry tank 15 tonnes		30.000 KG.

Except the machinery mentioned in Table 2, we know the large self propelled mobile viners for the harvest of peas and beans and a number of other machines. It is clear that field traffic with increasing tractor and machinery weight for soil tillage,fertilizer application, seedbed preparation and sowing, crop production, mechanical weed control and harvesting, has considerably increased. Therefore, compaction is more and more counteracting the loosening effect of the main tillage treatment.
The introduction of p.t.o. driven equipment enables to influence the top soil more unnaturally than we did in the past.
Considering these trends it is useful to investigate if other (probably better) tillage and transport systems can be developped.
It has to be discussed how the negative effect of using heavy machinery can be avoided. To understand the effect of an optimal soil structure and soil degradation effect of field traffic a serie of studies are either carried out or in progress.

A.LOOSE SOIL HUSBANDRY

If traditional soil tillage and standard use of modern mechanization is practiced, the soil might become too compact, especially in narrow crop rotations with a high percentage of root crops. Therefore alternative tillage systems are studied, to get a looser soil structure.
In general, almost any tillage operation, and especially ploughing, has a loosening effect on soil structure, while traffic over the field has an compacting affect.

In the traditional system in the autumn, the whole arable layer is loosened intensively yearly, but in springtime the original compaction of the soil is reached more or less. It means that the loosening effect has almost been lost at that time.
Loose soil husbandry tries to improve this situation by maximizing the loosening effect, and by minimizing compaction by reducing field traffic. Since 1967 several research institutions in the Netherlands have cooperated in research on soil tillage systems, with the main scope on the effect on soil structure and crop yield. A five year experiment on clay loam soil showed that restriction of both loosening and compacting effects, did not result in a looser soil than in the traditional tillage system. Zero tillage, based on the internatonal interest at that time (KUIPERS, 1970), was also studied to be informed on plant growth in a rather dense soil (BAKERMANS,et al 1974).

In 1972 an 8-year experiment was started at the same soil type, carried out by the Westmaas Research Group on New Tillage Systems, in which several research institutes participated. In a representative four year crop rotation (of potatoes - winter wheat + rye grass - sugar beet - spring barley + rye grass) three tillage systems are compared, namely:
A - loose soil husbandry
B - no tillage
C - rational tillage

The main tillage treatments were either ploughing each year (loose soil husbandry, system A), cultivating with a fixed tine cultivator (LUMKES,1974) and ploughing alternately (rational tillage, system C) and no tillage, modified from 1976 onwards in minimum tillage (system B). LUMKES & v. OUWERKERK, 1980.
In the loose soil tillage system (A), ploughing and drilling winter wheat was combined in one pass. For potatoes, sugar beet and spring barley seedbed preparation and planting or drilling was combined. So an advanced system was developped to reduce the number of passes and to prevent soil sompaction. The results of this loose soil tillage system were disappointing.
Most combined treatments proved to be principally wrong. Combining ploughing and drilling of winter wheat in one pass, caused an irregular depth of sowing and often a too coarse seedbed. Nitrogen fertilization, seddbed preparation, planting and ridging of potatoes, could only be performed with a heavy tractor ($>$ 80KW).
Also combining seedbed preparation and drilling of sugar beet and spring barley was not always a succes.
In spite of the aim to get a looser soil, system A did not result in a better soil structure and a better avarage crop yield (BOONE et al, 1980; LUMKES & v. OUWERKERK, 1980). Also in economic sence this form of loose soil tillage is not advised (CEVAAL,1978).
In system B, without any main tillage, gave a much more compacted soil and mostly lower yields soil (BOONE et al, 1980; LUMKES & v. OUWERKERK, 1980).

We concluded during this experiment, that this type of loose soil tillage did not result in a better alternative for the soil tillage in practice. Therefore in 1976 another experiment with bed culture of root crop and permanent trafic lanes was started. This was compared with normal traffic to study the differences in soil compaction.

B. BED CULTURE COMPARED TO NORMAL TRAFFIC IN ROOT CROP.

In a rotation of potatoes and sugar beet, we compare on a young medium textured marine loam soil at Lelystad since 1976 permanent bed culture with normal traffic. The beds have a width of 3 meter with 4 rows of potatoes and 6 rows of sugar beet.

The beds are bordered by traffic lanes of 0.30 meter width. So 91% of the land is in use for crop production and 9% is separated for traffic. Modified tractors and machinery enables us to avoid all traffic in the beds.
On other fields of 7,5 meter width in this experiment the normal intensive and heavy traffic in potato and sugar beet growing (especially for the harvest), soil fumigation and soil traffic is accepted. It is exactly recorded where the machinery passes, to carry out of fieldwork, are.
Also the weight and the soil pressure of the tractors and the machinery is studied, which enables an exact analysis of the relation field traffic - soil structure - crop response and this can be compared with the same aspects on the beds.
In the beds we have a loose soil, in the layer 12 - 17 cm in pore space about 54% v.v. in air content at pF 2.0 20% v.v., which is 6 and 38% respectively more than the avarage on the standard fields with normal traffic. The trend seems to be an increasing difference, positive for the beds.
On fields with normal traffic in some tracks pore space and air content are critically low, in the layer 12 - 17 cm pore space 48% v.v. and air content at pF 2.0 10% v.v. Also in mechanical soil structure aspects like vertical penetration resistance and shear strength this facts are illustrated.
In crop yields the beds compensate mostly the 9% loss of productive area on the fields. The tendence in the yield seems to be positive for the looser soil on the beds.
Especially the early spring field work on fields with normal traffic often proves to be negative for the soil structure and crop growth, especially in the previously made tracks. On the beds both negative effects, that of the early spring work and that of the autumn harvest, are avoided.
By means of bed culture or tramline systems we can create a production area separated from more or less permanent traffic lanes. We expect a better crop yield on beds - especially on long terms - as an effect of a permanent optimal soil structure. Moreover, systems based on bed culture can save costs, labour,- energy- and implements.
In practice we find a growing interest in the opportunities of permanent bed culture. Parts of the idea are already taken over in practice, e.g. by not growing crops like sugar beet and potatoes on tracks made in spring.
By standardization of working-widths and by marking the previous tracks this is possible. Another idea is to use the standard tractor with implements with a working-width of at least 6 meter, which can result in semi-permanent or permanent beds between two tractor passes.

The Institute of Agricultural Engineering (IMAG) at Wageningen is also testing the bed-culture system in arable farming, based on an automatic guidance steered by an underground insulated copper wire (PERDOK & TELLE,1979).

C. SOIL COMPACTION DEEPER THAN THE FURROW

Soil compaction deeper than the furrow is the result of traffic at high axle loads.
We extended existing research programs studying the effect of field traffic at high axle loads. For example, on a sandy soil with a self propelled slurry tank at 10 tonnes axle load and 0.50 m wide tracks of the wheels on one axle, at a moisture content of 17% v.v., a 0.15 m deep track was created, while the bulk density increased by about 10%. The compaction was found up to a depth of about 30 cm. In other experiments we have about the same experiences, the penetration resistance in the tracks also increased strongly, resulting in difficulties for root growth.

D. SUMMARY AND CONCLUSIONS

In the Netherlands the arable land is used intensively. This includes increasing heavy traffic over the fields.
By combining field operations "loose soil tillage" was compared with other systems. Later on, a bed culture systems with permanent traffic lanes is studied in an experiment with a crop rotation of potatoes and sugar beet from 1976 onwards.
To determine the effect of normal traffic all passes over the field are exactly analysed and the weight of the machinery on each wheel is studied.
It gives detailed information about the soil pressure, soil structure and crop response.
The effect of increasing machinery weight on sub-soil compaction is in study.

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PHYSICAL SOIL DEGRADATION IN THE NETHERLANDS

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Summary of a paper with the same title by D. Boels & L. Havinga in "Proceedings of Seminar on Soil Degradation, 1980, Wageningen".

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 strucutre 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 strucutre. This means under conditions prevailing in the Netherlands that if some structure damage is accepted, harvest time can by delayed. This implies a lengthening of the growing season and so a higher crop yield. Similar arguments hold for earth moving activities.

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 then 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 so-called critical state soil mechanics. 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. 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.

Soil Compaction Research in Denmark

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During the seventies 3 series of experiments with topsoil-compaction on 4 soil types were carried out in Denmark. A short summary and the references are given beneath.

1. Soil Compaction by Traffic in Spring

One-year field-experiments with compaction of the topsoil under different soil moisture conditions combined with increased number of runs over the field and different nitrogen-levels were carried out on autumn ploughed soils before seedbed-preparation and sowing of barley in the spring.

The experiments were carried out on coarse sandy soil, on a sandy loam soil and on a silty loam marsh soil during the years 197o-74.

The grain yield and a number of soil-physical parametres were measured. Soil wetness at compaction time and also the climate after compaction time were of vital importance for the grain yield.

Compaction under wet conditions followed by moisty climate has for some years given yield decreases, whereas compaction under dry conditions followed by dry climate has given yield increases.

2. Lysimeter-experiments with Soil Compaction

In lysimeters containing the soiltypes mentioned above the top-soil was compacted with different specific pressures.

Measurements of the soil-density and the water-content by means of the gamma-ray-radiation and neutron-scattering methods showed increased density to a depth of 7o cm after increased specific top-soil pressure.

3. Soil Compaction in Connection with the Harvesting and Transporting of Grassland-crops

Experiments with increased loads on tractor and truck and with increased number of runs over pasture in connection with the harvesting and transporting of the crop were carried out on a sandy loam soil and on a silty loam marsh soil.

The yield-depression after the heaviest traffic is mainly a result of leaves, stalks and roots being crushed rather than the influence of soil structure, even though the traffic reduced the soil porosity and increased the shearing strength.

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A review of soil compaction studies in Norway.

