MACHINERY-INDUCED
COMPACTION of ARABLE SOILS
INCIDENCE – CONSEQUENCES – COUNTER-MEASURES

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Abstract
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Incidence - Consequences - Countermeasures

This book describes various aspects of machinery-induced compaction of arable soils from both a scientific and a practical point of view. It is largely based on experiences from Sweden and other Scandinavian countries, where field experimentation on soil and crop responses to machinery traffic has been more extensive than in most other parts of the world. The following subjects are discussed in the book´s nine independent chapters: 1) Traffic intensity in arable fields 2) Stress distribution under wheels and tracks 3) Extent and persistence of soil compaction 4) Effects of compaction on soil properties and processes 5) Effects of compaction on crop growth and yield 6) Ecological and environmental effects of compaction 7) Methods to minimize compaction or its negative effects 8) Economic consequences of compaction 9) Current situation and need for load limits.

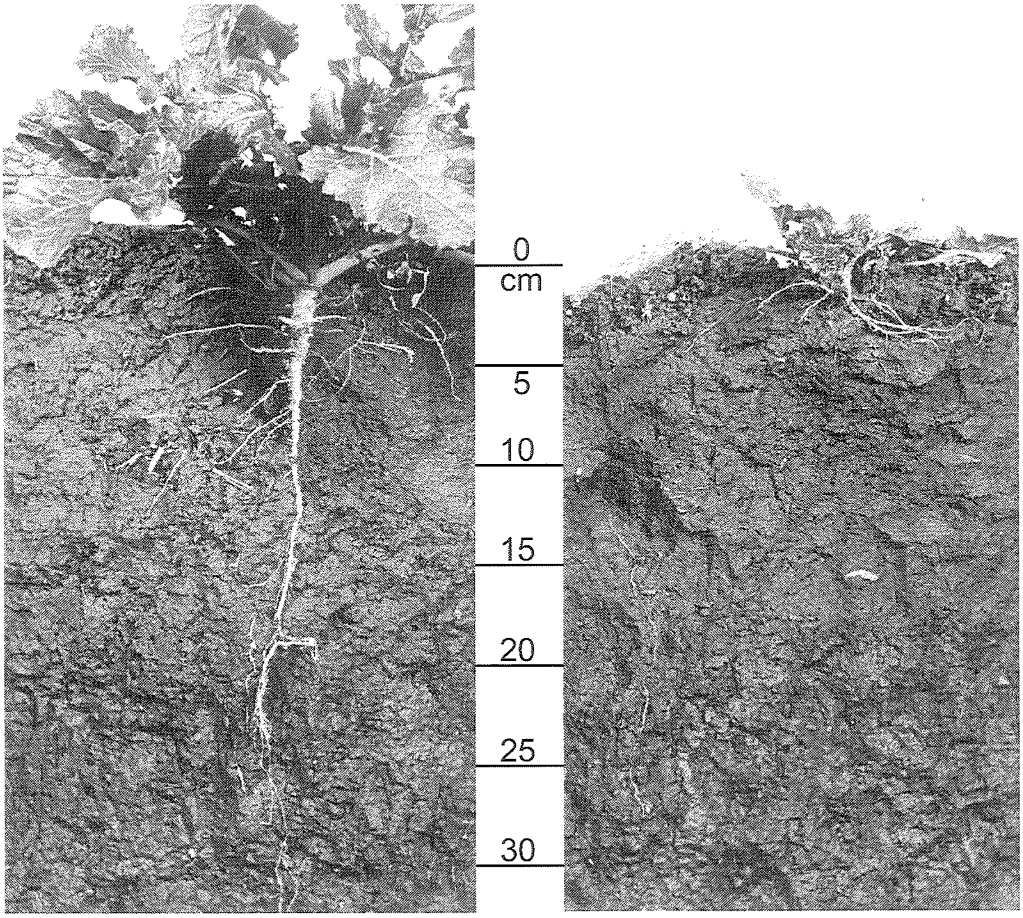

Fig. 1. When a soil is compacted, nearly all its properties change. This figure shows two 30 cm deep soil sections taken about two metres from each other in a field with a rapeseed crop. The section to the left is from an area where the plough layer was optimally recompacted after loosening by ploughing. Therefore, roots developed without problems, and the crop grew well. The section to the right is from an area over which a loaded manure spreader passed several times in wet conditions and compacted the soil intensively. Here, root growth ceased a few cm below sowing depth and the crop developed poorly.

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Preface

Ever since field operations became mechanized, traffic by tractors and other machines has caused soil compaction. Even though the draught animals previously used also compacted the soils, this was to a lesser extent. As long as only relatively light machines were used, the traffic mainly affected the topsoil. In this layer, tillage and natural processes alleviate the compaction effects within some years. However, when machine size increases, compaction extends to greater depth. In deep subsoil layers, the effects cannot be alleviated by either normal tillage operations or natural processes. Therefore, they become very persistent, or even permanent, and they tend to accumulate over time.