(By H.Riley, Kise Agricultural Research Station, N-2350 Nes Hedmark.)

Early experiments showed the negative effects of tractor traffic at high soil moisture contents, whilst a certain degree of soil compactness, afforded by extra rolling, gave yield increases in cereals (Njøs 1962), probably due to improved water transport in the seed-bed.

Since 1962 several long-term field experiments have been carried out in south-east Norway, mainly on clay and silty-clay loams derived from postglacial marine sediments, which represent an important proportion of the country's arable land (Njøs 1976,1978; Gaheen & Njøs 1977,1978ab). Compaction treatments usually comprised different intensities of wheel-by-wheel passes with a medium-weight tractor (around 2t) carrying a 400kg weight, at different soil moisture conditions or at different times of year. The compaction treatments have been applied annually, in addition to normal tillage operations, for periods of 8 to 14 years, followed in some cases by a period in which residual effects were monitored. Other treatments have been included, such as level of N-fertilization, liming and extra cultivation, in order to study possible interactions or remedial effects. The main crops studied have been spring cereals, though breaks of grass leys or oilseed rape have occurred in some cases.

In an experiment with compaction at different soil moisture status (moist = soil tension 0.07-0.5 bar at 5cm and 0.05-0.3 bar at 20cm; wet = soil tension <0.05 bar at both depths), cereal yields were lowered both by wet compaction and in many years simply by ordinary cultivations with the soil in a wet condition. Compaction when the soil was in a moist condition, however, gave relatively little yield decrease. During the first five years of the experiment an extra harrowing treatment was included to facilitate soil-loosening, but did not affect yields significantly. For the latter nine years a higher N-fertilization level was included instead, but, whilst yield levels in general were raised, there was no interaction with compaction. Cereal yields were depressed by 10-20 percent throughout the experimental period with compaction from a single wheel-by-wheel pass, but there was no cumulative effect with time. Grass leys showed no adverse effects of compaction at all. The yield reductions in this experiment were associated with reduced rooting depth, soil porosity, infiltration rate and hydraulic conductivity, and with increased soil shear strength, proportion of coarse aggregates in the seed-bed and weediness (Njøs 1976; Gaheen & Njøs 1977,1978a). An encapsulation effect of nitrate in the soil aggregates from wet-treated plots was also noticed.

In an experiment with autumn compaction before ploughing and spring compaction of autumn-ploughed land (Njøs 1976), when the soil was generally treated in a wet condition in both cases, the latter treatment had the greater adverse effect. The yield reductions were more marked for cereals than for hay or oilseed rape (20-7-11 % respectively for spring compaction and 4-0-8 % for autumn compaction). Increased N-fertilization lessened the effects of autumn compaction, but the opposite was true for spring compaction. After eight years of traffic, residual effects of the spring treatment lasted for only two years, and were absent in the case of the autumn treatment. Higher weediness and reduced porosity were associated with compaction in this experiment also, and a higher clover cover was found in ley years. The ability of clovers to thrive on compacted soil has also been noticed on clay subsoils after soil-levelling with bulldozers (Njøs 1980).

Several more experiments have been carried out since 1970, to assess the effects of liming in relation to compaction of silty-clay loams (Njøs 1978; Gaheen & Njøs 1978b; Njøs - unpublished data), using quantities of 10 and 20 t CaO ha^{-1} applied in two dressings. Wet compaction was in all cases more detrimental than moist, with one wet pass equally as damaging as six in the moist condition, causing cereal yield reductions of 10 - 15 percent. Extra harrowing did not alleviate the effects of compaction here either. Repeated wet passes reduced yields by up to 40 percent. The results of liming were somewhat variable, possibly due to the soils' initial lime status, but in no case was there a significant yield interaction of liming with compaction. However some evidence of a better effect of liming on nitrification on uncompacted soil was found, both in soil analysis data and reflected in straw yields. Grass yields were less sensitive to soil compaction than cereals in this study also, and residual effects after eight years of traffic were not found in cereals. Compaction was found to have reduced infiltration and air-filled porosity and to have increased bulk density, shear strength, the proportion of coarse soil aggregates and the degree of surface cracking of the soil under dry conditions. The latter parameter was significantly reduced by liming, suggesting that lime did indeed affect soil structure positively, though few other effects were measurable.

Following the damage that occurred to grassland in many parts of Norway in wet summers during the sixties, a national series of investigations was started in 1973 on the effects of traffic in connection with fertilizer spreading or harvesting operations (Myhr 1978). Sites on clays, loams and peat soils were included. After five years average yield depressions of up to 10 percent had been found with heavy traffic, but it would seem that grassland is generally more tolerant to compaction than are cereals. It may be, however, that the experimental period covered was drier than normal, and the series is still continuing. Porosity was reduced by traffic, especially on the peat soils, but the effect was not cumulative from year to year, suggesting that frost action loosened the soil each winter. However shear strength increased with time on all soils both for compacted and uncompacted treatments, possibly due to a reinforcing action of the plant roots. Sward age and grass species were found to be of importance for the soil's bearing-capacity, with Phleum pratense and Festuca pratensis less effective than Festuca rubra and Phalaris arundinacea.

Some further compaction work with cereal crops has been done on loam soils derived from glacial till in east Norway. Ekeberg (unpublished data) found yield reductions of 20 percent following autumn compaction befor ploughing, but residual effects were absent a year later. The need to establish the optimum degree of compaction (viz. Håkansson 1976) was illustrated by the work of Eggum (1972) who found a negative correlation with porosity to be the major yield determinant in a study of cereal crop variability. This finding was supported by Magnus (1980) who measured considerably higher yields in wheel tracks than between them. Work is currently in progress on several soil types to elucidate this matter, using the standard bulk density measure of Håkansson (op.cit.) to compare sites. Magnus (op.cit.) proposed the use of field penetrometers by farmers to assess seedbed conditions. Such instruments may also be of value from a research point of view, despite obvious limitations connected with soil moisture and stone content. Penetration resistance has for instance been found to increase by up to 50 percent in compaction trials, in cases where bulk density was only affected by a few percent (Riley, unpublished data).

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MEASUREMENTS OF COMPACTION IN THE SUBSOIL

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The present development in agriculture is towards larger and heavier transport vehicles, machinery and tillage implements. These heavy loads have resulted in increasing interest being focussed on the risk for subsoil compaction. Earlier investigations into soil compaction have largely been limited to the topsoil and the uppermost part of the subsoil, and only few measurements have been made at deeper depths.

The present investigation into subsoil compaction was started by the Swedish Institute of Agricultural Engineering (JTI) in 1969. The intention was to study whether heavy loads on the soil surface cause repercussions in the subsoil that might influence the physical properties of the soil.

The field measurements were conducted in 1971-1973, mainly in Uppland, central Sweden. Complementary measurements were made in other parts of southern Sweden.

In the investigation of compaction in the subsoil, use has been made of different, yet complementary, measurement techniques. The measurement of movements at different depths in the soil in connexion with compaction was made with special probes, using a technique developed at the JTI. Determinations of volume weight, pore space, air permeability etc. were made in accordance with methods developed at the Dept. of Soil Science of the Royal Agricultural College of Sweden.

A test vehicle was constructed by the JTI to enable different loads on the soil to be uniformly repeated under varying conditions. This vehicle was used in the Uppland experiments. Various agricultural vehicles, such as different tractors and lime-spreading trucks etc., were also used.

The results of the investigation into subsoil compaction are summarized below:

1. Tests with a tandem-axled vehicle resulted in less stress in the soil and less compaction down to depths of 30-50 cm than tests with single-axled vehicles. At greater depths the total load determined the degree of the stress.
2. A reduction of the inflation pressure reduced the specific pressure on the soil, which primarily reduced the stress and the compaction in the topsoil and very uppermost part of the subsoil.
3. An increase in driving speed from 2 km per hour to 4 km per hour resulted in a slight reduction in the influence on the probes at 30 cm and 50 cm. Tests on an uneven soil surface suggested that the higher speed resulted in increased stress on account of added swaying and bumping of the vehicle.
4. The movements that were measured in the soil were small when expressed as absolute values, but they should be considered in relation to the very small pore dimension in the soil.
5. The elastic movements in the soil were measurable down to a depth of 1 m, even at the relatively small loads of 2-4 tons. These movements were not of the extent that they caused measurable changes in the pore space.

6. The movements of the probes were much larger in connexion with the shrinking and freezing of the soil than in connexion with compaction, but despite this it appears that repeated freezing and drying-out for a number of years is necessary for the recovery of severely compacted soil.

7. The moisture content, and consequently, the season, is of great importance for the compactibility.

8. The soil type is largely decisive for the compactibility.

9. The pore space and the air permeability decreased measurably down to depths of 50-60 cm, when the heaviest loads were used.

10. Repeated compaction with 16 tons on a tandem-axle resulted in compaction that still remained after three years.

Thus, the measurements show that under certain circumstances compaction occurs in the subsoil below normal cultivation depths. Under these circumstances the relationship between, for example, soil conditions and vehicle weights is of great importance.

It is difficult to judge the risk for compaction in the subsoil under practical conditions and, similarly, it is difficult to estimate the economic consequences.

Generally, it can be said that even if exceptions do occur, a reduction of pore space in the soil means a deterioration in the conditions for plant growth on account of reduced drainage and air exchange capacities and that there is increased resistance to root penetration. The consequences of this for the economic result vary from year to year, depending on the precipitation.

The effect of a small annual change in the compaction situation towards an increased volume weight can be of little importance during a series of years with low or normal precipitation. In years with high precipitation during short periods the conditions for field operations can become more difficult, the development of the crop can be checked and, consequently, the overall economic result will deteriorate as the result of the changes brought about by compaction in the soil.

On cultivated soils an equilibrium eventually occurs as regards compaction that on one hand is dependent on soil type, drainage and rotation, and on the other, on the machinery used and on the way it is used. Developments towards larger and heavier machinery in the long run mean alterations in the equilibrium of soil physical conditions. Extremely wet or dry years, or deep frost penetration, may cause temporary alterations for a small number of years.

The aims of the investigation included the determination of the maximum loads by vehicles and machinery that different soils can be subjected to without resulting in deep and lasting compaction. The very wide variety of conditions concerning soil types, and especially moisture contents, means that it is impossible to define exact limits for the size of the load. However, the measurements and other observations made during the experiments enable some conclusions to be made.

The tables and diagrams in the quoted report (Danfors 1974) show that no measurable changes in, for example, pore space and air permeability, occurred in the subsoil under the prevailing conditions when the loads were 2 and 4 tons.

Under conditions that were unfavourable from the compaction point-of-view, measurable changes started to occur in the upper part of the subsoil at a load of 6 tons. Further increases in load resulted in larger changes in the upper part of the subsoil at the same time as the measurable influence penetrated to deeper depths. Under favourable conditions, i.e. on relatively dry clay, the load could be increased to 8 tons before measurable changes occurred in the subsoil.

The measurements showed that the loads used in the investigation influenced the sand and fine sand soils less than the clay soils. It was also found that sandy soils react in the same way as clay soils, but to a lesser degree, to loads in the form of heavy agricultural tractors and trucks of the type used to spread lime and fertilizer.

No measurements were made on organic soils as they were not considered to be negatively influenced by compaction.

The investigation into compaction in the subsoil was carried out over a period of some years at a total of eight sites spread throughout southern and central Sweden.

The measurements did not reveal any fundamental differences between the results at the various sites. The differences that were found can primarily be traced to differences in soil type and moisture content. This may be interpreted as meaning that these observations on subsoil compaction may have an application in Sweden that stretches beyond the geographical area covered by the investigation.

The above is an extract from the summary and discussion in bulletin S 24 from the JTI (Danfors 1974).

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RELATIONSHIP BETWEEN VEHICLE LOAD AND COMPACTION PRESSURE IN A SOIL

Some notes on different calculation methods

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The compaction pressure which a vehicle load gives on the soil surface decreases with the depth in a soil profile. This is generally shown by the pressure distribution theory for elastic mediums (Boussinesq 1885). Frölich (1934) modified Boussinesq´s formula by introduction of a concentration factor, e.g. the load is concentrated to the load axle when going from dry hard soils to moist soft soils. Söhne (1951) used this theory in calculation of the "pressure bulbs" in different soils due to tire loads. However, a plastic medium, such as soil, is more inert than an elastic one. The effect of surface loading is of this reason decreased over a shorter distance from the point of pressure application in a plastic material than in an elastic one.

Janbu (1970) took the special mechanical properties of soil into account when proposing a simple theory of pressure decrease adjusted to the properties of soil materials. This theory is illustrated in Fig. 1 where an example is given of the pressure contribution (q_m) under the centre of a wheel-track in a profile of clay induced by a surface load of q. Apart from being dependent on the soil characteristics the pressure contribution also depends on the shape of the loaded surface. In this case the pressure decrease curve is given for circular, rectangular, and oblong loaded surfaces. The difference between the elasticity theory and the theory adjusted to the soil material is that the latter shows that the effect of a load has almost disappeared at a depth corresponding to four times the width of the wheels or tracks.

Fig. 2 contains some comparisons of the pressure distribution in isotropic profiles of clay, silt, and sand with water contents at field capacity. The comparisons are made under conditions with a rectangular loaded surface. The variation in soil type means that the relative pressure at a depth corresponding to, for example, the tyre width, increases from 0.4 in clay to 0.5 in silt and 0.6 in sand. On the other hand, the pressure decreases more rapidly with depth in the latter case.

Besides the mentioned methods several studies is performed to adopt the numerical method commonly known as the Finite Element Method for predicting the stress distribution and soil deformation under a stationary or moving wheel (Perumpral et al. 1971, Bolling 1980). The basic concept of the finite element method is the idealization of the soil continuum as an assemblage of a finite number of elements or small segments which are interconnected at nodal points (Fig. 3). As in the case of other non-linear materials, the development of non-linear stress-strain relationship for soils is rather complex. The behaviour of the continuum when loaded is predicted by approximating the behaviour of the elements. Stress distributions obtained by the finite element method and that obtained from elastic theory agree well (Fig. 4).

The theories assumes in the basic case that the soil properties are isotropic in all directions, i.e. that the profile is uniform and without stratification. A given and uniform degree of saturation in the profile must also be assumed. In actual profiles there is nearly always a variation in the soil type with depth and, in addition, stratification will occur as a result of tillage or the drying out of the soil. A profile with horizons of varying structural strength will cause a more complicated distribution of the pressure.

The few experimental investigations made into pressure distribution under vehicle loads show that simple pressure distribution theories such as those mentioned above can be used in the schematic description and comparison of the compaction pressure and puddling forces in the soil under different vehicles.

Some information about the pressure distribution in a soil due to vehicular traffic can also be obtained by studying the resulting change in structure of the profile (Eriksson 1975).

In the referred investigation a comparison is made of the pressure distribution that occurs under heavy tanks with that under light and heavy tractors. The compaction pressures under a small tractor with 30 cm wide tyres and a load of 900 kg and under a large tractor with 60 cm tyres and a load of 4300 kg were determined by means of the diagrams 1 and 2. The surface load q for the tyres used, was determined for the contact surface obtained when the tyres sink 5 cm into the ground. The surface load q is the same in both cases and has a value of 120 kPa. However, the heavier tractor causes a considerably larger compaction pressure in the deeper layers of the profile. For example, the pressure in the 30-40 cm horizon is twice as high and increases from 40 to 80 kPa.

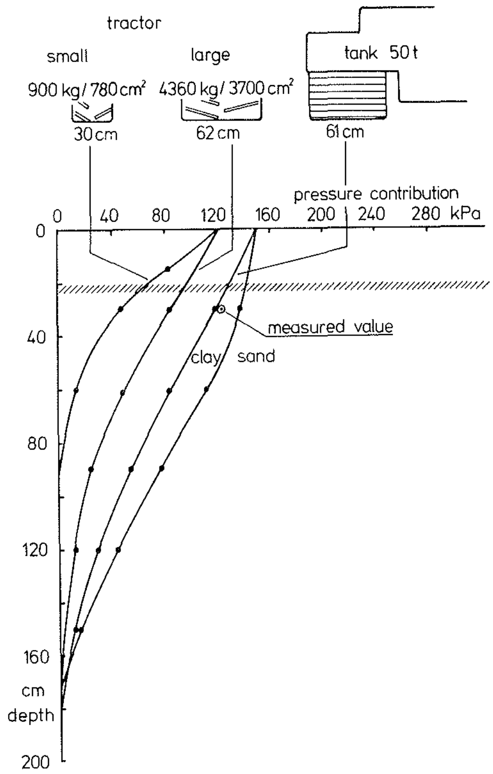


Fig. 5. Pressure distribution in the soil underneath
1) a tank with 50 ton total weight, track width 61 cm;
2) a large farm tractor with 4.4 ton wheel load, tyre width 62 cm;
3) a small farm tractor with 0.9 ton wheel load, tyre width 30 cm.
Acc. to diagrams in Fig. 1 and 2.

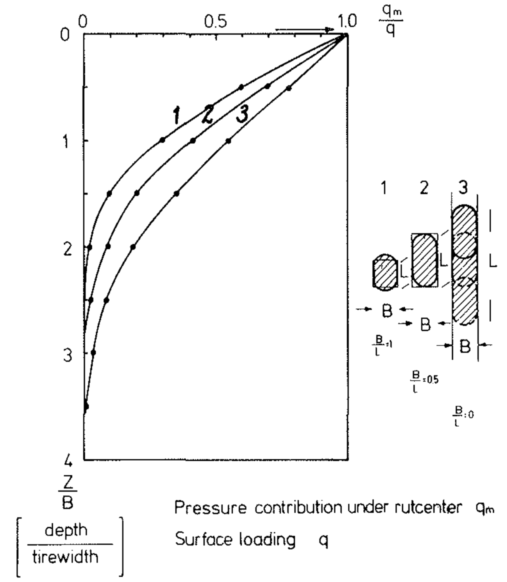


Fig. 1. Rel. pressure distribution below rut centre in a clay profile. Acc. to simplified theory by Janbu of pressure decrease.