Compaction affects nearly all soil properties, physical, chemical and biological, usually in a negative way. Crop yields decrease, time, cost and fuel requirements for tillage operations increase, soil aeration is hampered, denitrification increases and aerobic microbial processes are impaired. Therefore, knowledge about soil compaction in arable fields and its consequences are needed in many contexts and not only by farmers. To avoid permanent soil degradation, it is necessary to establish limits for the mechanical stresses.

Most soil compaction research in agriculture to date has concerned effects on soil physical properties and crop growth. The complex effects on soil chemical and biological properties and processes and on the environment are much less well-known, even though such effects are certainly substantial. Individual soil processes are affected by compaction in a similar manner everywhere, but the magnitude of the effects and their importance vary considerably depending on climate, soil, cropping system, etc. This means that the consequences of machinery traffic also vary considerably between farms and regions and therefore measures to manage soil compaction problems in practice must be adapted to the local conditions.

I have been involved in soil compaction research in Sweden since the late 1950s, and this book is largely based on results and experience gathered in this research. In Sweden and in the surrounding countries, research on soil compaction, particularly its effects on crop growth and yield, has been among the most extensive in the world. This region has a more or less humid climate, soils usually freeze in the winter and cropping systems are dominated by cereals. However, experience of soil compaction problems gathered in this region is certainly of value all over the world, bearing in mind that the quantitative effects on individual soil properties and processes and the best methods to minimize the problems depend on local conditions.

I have written this book as an introduction to soil compaction problems, mainly for people involved in agriculture and environmental protection. However, its format is such that it can be used as a concise reference book as well, since each chapter is written as an independent unit dealing with a specific aspect. This made it necessary to repeat some of the information in more than one chapter, but I hope that those who read the whole book will not find these repetitions too disturbing. Each chapter starts with a summary, and all summaries together provide a quick synopsis of the book.

Uppsala, June 2005

Inge Håkansson

Contents

Page

Chapter 1 **Traffic intensity in arable fields** 7
1.1 The loaded wheel - our most frequently used tillage tool 7
1.2 Size of the wheel track area 8
1.3 Wheel track distribution 10
1.4 Number of Mgkm ha^{-1} 14
1.5 Other measures of traffic intensity 15
Chapter 2 **Stress distribution under wheels and tracks** 17
2.1 Ground pressure induced by wheels 17
2.2 Stress propagation in the soil 20
2.3 Tracked vehicles 24
Chapter 3 **Extent and persistence of compaction in arable soils** 27
3.1 Relationships between stress and compaction 28
3.2 Extent of compaction in the plough layer 33
3.3 Extent of compaction in the subsoil 39
3.4 Persistence of compaction effects 43
Chapter 4 **Effects of compaction on some soil properties and processes** 51
4.1 Pore volume and pore size distribution 51
4.2 Hydraulic conductivity, infiltration and drainage 53
4.3 Root growth and function 54
4.4 Soil structure and seedbed quality 58
4.5 Soil biological effects 60
4.6 Effects on soil trafficability 60
4.7 Effects of intensive loosening 60
Chapter 5 **Effects of compaction on crop growth and yield** 61
5.1 Various types of effect of machinery traffic 62
5.2 Short-term effects of recompaction of a loosened ploughed layer 62
5.3 Effects in the plough layer that persist after ploughing 74
5.4 Compaction effects at reduced tillage or direct drilling 79
5.5 Subsoil compaction 82
5.6 Effects of machinery traffic in established crops 85
Chapter 6 **Ecological and environmental effects of compaction** 91
6.1 All soil properties and processes are affected 91
6.2 Water economy, surface runoff and soil erosion 91
6.3 Efficiency in the use of commodities in crop production 93
6.4 Leaching of plant nutrients 93
6.5 Biological activity in soils 94
Chapter 7 **Methods to minimize compaction or its negative effects** 99
7.1 Measures must be adapted to the conditions on individual farms 99
7.2 General crop production measures 100
7.3 Machinery 101

7.4 Soil tillage 105
7.5 Operational systems and routines 106
7.6 Future possibilities 108
Chapter 8 Economic consequences of compaction 113
8.1 Various models to estimate compaction effects 113
8.2 A model to predict effects of compaction on crop yield 115
8.3 Example of economic calculations 120
8.4 Draught requirement in compacted soil 126
Chapter 9 Current situation and need for load limits 129
9.1 Current situation 130
9.2 Need for load limits 134
References 139
Index 151

Boxes

1 Soil horizon terminology used in this book 13
2 Stress and pressure 18
3 Definition of soil compaction and compactness 29
4 Classification of soils according to their texture 30
5 Definition of some soil physical terms 32
6 Soil freezing - depth, frequency and frost action 46
7 Subsoil loosening 48
8 Influence of compaction on volumetric relationships and pore size in soils 52
9 Root growth and rooting depth 57
10 The penetrometer and the shear vane tester 59
11 Degree of compactness and other relative bulk density values 64
12 Climate, soils and crop production systems in Scandinavia 66
13 Scientific names of crops mentioned in this book 69
14 Sensitivity of various cultivars to soil compaction 71
15 Effects of reduced tillage in various soils in Northern Europe 82
16 Water requirement and water uptake by crops 86
17 Early sowing in various soils 103
18 Trials with cable-drawn implements 110

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Front cover: photo Lennart Henriksson.