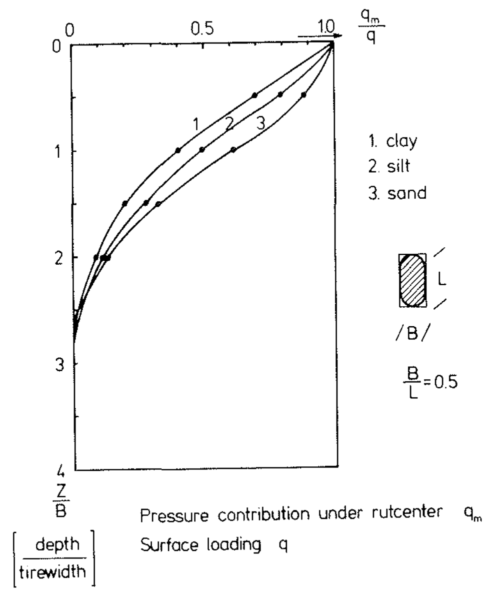
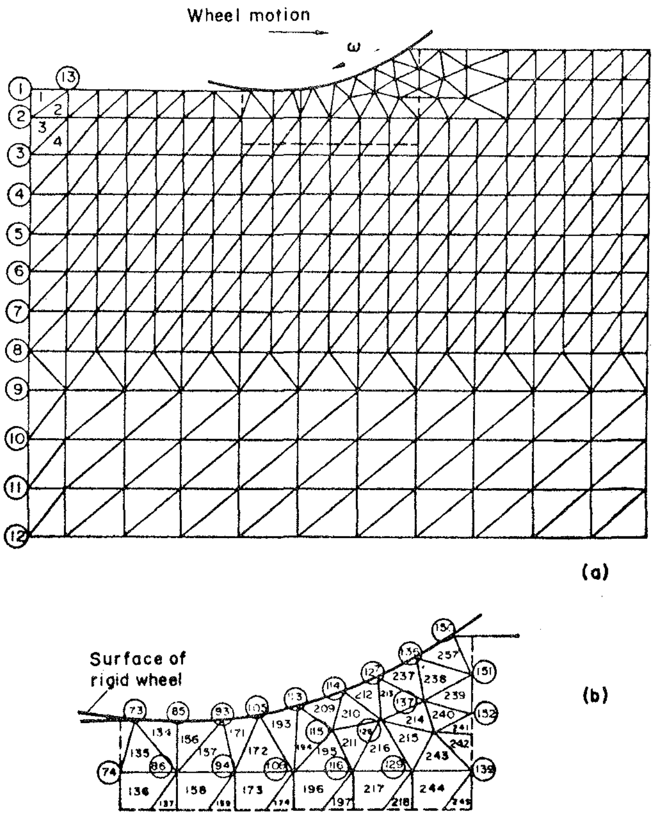


Fig. 2. Rel. pressure distribution below rut centre in soil profiles of different kinds with a load surface of the shape L = 2 B. Acc. to the theory of Janbu.



Idealized soil wheel system indicating the element and nodal numbers. **(a) Total system.**
(b) Region near wheel boundary.

Fig. 3. Ex. of soil-wheel system with an idealization for the finite element analysis (Perumpral et al. 1971).

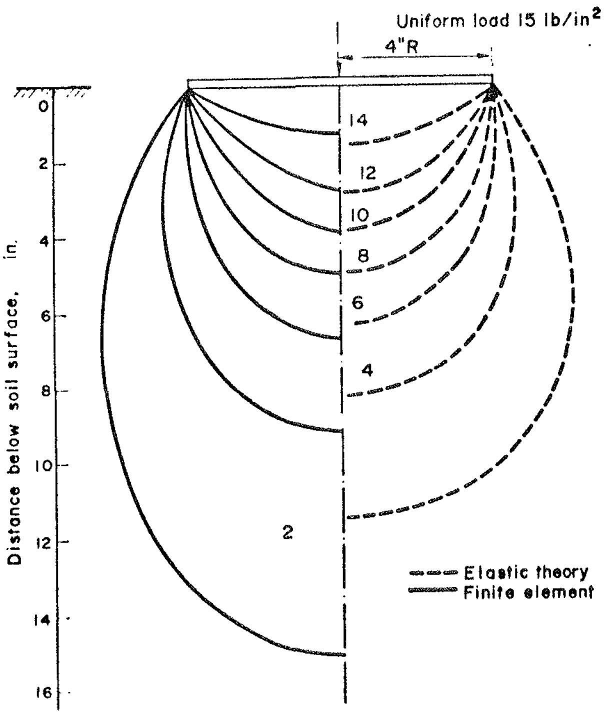


Fig. 4. The congruens of "pressure bulbs" calculated acc. to elastic theory and finite element method (Perumpral et al. 1971).

Under the tracked vehicle the surface load q that should be considered for use in the calculations will be between 150 and 160 kPa. The pressure distribution so obtained in the profile under the 60 cm wide track is illustrated in Fig. 5. Direct measurement with pressure sensors at a depth of 30 cm below a 50-ton tank gave a maximum value of 124 kPa. This value has been included in Fig. 5 and is in good agreement with the value calculated.

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SWEDISH EXPERIMENTS WITH CROP RESPONSE TO WHEEL-INDUCED SOIL COMPACTION

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Since 1960 an extensive experimental program on crop response to wheel-induced soil compaction has been conducted in Sweden. Some main results from this experimentation will be summarized here. A more comprehensive revue of the results up to 1973 was published earlier (Eriksson, Håkansson & Danfors 1974).

At low or moderate axle loads the compaction is mainly restricted to the plough layer. Therefore, most of the field experiments have concerned compaction of this layer. In one group of experiments the longterm accumulative effects of soil compaction are being studied. Nineteen experiments of this kind have been started, some of which are still in progress. The plots are trafficed annually with medium size farm vehicles. This is done every autumn when the soil normally is rather wet. Afterwards the plots are ploughed. The soil normally freezes in the winter.

The compaction and puddling of the plough layer caused by the traffic has resulted in yield decreases in the subsequent crops. The crop yield effects have increased year by year during the first four years after start. After that an equilibrium stage is reached. Fig. 1 gives the effects in the individual experiments during the equilibrium stage as a function of the clay content of the soil. The effects increase markedly with the clay content.

After 7-10 years the annual compaction treatments are terminated and the residual effects on the crops are studied for some years. After about four years all effects seem to have disappeared. The conclusion is that it takes more than one year for a compaction of the plough layer to disappear, but with annual ploughing and freezing it disappears within a five-year period.

The effects in Fig.1 were the result of a traffic intensity of about 300 tonkm per ha, in most cases with medium size tractors and trailers, having normal or relatively small wheels. Other treatments in the experiments indicate that up to the traffic intensity mentioned the effects are nearly proportional to the intensity.

Soil compaction, however, may in addition have effects beneficial to the crops. If the soil is ploughed it is loosened to an extent that is often too large for the next crop, and a moderate recompaction may be essential for maximum production. A large number of one-year experiments with compaction of ploughed fields during seedbed preparation show that there is always a certain degree of compactness in the plough layer that is optimal to the crop. The optimum, however, is influenced by many factors.

If the growing season is wet the optimum degree of compactness is lower (the soil should be looser) than if it is dry. Some plant nutrient factors may also influence the optimum, as well as the weed situation. The optimum is different for different crops. Some crops can be listed as follows - from the crop having the highest optimum (wanting the densest soil) to the one having the lowest optimum (wanting the loosest soil) : Wheat and barley, sugarbeet, rye and oats, peas, rape and field beans, potatoes. Of course, the order may change to some extent if the conditions are changed, and there may be differences between varieties. Therefore it must be stressed that the list applies to the present Swedish varieties grown under normal Swedish conditions.

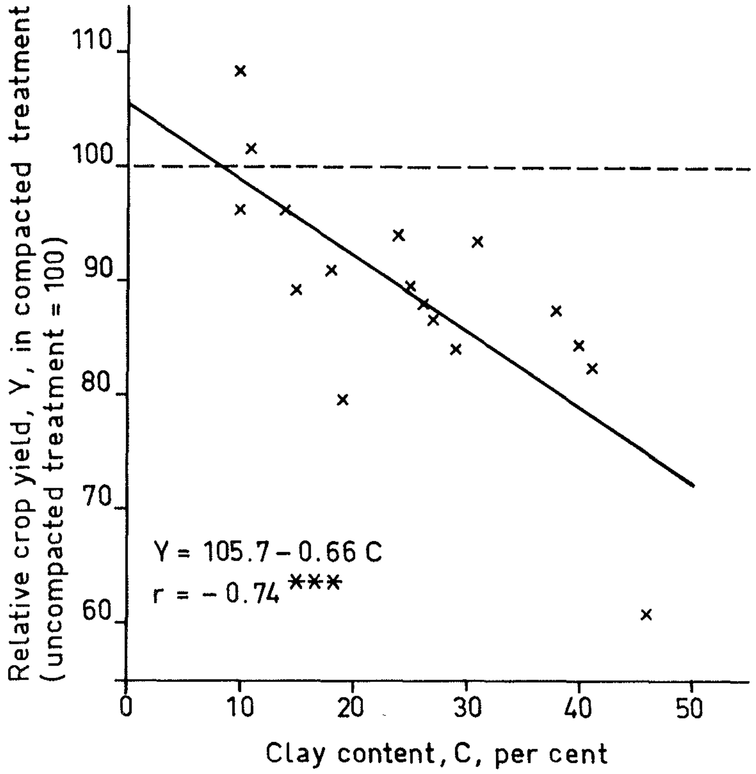

Fig. 1. Longterm field experiments with annual compaction of the plough layer. Traffic intensity every autumn about 300 tonkm per ha. Relative crop yield as a function of the clay content of the surface soil. Average results for year 4 and subsequent years in 17 individual experiments.