Chapter 1
Traffic intensity in arable fields

Summary

In most mechanized farming systems throughout the world, field traffic by tractors and other machines usually results in a total annual wheel track area that is several times the field area. Therefore, practically each point in a farm field is run over by loaded wheels several times per year, unless a controlled-traffic system is used. In intensive cereal production, the mean annual number of wheel passes is at least three, and in sugar beet production usually six to eight. This makes soil compaction an important concern in crop production.

Another simple measure of traffic intensity is the number of Mgkm ha^{-1}. For an individual field operation, this is the weight of the machine multiplied by the distance driven in km per ha. All field operations throughout a year usually generate a total of 100-150 Mgkm ha^{-1} in cereal production and nearly twice as much in sugar beet production. However, the amount of soil compaction, and consequently the effects on the functions of the soil, depend on several other factors as well. The wheel track distribution may be crucial and may vary from completely random to completely controlled. Examples of track distributions in various farming systems are presented. The importance of several other factors, such as ground pressure, load on individual wheels, soil texture and soil water content, are discussed in subsequent chapters.

1.1. The loaded wheel - our most frequently used tillage tool

The loaded wheel is sometimes mentioned as our most frequently used 'tillage tool'. In mechanized farming systems, wheels of tractors and other heavy machines affect most arable soils more often than any of the actual tillage tools. Recurrent machinery traffic often leads to intensive compaction of the upper soil layers (Fig. 1), and sometimes of deep subsoil layers as well. As shown in subsequent chapters, this may substantially influence all functions of the soil.

The present chapter deals with the intensity of traffic by tractors and other machines in farm fields. Data are given on total wheel track area per ha as well as on track distribution and on traffic intensity in Mgkm ha^{-1} (the product of the machinery weight in Mg and the distance driven in km ha^{-1}). Although such simple figures cannot provide detailed information on the compactive stresses induced by machinery traffic in soils, they clearly demonstrate why this traffic often leads to compaction problems and why it is important to always try to minimize its negative effects while benefiting from its positive effects.

In addition to compaction, machinery traffic often causes deep ruts that may obstruct subsequent field operations or necessitate additional tillage operations just to level the soil surface. From a practical point of view, this is sometimes as important as the compaction effects of the traffic. However, this aspect will not be further discussed in this book.

Although the effects of soil compaction are largely negative, it should be pointed out already at this point that positive effects also occur. For instance, after ploughing or other deep loosening of the soil, a moderate recompaction of the loosened layer usually improves crop growth. Optimal recompaction is often obtained by one pass of a wheel with a low ground pressure. This aspect is discussed in Chapter 5.2.

1.2. Size of the wheel track area

The total wheel track area in a farm field resulting from all field operations throughout a year is usually several times the field area. This means that on average, each surface element in the field is affected by machinery induced mechanical stresses several times each year. In the case of more than one crop per year, this may be true for each individual crop. However, the track area varies widely between farms and fields depending on the crops grown, the number and type of field operations and the working width and wheel equipment of the machines.

For an individual field operation, the total wheel track area can be estimated as the product of the distance driven by the vehicle and the sum of the widths of all its wheels. For a tillage or sowing operation the distance driven can be quite accurately estimated in a simple way such that the 'productive driving distance' in km ha^{-1} is 10 divided by the working width in m. There is, however, an 'additional driving distance. for turning, overlap etc. This is usually about 25% of the productive distance, but it may vary from less than 15% in large and regularly formed fields to more than 35% in small, irregular fields.

For field operations comprising an appreciable transport component, such as manure spreading or harvest of root or forage crops, the additional driving distance is usually much larger. It also varies much more and cannot usually be estimated as a stereotyped percentage of the productive driving distance. A study of slurry manure spreading in some Swedish farm fields (I. Håkansson, unpublished data) showed that the additional driving distance in irregular fields could be as large as four times the productive driving distance. In this type of operation the additional driving distance depends on many factors such as type and size of machines, distance required for loading or unloading, driving pattern, field size and form and number and positions of entrances/exits to the field. Good planning and many entrances can often reduce this distance considerably.

Table 1 shows the size of the wheel track area as a percentage of the field area when using traditional machinery and crop production systems. Data are given both for some individual field operations and for the whole year in crops of various types. The values in the table show the sum of the track areas of all individual wheels, even though some of them follow the same tracks. These values are estimated for Scandinavian conditions, but for individual operations similar values would be obtained in most parts of the world with mechanized agriculture. On the other hand, total values per year or per crop may vary greatly depending on the production system.

For ploughing and other deep tillage operations the track area is much larger than for shallow tillage due to a smaller working width. For the same operation and when using wheels with the same ground pressure, a heavier tractor usually results in a somewhat smaller wheel track area than a lighter tractor, since when the tractor weight increases the width of the wheels increases relatively less than the working width.

In cereal production with the number and type of field operations and with the types of machines traditionally used in

Table 1. Estimated traffic intensity in arable fields (specified as the wheel track area as % of the field area and as Mgkm ha^{-1}) for some selected field operations and for the whole year in various crops on normal Scandinavian farms with conventional soil management. Track areas are the sums of track areas of all individual wheels, even though some of them follow the same tracks

Field operation	Track area, % of field area	Number of Mgkm ha^{-1}
Mouldboard ploughing, 20 cm depth		
4 Mg tractor, 3-furrow plough	90-170	35-50[a]
10 Mg tractor, 8-furrow plough	70-130	32-46
Chisel ploughing, 12 cm depth		
4 Mg tractor, 3 m plough	45-110	15-20
12 Mg tractor, 9 m plough	30-70	15-20
One harrowing, 5 cm depth		
8 Mg tractor, single wheels, 9 m harrow	20-38	10-12
8 Mg tractor, dual wheels, 9 m harrow	32-55	10-12
Sowing of cereals		
Combi-drill[b], 5 Mg tractor, dual wheels, 3 m drill	100-170	25-35
Separate drilling, 5 Mg tractor, single wheels, 7 m drill	25-65	10-15
Cereal harvest[c]		
3.6 m harvester, 5 Mg empty, 7 Mg fully loaded	40-55	18-23
6.6 m harvester, 14 Mg empty, 19 Mg fully loaded	40-60	28-35
Sugar beet harvest		
6 Mg tractor, 3-row harvester, 6 Mg empty, 12 Mg loaded	120-180	120-160
6-row harvester, 20 Mg empty, 40 Mg fully loaded	120-180	120-160
Spreading of slurry manure		
Regular fields, many entrances	40-150	15-60
Irregular fields, few entrances	80-250	30-110
For the whole year (when growing one crop per year)		
Cereals, high-intensity production, mouldboard ploughing	300-650	100-220
Cereals, low-intensity production, reduced tillage	170-400	70-140
Root crops and potatoes	400-800	200-400
Ley for silage, 3 harvests, high yield	600-1000	180-350

[a] When making model estimations according to Chapter 8 the Mgkm-values are adjusted for tyre inflation pressure and soil moisture situation, and when estimating subsoil compaction the load on each axle is reduced. The Mgkm-values in this table are neither adjusted nor reduced.

[b] Sowing of cereals combined with fertilizer banding.

[c] Only the combine harvester; transport of grain is not included.

Northern and Central Europe (in Table 1 called high-intensity production), the total annual wheel track area is usually between 3 and 6 times the field area. This means that each point in the field, on average, is affected by stresses from loaded wheels 3 to 6 times each year. In farming systems with reduced or zero tillage or with less intensive production, the track area may be considerably less.

For a specific operation, the smallest wheel track area is obtained when using a machine with narrow, high pressure tyres. If wider low-pressure tyres are used with the aim of protecting the soil from over-compaction, the track area is larger. This shows that the total track area is not an appropriate measure of the potential of a machine to cause soil compaction. For that purpose, it is necessary to consider several other factors as well, such as the type of tyres used, the inflation pressure, the load on individual wheels and the track distribution. The response of a soil to the traffic also depends on the compactibility of the soil. This is further discussed in subsequent chapters.

In root crops and potatoes the annual wheel track area is generally much larger than in cereals, particularly at harvesting. In forage crops, such as ley of grass, lucerne or clover, the annual track area varies considerably and depends on harvesting method, number of harvests and type of machines used. The less the forage product is dried in the field (e.g., wet silage instead of dry hay) the heavier is the material that must be transported out of the field, the greater is the number of trailer loads and the larger is the wheel track area caused by the transport. For quality reasons, a ley crop must often be harvested at a predetermined stage of development, and therefore, harvesting may have to be made even when the soil is wet and susceptible to compaction and when the ley plants are vulnerable.

1.3. Wheel track distribution

Effects of machinery traffic on soils and crops are influenced by several factors besides the total wheel track area. One factor of importance is the track distribution over the fields. However, the importance of this factor varies considerably. For instance, when harvesting a crop in a field that is to be ploughed afterwards, the track distribution is usually rather unimportant, since the residual effect per wheel pass is relatively constant up to several passes (Chapter 5.3). On the other hand, traffic in ley fields or other fields where established plants can be damaged should usually be concentrated as much as possible to the same tracks, since the crop yield reduction per pass gradually decreases with the number of passes (Chapter 5.6).

The wheel track distribution is of great importance at seedbed preparation and sowing in fields where the soil has been loosened by previous ploughing or other tillage to similar depth. When growing small grains or other crops with small row spacing, row and inter-row zones cannot be treated differently. Then the goal should be a moderate and uniform recompaction of the loosened layer throughout the field (Chapter 5.2). This means that the whole field area should be covered as uniformly as possible (preferably only once) by tracks from wheels with a low ground pressure. No sub-areas should be uncompacted and no sub-areas should be exposed to too many wheel passes or too high stresses.