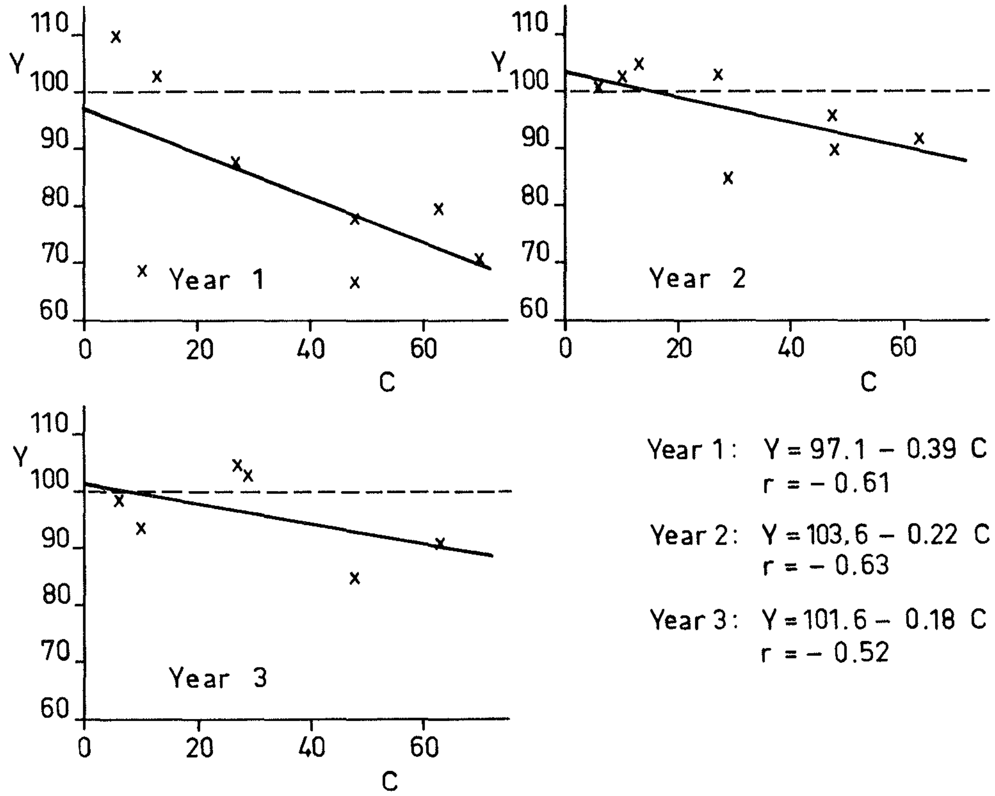

Fig. 2. Field experiments with subsoil compaction by vehicles with high axle load. The plot surface was covered four times by tracks from a 26 ton vehicle at start of the experiments. Relative crop yield (Y) in individual experiments (uncompacted treatment = 100) as a function of the clay content (C) of the subsoil.

Great efforts have been made to characterize the state of compactness in the plough layer. The "degree of compactness" is now defined as the bulk density of the plough layer (excluding the loose seedbed) in per cent of the bulk density of the actual soil in a compacted standard state. This standard state is approximately the most compact state that can be inflicted on the soil by a static pressure of 200 kPa. With the same crop and under similar conditions (weather and others) the optimum degree of compactness, when defined as mentioned, seems to be very similar for different types of soils.

The degree of compactness in the plough layer resulting from tractor traffic was determined in a large series of measurements in the years 1974-1976 (Ljungars 1977). Many different factors were varied. The two factors of greatest importance for the resulting compaction appeared to be the moisture content in the soil, and the number of passes in the same track. The tractor size, the wheel arrangement (single or dual wheels), the tyre inflation pressure, and the tractor speed were of somewhat less importance. The draught was virtually unimportant.

The higher the axle load the deeper in the soil the compaction extends, and the longer time it seems to persist. In 1976-1978 nine longterm experiments were started to study the crop response to subsoil compaction by vehicles with high axle load and its persistence (Håkansson 1979). The plots were exposed to traffic on one single occasion by a 26 ton vehicle, 10 tons on a single front axle, and 16 tons on a rear tandem axle unit.

Fig. 2 shows the crop response during the first years in a treatment with the plot surface covered by tracks four times. After three years there were still significant yield reductions on soils with high clay content. However, the compaction in the plough layer may contribute to the effects during the initial period, and has probably not disappeared totally until the fourth year.

In the autumn of 1978 measurements of bulk density and vane shear resistance were made in the subsoil in six of the experiments. They showed that the traffic had resulted in compaction to a depth of at least 50 cm. In some of the experiments measurements of vane shear resistance were repeated in the autumn of 1980. Virtually no alleviation of the compaction had occurred in the meantime in the actual layer (35-45 cm) in spite of freezing in the winters.

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SOIL COMPACTION - A SEVERE PROBLEM IN FINNISH AGRICULTURE

Introduction

Soil compaction is a problem especially in southern Finland, where soil types, primarily clay soils, are susceptible to compaction, and where fields are mainly under open cultivation. Due to the shortness of the growing period, cultivation operations have to be started as early as possible when the soil is moist and susceptible to compaction. Also in the autumn the harvest time is short, and if the days are rainy, the field operations have to be done on a very wet ground.

Unfavourable consequences of soil compaction have been very clear in the last years of 1970-decade, when the late summers and falls were exceptionally rainy and due to harvest and ploughing the field soils were badly compacted. Water permeability of compacted soils has on many fields weakened so much that extra water does not find its way to drainpipes. This, again, has weakened soil capacity to carry harvesting machines and has in some cases actually prevented the harvest of yields. In the spring time the bad soil water permeability has delayed the start of sowing. Soil wetness has also weakened the growth of plants and decreased yields in rainy middle and late summers.

A special feature in southern Finland is in addition the fact that a moist late summer is preceded by a dry early summer. In dry periods compacted clay soils are hardened so much that it prevents the growth of roots and therefore soil compaction is detrimental in dry weather conditions, too.

Sugar beet growers have found soil compaction such a severe problem that some of them have had to stop the cultivation. Also grain growers in southern Finland find soil compaction a severe problem.

Soil compaction experiments on a clay soil in 1973-75

In the years of 1973-75 a large soil compaction experiment, consisting of 162 plots, was carried out on a clay soil. The clay content ($<2\,\mu m$) was 46 % in the topsoil and 69 % at the depth of 30-40 cm. The treatments were as follows:

- A_1 = Early sowing time
- A_2 = Normal sowing time
- B_1 = Tractor equipped with dual wheels, no extra drivings
- B_2 = One extra driving with normal wheels, track by track immediately before sowing operations. Axle load 2910 kg, breadth of rear wheels 35 cm, inflation pressure 140 kPa.
- B_3 = Three extra drivings. Equipment as before.
- C_1 = No driving after sowing
- C_2 = After sowing one driving with dual wheels, track by track
- C_3 = After sowing one driving with normal wheels
- D_1 = No irrigation
- D_2 = Moderate irrigation, 25-50 mm, in June
- D_3 = Abundant irrigation, 50-100 mm, in June

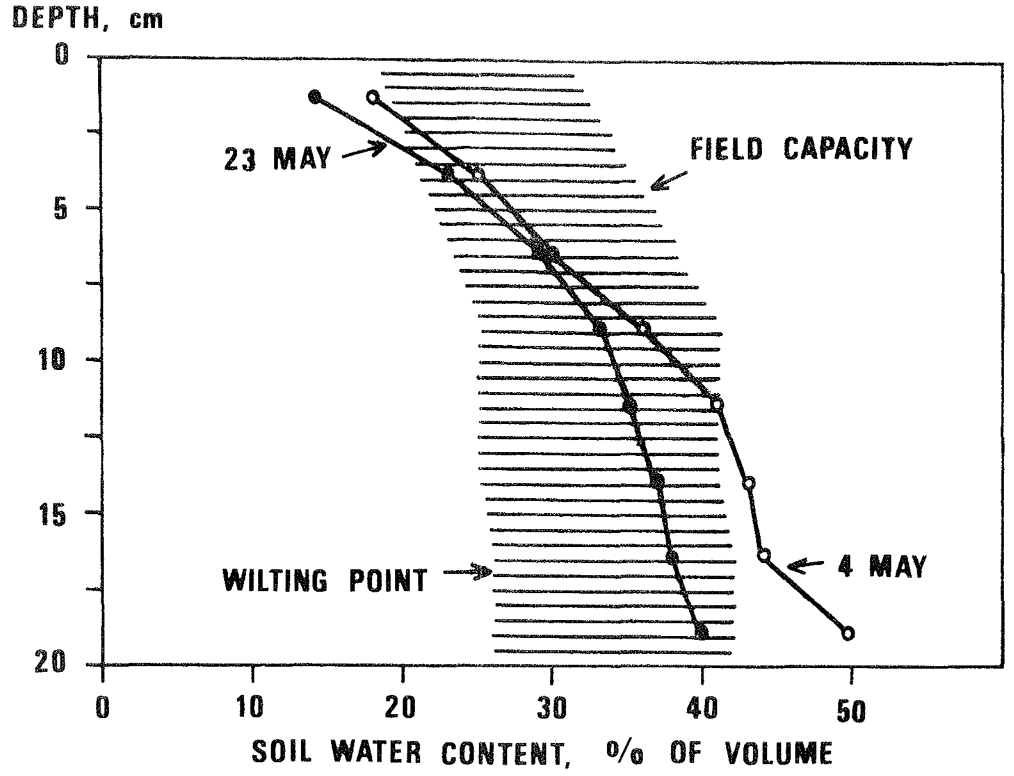

Fig. 1. Water condition in a heavy clay soil from the surface to the ploughing depth at the sowing times on May 4th and May 23rd 1973. Shadowed area = available soil water capacity.

Table 1. Effect of compaction of a heavy clay soil by tractor wheels on the grain yields of spring wheat, kg/ha. Degrees of soil compaction:
light = double wheels, no extra drivings
normal = normal wheels, one extra driving track by track, immediately before sowing operations
heavy = normal wheels, three extra drivings

Year	Sowing time	Irrigation in June	Degree of compaction		
			light	normal	heavy
1973	4 May	unirrigated	2350	1990	1340
		irrigated	3600	3330	2380
	23 May	unirrigated	2000	1750	1640
		irrigated	3530	3550	3160
1974	4 May	unirrigated	4370	4040	3260
		irrigated	5530	5240	4810
	10 May	unirrigated	5600	5010	3870
		irrigated	5680	5260	4320
1975	Residual effects:				
	plots sown early		3350	3330	3300
	plots sown later		3440	3460	3400

Figure 1 shows soil water condition at the sowing dates 1973. It is typical of a heavy clay that in the spring the soil surface quickly dries and reaches the wilting point but under the surface the soil keeps very moist and susceptible to compaction. In the spring 1973 the ground stayed late frozen and for that reason in the sowing time there was still free water left at the ploughing depth.

Table 1 reports results of soil compaction carried out immediately before sowing. One driving track by track decreased the yields of spring wheat in trials carried out at four dates from 8 to 15 %. When the soil was compacted three times, the yields were decreased as much as 18-41 %, depending on soil moisture condition. Due to harrowing after soil compaction treatments, the sprouting of wheat was almost equal on all the plots. Therefore, the differences in yield were primarily caused by the differences in soil compactness under the harrowing depth.

Irrigation in June relieved unfavourable effects of soil compaction. Corresponding the figures above, one compaction decreased wheat yields by 0-7 % and three compactions 10-34 % on the irrigated plots. This indicates that soil hardening in dry periods is an important unfavourable result of soil compaction. Irrigation softens soil and helps the root growth.

Compaction after sowing, which is not reported in Table 1, decreased wheat yields about as much as the corresponding compaction treatment before sowing.

Possible residual effects of soil compaction of two previous years were studied in 1975. Residual effects could not, however, be indicated. Yield results were equal at the range of one per cent. Ploughing and winter frost had obviously completely improved the damages in soil structure caused by soil compaction.

Effects of tractor wheel equipment, experiments in 1975-78

The above reported study indicated that extra wheel tracks in the spring time may considerably weaken the growth of soil in the same year. In the following experimental serie the effects of tractor wheels and wheel equipment directly in connection of harrowing and sowing operations were studied. The treatments of six field trials lasting four years were as follows:

- A_1 = Early sowing time
- A_2 = Normal sowing time
- T_0 = No wheel tracks. The tractor was equipped with dual wheels with very low inflation pressure in the inner tires, and all drivings were done to and fro along the same tracks. In this way uncompacted experimental plots, with the breadth of about 2 m, were left under the tractor.
- T_1 = Dual wheels. Three drivings: two harrowings and one combined fertilizer placement-sowing as in practical farming.
- T_2 = Metal cage wheels. Three drivings as above.
- T_3 = Normal wheels. Three drivings as above.
- T_4 = Normal wheels. Immediately before harrowing the soil surface was twice covered by tracks.

Table 2 reports the results of the earlier sowing time, which clearly was better than the later sowing time. The extra driving before harrowing (T_4) decreased wheat yields by 610 kg/ha in average. On the other hand, also plots without any compaction (T_0) produced less wheat than

Table 2. Effect of soil compaction and tractor wheel-equipment on the grain yields of spring wheat, kg/ha. The results are from four years, 1975-78, average.

Trial No.	Soil type 15/35 cm depth	un-compacted T_0	double wheels T_1	cage wheels T_2	normal wheels T_3	extra compaction T_4
1.	silty clay/ heavy clay	4130	4180	4170	4180	3610
2.	silty clay/ silty clay	3280	3450	3400	3410	3200
3.	silty clay/ heavy clay	3570	3810	3710	3740	2930
4.	sandy clay/ heavy clay	2270	2850	2590	2730	1980
5.	silty clay/ heavy clay	3590	4000	3900	3750	3020
6.	silt/silt	3210	3320	3390	3550	3460
Clay soils, in aver.		3370	3660	3550	3560	2950
Years susceptible to compaction1)		3850	4580	4430	4380	3020

1) Years (one year per every trial), when the difference T_3-T_4 was the greatest. Means of clay soil trials.

Table 3. Residual effect of soil compaction on the grain yield of spring wheat, kg/ha. Symbols as in Table 2.

Trial No.	Treatment years 1975-77			The following year 1978		
	Normal operations T_3	Extra compaction T_4	T_4-T_3	T_3	T_4	T_4-T_3
1.	4400	3930	- 470	3790	3610	- 180
2.	3640	3360	- 280	2950	2960	+ 10
3.	3790	2940	- 850	3680	3590	- 90
4.	3000	1960	-1040	2240	2150	- 90
5.	3980	3270	- 710	3420	3170	- 250
6.	3590	3510	- 80	3510	3570	+ 60
Clay soils in average	3760	3090	- 670	3220	3100	- 120

the normally cultivated plots (T_3); the difference was -190 kg/ha in average. On the plots without any tracks the seedbed remained coarser and sprouting was not as good as on the other plots. Also the loss of water by evaporation was higher from a coarser than a finer soil surface. Accordingly, a moderate compaction has favourable effects on the seedbed.

The use of rubber dual tires in normal seedbed preparation and sowing increased wheat yields by 100 kg/ha or 3 %, in average. In the years when soil compaction was unusually detrimental, the use of dual wheels increased yields 200 kg/ha. At the field ends the profitable effect of dual wheels is even more distinct.

Metal dual tires did not prove as good as rubber tires obviously due to the reason that their diameter is a little smaller than that of tractor wheels. They don't divide the weight of the tractor as evenly as the rubber wheels do.

The silt soil was fully inactive to compaction treatments. As the result of a strong capillary water flow, the silt dried very deeply already early in the spring and changed to be very firm and supporting.

Table 3 shows that after one year the effects of soil compaction have almost fully disappeared. In the following year only about 1/6 of the yield reducing effect of compaction was left.

Summary

On clay soils in southern Finland compaction of soil surface during the sowing time once by tractor wheels track by track at the axle load of 3 tons decreases the grain yield of spring cereals by about 10 %, in average. If soil is compacted twice or three times, the decrease in yield is respectively about 20 % or 30 %. The detrimental effect of compaction disappears, however, almost entirely after one year, due to the frost action.

In practice, the use of rubber dual wheels during sowing time seems to increase the grain yield of spring cereals by about 3 %, in average. In the years when soil compaction is unusually detrimental, the corresponding increase may be 6 %. At the field ends the profitable effect of dual wheels is even more distinct.

Soil compaction is even stronger and deeper during harvest time in the autumn than in the spring. This has, however, not been studied in Finland. Instead, in southern Finland in 1980 a new experiment serie of soil deep-loosening into about 70 cm depth has been started.

COMPACTION OF SOIL

Field Experiments with Winter Wheat and Sugar Beets

by

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I. INTRODUCTION

The problem of soil compaction by farm machines and tractors and its influence on the yields has been a subject of interest for many years in Poland. One of the first indications on damaging effect of compacted soil may be found in a study by Świeżawski /6/ which appeared in 1928.

At the turn of 50's and 60's there appeared in Poland the first post-war publications on the subject. But it was only in the 1970's that a considerable advance was made in the studies on the subject.

In 1976 Poland took over coordination on a demonstration project concerning the influence of vehicle mechanisms on the soil. Studies on the project are under way in Czechoslovakia, German Democratic Republic, Poland and the Soviet Union. The project is led by the Institute for Buildings, Mechanization and Electrification in Agriculture (IBMER) in Warsaw. The studies deal both with fundamental questions of soil stress and strain, under the impact of forces, and the influence of vehicle mechanisms on the compaction of soil and the yields of crops. In 1976 a comprehensive survey was made /2/ on the most previous projects dealing with the compaction of soil by farm machines and tractors and the influence of compaction on the yields. It includes 88 items of Polish and foreign literature. Following this analysis a research team of Agricultural Academy in Lublin devised a test procedure and started tests on experimental plots.

The present report deals mainly with test procedure and some more interesting results of tests started in 1977.

II. TEST PROCEDURE

The so far results from tests on the soil compaction indicate that the fundamental parameter to define the state of soil in view of its concentration is the bulk density of soil. To know the bulk density and the volume humidity is to be able to predict the remaining physical parameters of importance for the growth of a crop.

As a result of surveying the available test procedure to measure the volume density of soil the most precise was found to be a measurement by way of scintillation probe /4/.

Table 1.

URSUS C-4011

Total weight	2690 kg	
Front axle	830 kg	
Rear axle	1860 kg	
Tyres (standard)		
Front	6.00 x 18	
Rear	14.9/13-28 or 9.5/9-32 (narrow tyres) for inter-row cultivation	
Twin tyres for rear axle		
Total weight	2967 kg	
Front axle	862 kg	
Rear axle	2105 kg	
Tyres		
Front	10-15	
Rear	14.9/13-28	
Inflation pressure	Front	Rear
Winter wheat		
Standard	p_o= 180 kPa	p_o= 80 kPa
Low pressure	p_o= 90 kPa	p_o= 40 kPa
Twin with low pressure	p_o= 120 kPa	p_o= 40 kPa
Sugar beets		
Standard	p_o= 180 kPa	p_o= 80 kPa
Narrow tyres	p_o= 180 kPa	p_o= 150 kPa

It was found useful to effect the tests on the influence of soil compaction on the yields as comparative tests by using different tractor vehicle mechanisms.

It was decided to compare yields of crops obtained by carrying out tillage and the remaining field operations by using chosen design of tractor vehicle mechanisms.

In the experimental plots winter wheat and sugar beets are grown. All field operations are carried out by a tractor URSUS C-4011 (for technical details see tab.1), equiped with an assembly of tilling and cultivation implements. For the winter crop three vehicle mechanisms were chosen:

W_1 - a standard tractor. Front tyres 6.00-18, inflation pressure p_o = 180 kPa, rear tyres 14.9/13-28, inflation pressure p_o = 80 kPa.

W_2 - a standard tractor - low inflation pressure of front tyres p_o = 90 kPa and p_o = 40 kPa for rear tyres.

W_3 - a tractor with alternative front tyres 10-15 inflation pressure p_o = 180 kPa, tandem rear tyres 14.9/13-28 and p_o = 40 kPa for rear tyres.

The experiments are carried out in a set of three ranges and 4 alternatives.

The experiments in the following years were carried out in the same area. The only difference is changed place for winter wheat and beet crops. Results of granulometric analysis of soil (acreage of 1 ha) are provided in table 2.

For the sugar beet crop two designs of tractor vehicle mechanisms were chosen:

W_1 - a standard tractor. Front tyres 6.00-18, inflation pressure p_o = 180 kPa, rear tyres 14.9/13-28 inflation pressure p_o = 80 kPa.