Fig. 2 provides an example of the wheel track distribution in a cereal field where traditional seedbed preparation and sowing are carried out using several operations in various directions in such a way that the track distribution can be regarded as 'random'. The field area is divided into sub-areas with different number of passes by the wheels from zero and upwards. In reality the individual sub-areas are composed of small spots or strips spread over the field in a more or less regular pattern. With dual wheels, the untrafficked area is small, particularly in the headlands. A relatively large area is trafficked several times, but by wheels with relatively low ground pressure and low compaction potential. With single wheels, the untrafficked area is larger and in the main (inner) part of the field in the example it is nearly 40%. This is a disad-

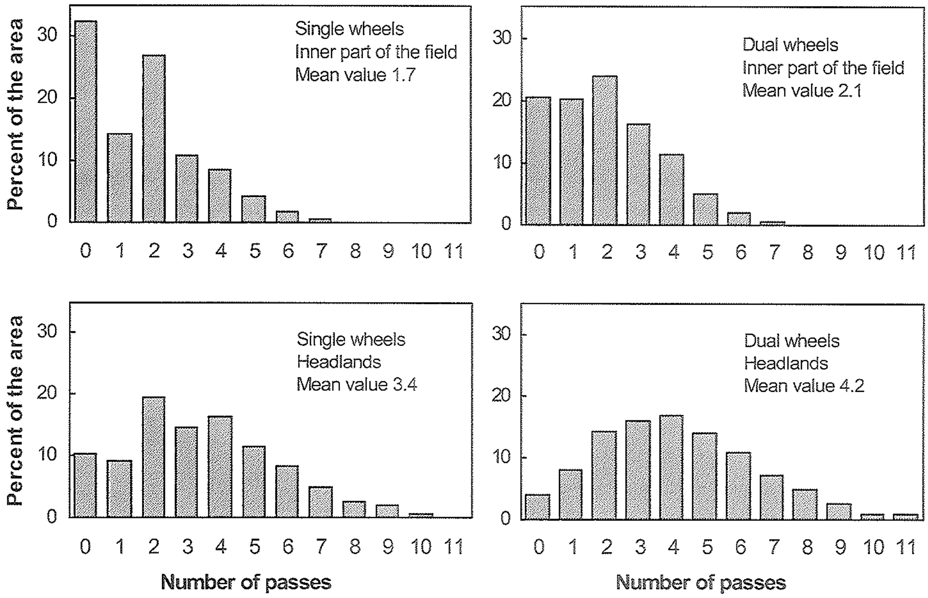


Fig. 2. Partitioning of the field area into sub-areas with different number of passes by wheels of tractors and other machines during a series of five seedbed preparation and sowing operations, viz. three harrowings, fertilizing and sowing. Widths: harrow 8 m, fertilizer spreader 12 m, seed drill 6 m, tractor rear wheels 0.65 m (single) or 0.94 m (duals), tractor front wheels 0.55 m, wheels of seeder and fertilizer spreader 0.50 m. Data are shown separately for the headland and for the rest of the field (the inner part).

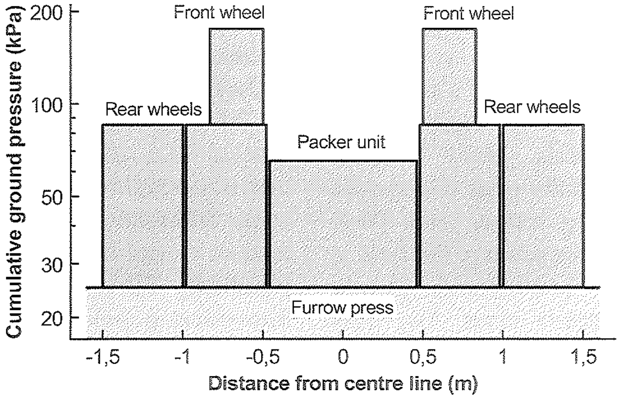


Fig. 3. Cumulative ground pressure in the tracks of tractor wheels and packer unit when the only field operation after ploughing is combined sowing and fertilizing using a 3 m wide tractor-drill unit equipped for 'full-width recompaction'. A furrow press (ground pressure 25 kPa) was attached to the plough. The tractor has wide dual-mounted rear wheels (60 kPa). A packer unit (40 kPa), loaded by the drill, is placed between the tractor and the drill to compact the area between the tracks of the tractor wheels.