W_2 - a tractor with tyres for inter-row cultivation 9-32. Inflation pressure of front tyres p_o = 180 kPa and for rear tyres 150 kPa.

In view of the cultivation techniques for sugar beets no other designs of vehicle mechanisms could be taken into account. The experiment is carried out in a setting of two ranges in 4 alternatives.

Following this line of testing it will be possible to identify the most promising designs of tractor vehicle mechanisms. It was found useful to assess also the influence of travel speed and the frequency of running on the behavior of soil compaction under the wheels of farm machines Fig.1 /1, 5/ as well as the influence of the tractor wheel slip on the soil compaction Fig.2 /3/.

III. DISCUSSION OF TEST RESULTS

Tests on the influence of soil compaction on the yields of winter wheat were started in autumn 1977 and for sugar beets in the spring 1978.

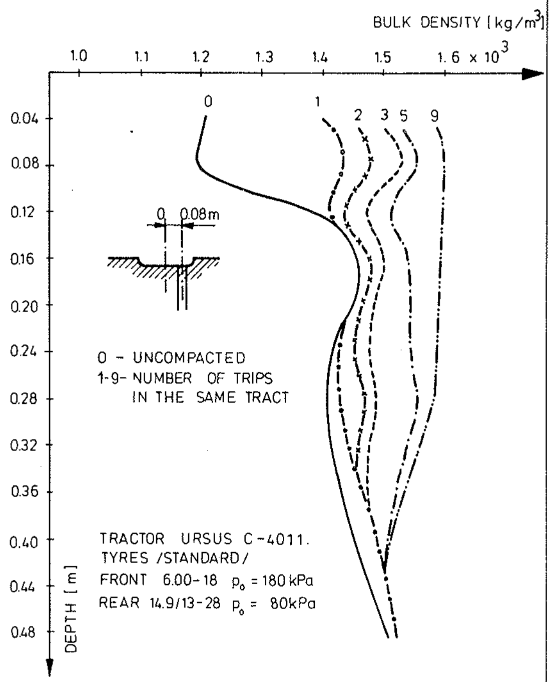

Fig.1 BULK DENSITY vs. DEPTH
according to W. Skowronek

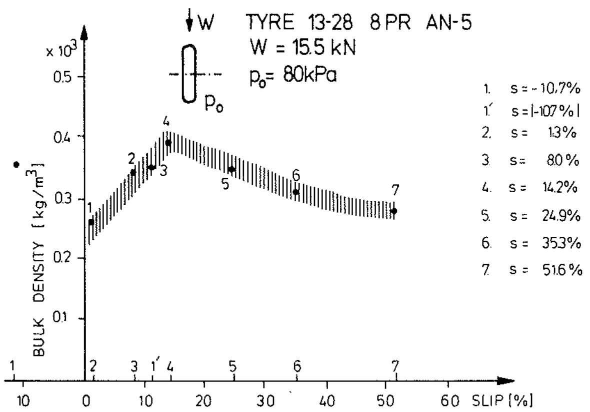

Fig. 2 INCREASE OF BULK DENSITY vs SLIP
according to J. Przesmycki

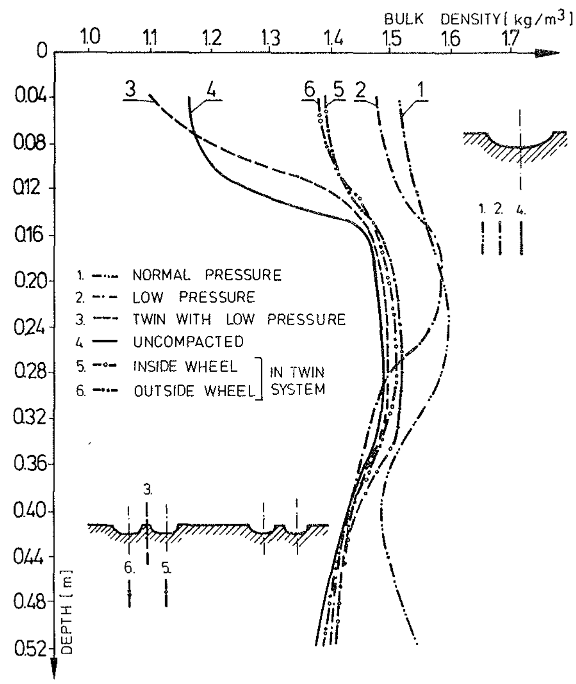

Fig. 3 BULK DENSITY vs. DEPTH. MEASURING IN THE CENTRE OF TYRE RUT. according to E. Krasowski

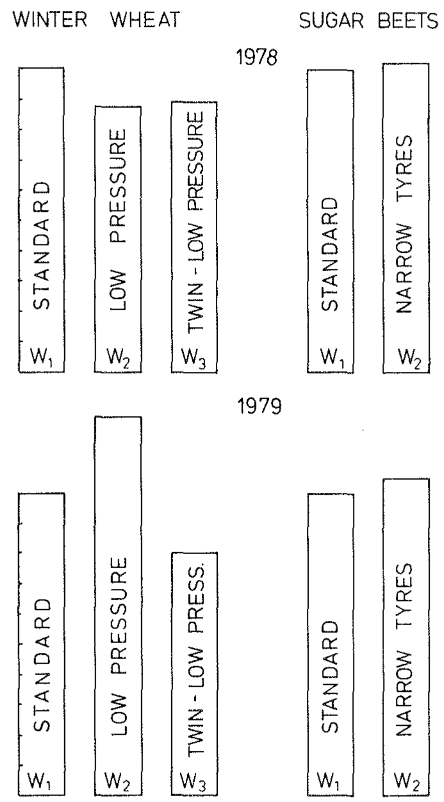

Fig.4 YIELDS. Standard 100 per cent

Table 2

PTG Standard

Kind of soil	Mechanical composition of soil					
	Sand	Silt		Clay		
	1-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002
Silty clay	22	6	39	18	3	12

The field operations required for both crops were carried out following the accepted way of cultivation. The measurements of changing bulk density and the humidity of soil were effected in each plot. The results of measurements of the bulk density in the centre of tyre rut are presented in the Fig.3.

In the second year the tests were continued with there changed place for the wheat and sugar beet crop.

During the experiments observations were made on the growing of crops in the individual experiment plots in addition to biometric measurements. The obtained yields of winter wheat and sugar beets from harvests in 1978 and 1979 are presented in table 3. It has to be emphasized that the rainfalls in 1978 affected the yields and reduced the sugar content in the beets. The test are being continued this year.

Taking as a reference of 100 per cent the yield obtained when using the design standard - W_1 the yield for 1978 was found to be reduced for the design of low pressure (W_2) by 12.2 per cent but in 1979 it was increased by 25 per cent. For the design with tandem wheels (W_3) the yield in 1978 was reduced by 10.3 per cent and in 1979 it was reduced as much as 19.3 per cent Fig.4.

As far as the sugar beets are concerned, under the use of narrow tyre tractor, the yield was increased by 2 per cent in 1978 and 5 per cent in 1979.

The results obtained so far, due to rather a short testing period (2 years) are not relevant enough. The full analysis will be provided after completing the tests.

IV. CONCLUSIONS

Parameters of appreciate

- bulk density
- structure
- cohesion
- moisture
- cultivation resistance
- depth of tyre rut
- quality of cultivation
- yield

Results of soil compaction

- increased bulk density
- increased cohesion

Table 3

YIELDS

WINTER WHEAT q/ha

Tyres	1978	1979
Standard	41.81	35.8
Low pressure	36.73	44.8
Twin with low pressure	37.5	28.9

SUGAR BEETS q/ha

Tyres	Roots	Leaves	Sugar
	1978		
Standard	340	374	15.1 %
Narrow tyres	347	422	13.5 %
	1979		
Standard	346	512	15.22 %
Narrow tyres	364	487	15.72 %

- increased cultivation resistance
- increased clods
- increased erosion
- quality of cultivation is reduced
- decreased performance of farm machines and their reliability
- decreased yield

Relationships

- vertical load - compaction
- compaction top and subsoil-yield
- compaction - losses of energy
- compaction - erosion

Problems

- influence of traction elements on the physical properties of soil and soil resistence in cultivation
- determine of stress in the soil (top and subsoil)
- influence of spot compaction on the yield - tyre rut

Investigations

In this investigations in Poland have to be tested:

- three kinds of soil (light, middle, heavy)
- crops (wheat, sugar beet and potatoes)
- inflation pressure and travel speed of vehicle should be variated
- tractors, combines and trailers have to be tested.

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RESULTS OF THE DISCUSSIONS AT THE MEETING

During the meeting there was a general discussion about the state of knowledge concerning the soil compaction by vehicles, and its effects on crops. Available information about subsoil compaction caused by vehicles with high axle load (depth of compaction, persistence, crop response) was of course particularly discussed. After having concluded that there is a need for new information concerning the effects on soils and crops caused by very heavy vehicles, the outline of new experiments was thoroughly discussed. The result of this discussion is summarized below. The conclusions adopted by the participants during the meeting are also included in this report - on the last page as a kind of summary - although, from a logical point-of-view, they should have preceded the discussion of the experimental outline.

As stated in the conclusions, axle loads at least as high as the maximum axle load permitted on the highways should be considered in the experiments. An inquiry showed that in the participating countries the maximum load permitted is normally 10 tons on a single axle and 16 tons on a tandem axle unit, though in some countries lower limits apply to old or small highways. Therefore the 10/16 ton load limits were regarded as being of particular interest.