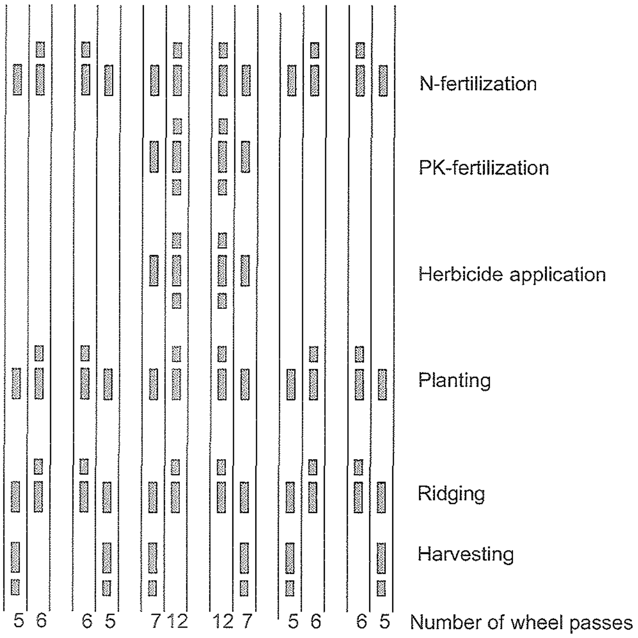


Fig. 4. Track pattern for all field operations throughout the year in an American ridge tillage system for maize and soya bean, both grown with a row spacing of 75 cm. The crops are sown in the tops of low permanent ridges. The number of annual wheel passes in each inter-row is indicated. No wheels pass in the row zones. Therefore, the need for deep, annual soil loosening is minimized and the tillage can be limited to clearing of the ridges when planting and reshaping them after crop establishment. (After Parsons et al., 1984.)

vantage, since in these areas the plough layer (Box 1) remains too loose and crop growth is likely to be sub-optimal. On the other hand, the area trafficked several times is smaller, but the wheels have relatively high ground pressure and compaction potential. The resulting compaction effects and crop responses are discussed in Chapter 8.2.1.

Fig. 3 shows an example of a more 'organized' track system for sowing of cereals with small row spacing. Many Swedish farmers have successfully used this system on sandy soils during recent years (Box 17). Immediately before sowing, the field is ploughed with a mouldboard plough equipped with a furrow press. The only subsequent operation is combined fertilizing and sowing with a tractor-drill combination equipped for 'full-width recompaction'. The aim is to achieve as uniform a state of compactness as possible over the whole field area. Fig. 3 shows the cumulative ground pressure across the working width of the drill. A logarithmic scale is used, since the amount of compaction caused by machinery traffic on a loose soil has sometimes been reported to be approximately proportional to the logarithm of the cumulative ground pressure (Chapter 3.1). Equipment of this kind can be designed in various ways, but the goal should be to achieve as uniform cumulative ground pressure as possible over the entire working width and a resulting compaction as close to the optimum as possible.

When growing crops with wide row spacing such as maize, soya bean or potatoes it is possible to treat row and inter-row zones differently, e.g. by driving only in the inter-rows and by utilizing the same tracks repeatedly throughout the year or even throughout periods of several years. Fig. 4 shows the track distribution in an American system for maize and soya bean, both of which sown with 75 cm row spacing. The rows are sown in the tops of shallow ridges kept in the same position year after year and all traffic is applied in the furrows (inter-rows). This can minimize or even eliminate the need for soil loosening. The annual tillage can then be limited to clearing the

Box 1

Soil horizon terminology used in this book

Plough layer

This is the upper soil layer that is annually or periodically loosened by primary tillage or has been treated in that way until recently. In Northern Europe, this loosening is traditionally achieved by mouldboard ploughing. Most experimental work referred to in this book was carried out in a system with this type of primary tillage. Then, the plough layer is usually the same as the Ap horizon. Unless otherwise stated, the plough layer is assumed to be about 25 cm deep. Because of temporal and spatial variations in ploughing depth, the depth is somewhat greater than the mean annual ploughing depth. Soil textural composition and organic matter content are relatively uniform throughout this layer due to the recurrent mixing.

Topsoil

When talking about soils that have never been tilled or soils where reduced tillage depth is continuously practised, a layer corresponding to the plough layer is sometimes named the topsoil. If the soil has never been tilled, there are usually gradients both in texture and organic matter content within this layer. If the soil has been previously ploughed to the traditional ploughing depth, which is the case in most arable fields, the textural composition is uniform to the previous maximum ploughing depth. After changing from traditional to reduced tillage depth, the content of organic matter is also relatively uniform for many years until an appreciable gradient has developed.

Subsoil

This term is used here for all layers of a soil profile below the plough layer (topsoil). In many cases, the natural stratification of this layer has never been disturbed by deep tillage.

Seedbed

This term is used for a shallow, and usually loose, surface layer. This is in accordance with the use of the term in Scandinavia, where seedbed preparation (secondary tillage, usually harrowing) is carried out only to the depth required for appropriate placement of the seed. This depth depends on the type of crop, but is normally 3-6 cm. The seed is usually placed at the base of this layer. There is usually a sharp boundary between this layer and the layer underneath, which usually becomes compacted by machinery traffic during seedbed preparation and sowing. It is important to distinguish between these two layers, since there are quite different requirements on the soil that covers the seed and the soil underneath. The properties of these layers can also be controlled by the farmer independently of each other. A seedbed in this sense usually contains 10 to 20% of the soil in the plough layer. This terminology is most appropriate for crops with small row spacing where the whole field area is uniformly tilled. In crops with large row spacing, row zones and inter-row zones can be treated differently, and this may require a modified terminology.

tops of the ridges in front of the seed coulters at planting and reestablishing the ridges after crop establishment. Such a system requires that all crops are grown with the same row spacing, and usually with efficient chemical weed control.