The participants also discussed the desirable extent of the experimental work. The effects of vehicular traffic will, no doubt, be greatly influenced by the site. Therefore it is necessary to carry out experiments on many sites. To sufficiently cover the variations in soil, climatic, and cropping conditions in the region, 30-35 sites seem to be necessary. The participants estimated that they would be able to get financial support for about 15 experiments in all, in addition to the 9 experiments already running in Sweden. Ireland and BRD may also be included in the actual region, but they were not represented at the meeting. If they join the group it will be easier to reach the desirable number of experiments. However, the participants in the meeting will try to start experiments in their respective countries in a near future to the extent that financial and personnel situations permit.

Thus it seems as if an international series of similar experiments will be started. All the experiments should include two common "standard treatments", specified below. In addition, a varying number of additional treatments may be included according to local wishes and facilities.

I.H.

SUMMARY OF DISCUSSIONS ABOUT EXPERIMENTAL OUTLINE, VARIABLES OF INTEREST, AND MEASUREMENTS

Title: Long term effects of vehicles with high axle load on subsoil compaction and plant response.

Objectives: (1) Measure extent and persistence of soil compaction caused by high axle loads applied on soil surface.

(2) Measure crop response to subsoil compaction under high axle loads for a period of several years.

(3) Formulate general conclusions regarding upper limits of axle loads to be used on arable fields.

Standard Treatments: Two "standard treatments" common to all experimental sites should be:

(1) At least 4 repeated passes of a vehicle loaded to 10 tons/single axle (alternatively 16 tons/tandem axle) on soil at or near field capacity water content. This treatment is to be applied just once during the experiment, and is to be applied on the soil surface, not at some depth in the soil. Tires with about 300 kPa inflation pressure should preferrably be used.

(2) Control treatment in which axle loads shall not exceed 5 tons. Inflation pressure shall not exceed 150 kPa.

Variables: The following variables should be considered when applying the 2 standard treatments, and may be included as additional treatments if desired.

(1) Soil type - Soil types common to the area is first criteria, but it is desireable to have a minimum of 3 types (high, medium, heavy or sandy, loam, and clay).

(2) Drainage - Select sites that have drainage consistent with good normal agricultural practices. Some estimate of internal drainage characteristics should be made.

(3) Climate - Will be determined by site selection and can perhaps be modeled to project plant response without running all experiments for 10 years.

(4) Site pretreatment - Avoid sites which currently restrict root growth to the tilled layer. May be desireable to observe plant growth on the general site one year before applying treatments to study uniformity of soils. Site should not have previously been subjected to axle loads comparable to the axle loads of the standard treatment. Subsoiling is a possible additional treatment.

(5) Tires vs tracks - Rubber tire wheels will be used in the standard treatments, tracks possibly in additional treatments.

(6) Axle load - 10 tons (± 1 ton)/single axle or 16 tons/tandem axle will be used in the high axle load standard treatment. 10 tons/single axle is preferred. 5 ton/axle should be the upper limit used on the control standard treatment, and in the high axle load standard treatment after the treatment has been applied. Axle loads >6 tons often causes compaction at depths of 40 cm.
Additional treatments of very high axle loads such as 20 tons would be of big interest.

(7) Single or dual wheels - Single wheels should normally be used in the standard treatments, duals possibly in additional treatments.

(8) Tire size - Front and rear wheels should be about the same size on the vehicle applying high axle load to standard treatment. Do not use wide flotation-type tires. Road construction equipment, such as a Volvo dumpster, has 18 x 25" front tires and 16 x 24" rear tires. Tires of about that size should preferrably be used in the standard treatment. It is of big interest to include some other tire size as an additional treatment if a big enough size difference can be obtained. (Inflation pressure may simultaneously be varied.)

(9) Inflation pressure - Use about 300 kPa or higher inflation pressure on high axle load standard treatment, and no more than 150 kPa inflation pressure on the control treatments.

(10) Number of passes - This is a very important factor. High axle load standard treatment do consist of 4 repeated passes of vehicle, with strong emphasis to also include 1 pass as a treatment if possible. Depending on current practices, a farmer may put on 4 passes with a heavy load over the course of one or more growing seasons, or may put on 4 passes of a heavy load just during harvest operations. An additional treatment of "many" passes (15-20) might be considered as a way to ensure getting subsoil compaction, if subsoil compaction at all is achievable with the vehicle used.

(11) Speed - Compaction effect decreases as speed of compacting wheel increases up to a point. Further increases in speed then may result in higher bulk density because of vehicular bouncing and dynamic loading in addition to static looding. A speed of about 5 km/h is desired. Avoid speeds $\leq$ 2 km/h.

(12) Wheel slip - This is probably not a large factor in subsoil compaction but should be observed or measured. Avoid high slip to prevent deep rut formation.

(13) Interval between passes - In the standard treatment the 4 passes should be completed within a period no longer than 5 days. The interval between passes should be kept constant between replications and sites, and should be recorded. Long intervals invite delays because of rain.

(14) Starting time - The time of year as such that the high axle loads are applied is probably not important, or at least, does not have to be standardized among sites. However it may strongly influence the soil water content. The standard high axle load treatment is to have all 4 repeated passes put on at once (within 5 days) and not repeated again later.
Additional treatments may consist of applying high axle loads in succesive years, providing a way to separate the effects of actual year from age of experiment.

(15) Soil water content - This variable is very important, but extremely difficult to specify. "Near field capacity" was decided as the water content at which to apply the high axle load, with emphasis to include an additional treatment, if possible, simply defined as "drier than field capacity". Several techniques were discussed to alter and control the soil water content. Irrigation may lead to increased heterogeneity of water distribution above that normally found in the soil. It might be easier to let crop take out water to various stages but this won't be uniform either.

(16) Compaction alleviation - The compaction in the surface or tilled layer should be alleviated as soon as possible after the high axle loads have been applied. This is to insure that crop response in due to subsoil compaction and not surface compaction. However, alleviation of the compaction effects in the tilled layer may not be possible in one year. Alleviation of compaction in the subsoil should be considered as additional experimental treatments and may include subsoiling, and possibly snow packing or snow removal to increase frost depth.

(17) Crops - Any crops normally grown in the area may be used. It is desireable to have crops as treatments to avoid complications of crop - climate interactions.

(18) Tillage depth - Use same tillage over all plots and at normal depths except if used as a means of alleviating subsoil compaction. 25 cm deep can be considered as a normal plowing depth.

(19) Fertilizer placement and weed control - Should be at optimum levels and consistent with good farming practices.

Measurements:

(1) Extent of soil compaction (mainly depth, intensity and duration) - There is probably no single measurement that is "best". One may use whatever experience and availability of equipment dictates. Bulk density, penetrometer resistance, vane shear resistance, water infiltration, air permeability are some possibilities.

It is necessary to recognize effect of soil water content on measurements such as penetrometer and vane shear resistance. If these data can not be corrected to a common water content then perhaps they should be taken when the soil is at some "standard" water content such as field capacity.

If surface compaction differences are not eliminated, then there may be a need of some measurements of aggregate or cold density, aggregate size distribution, depth of seedbed etc. These types of measurements can also be used to determine if there are differences in the surface soil remaining after high axle load treatment.

(2) Crop response - Yield is the most important data, but measurements of growth rate, root growth, and maturity or grain quality at harvest time is also of importance. It must be recognized that crop response for the first couple of years after application of high axle loads may be due in part to surface soil compaction.

(3) Basic soil characteristics - Particle size distribution, type of clay, % organic matter. Moisture characteristic curve should be determined if moisture content at treatment is used as a variable.

(4) Climatic conditions - Precipitation, air temperature, potential evaporation, snow cover. Depth of frost penetration can be useful and is easily determined, using the frost depth probes used in Uppsala.

W.B.V., I.H.

WORKING GROUP ON SOIL COMPACTION BY VEHICLES WITH HIGH AXLE LOAD.
ORGANIZATIONAL MEETING AT UPPSALA 1980-09-02--04.

Conclusions adopted by the participants:

1. Vehicular traffic on arable fields causes compaction which may go deeper the higher the axle load. At axle loads higher than 6 tons, compaction has been observed to depths deeper than 40 cm.

2. Vehicular traffic on arable fields has influence on the soil which is frequently negative to the subsequent crops.

3. Plant response to vehicular compaction in an annually tilled layer in areas subjected to annual freezing does not seem to persist for more than a few years. However, compaction in deeper soil layers seems to persist for a longer time with adverse crop effects. Tillage to alleviate the compaction is more difficult and expensive the deeper the compaction goes.

4. At present there is considerable information available concerning the compaction in the tilled layer and the resulting crop response. However, there is little data available concerning compaction in deeper layers caused by high axle loads and its effects on the crops.

5. Because the size of the machinery is steadily increasing there is a need for new information concerning the compaction effects of very heavy vehicles. The market for farm machinery is becoming increasingly international. Therefore it is desirable to collect this information by an international cooperative effort.

6. The compaction effects on yield are strongly dependent on soil, climate and crop. Therefore the international cooperation may be restricted to regions with similar physiographic properties. The participants have identified Northwestern Europe and similar physiographic areas in North-America as one appropriate region.

7. The participants, all of them currently active in research work on soil compaction, desire to initiate experimental work in their respective countries on the problems identified above.

8. The compaction problems differ to some extent among the participating countries which gives rise to variation in specific experimental objectives. However, because the central problem is international, "standard" treatments common to all experiments should be included.

9. The participants identified the following as the most important variables for the experimental work: Soil type, climate, wheel arrangement and characteristics, axle load, number of passes, soil water content and crop species. Axle loads at least as high as the maximum axle loads permitted on the highways should be considered. However, it is not the intention to test specific vehicles or tires.

10. If a few experiments relating crop response to high axle load will be carried out in each of the participating countries, the results will form a sound basis for developing guidelines for maximum axle loads on arable fields. This will have practical and economical significance in the design and use of farm equipment.