In some parts of the world, particularly where continuous direct drilling is a viable option (relatively dry climate, no root crops, moderate quantities of crop residues, moderate weed problems), a complete so-called controlled-traffic system (Section 7.5.5) has been introduced recently and may be a prerequisite for successful direct drilling. Excessive compaction may then be limited to a sparse system of repeatedly used wheel tracks. For full advantage, the tracks should never be moved. They should only cover a small part of the field area, which may require quite large machines.

1.4. Number of Mgkm ha^{-1}

Another simple possibility to quantify the intensity of machinery traffic in a field is to calculate the number of Mgkm ha^{-1}. For each operation this is the weight (mass) of the vehicle in Mg multiplied by the distance driven in km ha^{-1}. For instance, if the distance driven in a field by a tractor and trailer with a total weight of 10 Mg is 1 km ha^{-1}, i.e. one track every 10 m, the traffic intensity is 10 Mgkm ha^{-1}.

Normal values of the number of Mgkm ha^{-1} for individual field operations as well as total annual values for some crops are shown in Table 1. These values are similar to those given by Kuipers & van de Zande (1994). Ploughing, manure spreading and sugar beet harvesting are examples of individual operations generating large values. For tillage operations, the number of Mgkm ha^{-1} usually only increases marginally with increasing tractor size, since the working width increases and the driving distance decreases nearly proportionally to the tractor weight. On the other hand, for many harvesting and transport operations, the working width does not increase proportionally to the weight of the vehicles, and this may lead to considerably larger traffic intensity for heavier vehicles than for lighter ones as measured by the number of Mgkm ha^{-1}. Then it is particularly important to plan the traffic systems in such a way that the driving distances are minimized.

In traditional systems for production of small grains and similar crops in Scandinavia (one crop per year), normal annual operations for tillage, sowing, fertilizing, weed control and harvesting usually result in a total of 120-150 Mgkm ha^{-1}. In regions with double-cropping, these values may apply to each crop rather than to each year. If other operations, such as straw harvesting, stubble cultivation and spreading of manure are also carried out, the total annual value may be over 200 Mgkm ha^{-1}. In root crops and potatoes, the traffic intensity is much higher than in cereals, particularly at harvest. In ley crops, the traffic intensity largely depends on harvesting method and number of cuts but is often high.

Pure Mgkm-values as presented in Table 1 facilitate rough comparisons between machines or machinery systems concerning their compaction potential, and therefore also concerning the risks of detrimental soil compaction. However, for more accurate estimations of compaction effects actually generated by the machines such values are insufficient, since these effects also depend on other factors. For example with high-pressure tyres, the compaction potential is greater than with low-pressure tyres. Furthermore, the amount of compaction actually induced also depends on the compactibility of the soil, which is largely dependent on the water content. At least in the upper soil layers, a particular machine usually causes more compaction under wet conditions than under dry. A better indication of the compaction effects actually generated is obtained if the stresses in the ground contact areas of the wheels (usually called the ground pressure) and the soil moisture situation are also considered. In Chapter 8.2 a model to predict crop responses to machinery-induced soil compaction is described. In this model, before a Mgkm-value is used to estimate crop responses, it is multiplied by an adjustment factor for ground pressure and soil moisture. This factor (Fig. 42) can vary from nearly 0 for low-pressure tyres under very dry conditions up to a maximum of 1.5 for high-pressure tyres under wet conditions. (For trafficability reasons a higher value than 1.5 cannot occur.) For traditional tyres running on moist soils the value is usually between

0.5 and 1.1.

Adjusted Mgkm-values as described provide information on the compaction potential of the machines in relatively shallow soil layers (in the plough layer). To get information on the potential for subsoil compaction it is also necessary to consider that the stresses induced by the wheels gradually decrease with depth. For this purpose more or less sophisticated models have been developed (Chapter 2.2). The model in Chapter 8.2 uses a very simple, approximate method. When estimating the compaction potential in the subsoil by this model, the load on each axle is reduced, and only the reduced load is used to calculate the Mgkm-value. The reduction increases with increasing depth. For the 25-40 cm layer a reduction of 4 Mg per axle is used, and for the >40 cm layer a reduction of 6 Mg per axle. The reduced Mgkm-value is then adjusted for ground pressure and soil wetness as described in previous paragraph.

1.5. Other measures of traffic intensity

Besides wheel track areas and Mgkm-values several other parameter have been used in international literature to characterize the traffic intensity or compaction potential of a machine or machinery system (Kuipers & van de Zande, 1994). For most parameters aimed to characterize the compaction potential, the weight of the machines is a basic factor, but information on other factors such as wheel dimensions, tyre inflation pressure, driving distances or number of operations in the field, is utilized in various ways. Kuipers & van de Zande (1994) compared some parameters of this kind as estimates of the compaction potential of machinery systems used in various crops and farm sizes. They argued that the number of Mg h ha^{-1} as calculated according to Kuipers (1986) was the best parameter from a theoretical point of view. However, all parameters compared resulted in similar relative values for all crops and farm sizes considered. Since none of them can result in more than approximate and relative estimates of the compaction potential of individual machines or machinery systems, it may also be argued that the parameter that is easiest to calculate is the most useful for practical applications. Usually, this is the number of Mgkm ha^{-1}, since this is calculated on the basis of easily-available information on driving distances and total weights of the machines, or (when subsoil compaction is concerned) on loads on individual axles or wheels.

Chapter 2
Stress distribution under wheels and tracks

Summary

Ground pressure is the term commonly used for the normal vertical stress in the ground contact area of a wheel or track. A relatively soft agricultural tyre loaded and inflated as recommended and running on an agricultural soil of good bearing capacity usually exerts a mean ground pressure slightly higher than the inflation pressure. Under other load or soil conditions, or with other types of tyres, mean ground pressure may differ more from the inflation pressure. Higher tyre stiffness tends to increase the mean ground pressure and softer soil tends to decrease it. However, because of uneven distribution, maximum ground pressure within the ground contact area is usually considerably higher than the mean value.

Theoretical models and field measurements have provided information on stress propagation in soil profiles under loaded wheels. In the topsoil, a traditional agricultural machine with normal wheel equipment usually exerts a stress of the same magnitude as the ground pressure. The stress gradually decreases by depth, but less rapidly the greater the wheel load is. In the upper part of the subsoil, the stress is often about equally determined by the wheel load and the ground pressure, provided these factors remain within their normal variation range. In deep subsoil layers, the wheel load is the most influential factor. Therefore, when wheel loads increase, critical stresses propagate deeper. The stress propagation under a pair of narrow dual wheels mounted close together is similar to that under a single, wide wheel, provided axle load and ground pressure are the same. Therefore, axle load rather than wheel load is sometimes quoted as the factor most decisive for the maximum depth of critical stresses, but when wide low-pressure tyres are dual-mounted this is misleading. Stresses are usually thought to penetrate somewhat deeper in wet than in dry soils, but recently some contradictory results have been presented.

Information on stresses exerted by tracked vehicles is more sparse. However, the measurements have consistently shown a concentration of stresses under the roadwheels. Therefore, tracked vehicles may cause more compaction than indicated by the mean ground pressure of the tracks, but the area affected is usually relatively small.

2.1. Ground pressure induced by wheels

Ground pressure is the term usually used for the normal, vertical stress in the ground contact area of a wheel or track, although in a strict physical sense, this is actually a stress and not a pressure (Box 2). As discussed by Tijink (1994) the ground pressure of a tyre depends, in a complicated way, on many factors, such as type, dimensions, load and inflation pressure of the tyre and strength of the soil. The latter in turn depends on soil water content and state of compactness. For soft pneumatic rubber

Box 2

Stress and pressure

Machinery traffic induces mechanical stresses in the soil. In many stress propagation models, the soil is regarded a homogeneous medium in which stresses can cause elastic (recoverable) or plastic (nonrecoverable) deformations. The stress system acting on a small cubic volume element in a soil under a loaded wheel comprises normal stresses and shear stresses. *Normal stresses* (σ) act perpendicular to the surfaces of the element and *shear stresses* (τ) act parallel to the surfaces. A complete description of the stress system requires that both normal stresses and shear stresses are measured in three directions perpendicular to each other. However, it is always possible to find one orientation of the stress system such that all shear stresses disappear and only three normal stresses remain. These are named the major, intermediate and minor *principal stresses*. At some depth under the centre of a loaded wheel, the vertical, normal stress usually approaches the major principal stress.

For simplicity, when effects of machinery traffic in soils are studied, often only one of the stress components is measured. In soil compaction studies, the measurements often only include the vertical, normal stress, since this component is relatively easy to measure and is regarded as being largely decisive for the amount of compaction. Up to now, it has usually been assumed that plastic deformation (compaction) occurs only when this stress exceeds the so-called *precompression stress* in the soil layer in question at the time of traffic. This view implies that up to this stress the deformation is only elastic, but recent studies (e.g. Arvidsson & Keller, 2004; Keller et al., 2004) show that in a real soil there is usually no sharp stress threshold below which soil deformation is completely elastic.

Another stress component often of interest is the horizontal shear stress induced by a wheel parallel to the direction of travel. This component depends on the rolling resistance of the wheel and on the draught force, if such a force is produced. Such a shear stress sometimes influences the superficial soil layer very negatively by causing wheel slip, smearing and severe structure deterioration. It may also intensify soil compaction, since at a certain normal stress, compaction often increases when a shear stress is also applied. The soil can raise a maximum resistance against a shear stress called the *shear strength* (τ_{max}). This increases with the normal stress (σ) according to the formula $\tau_{max} = c + \sigma \tan \varphi$, where the parameters c (soil cohesion) and φ (angle of internal friction) characterize the state of the soil. If the shear stress in a soil reaches the value of the shear strength it induces displacement (shearing) along the surface where it acts. According to the formula above, the maximum draught force of a tractor increases when the load on the wheels increases.

In this book, the term *ground pressure* is used for the vertical, normal stress induced by a wheel or track in the ground contact area. This is done because this term is the one usually used in practice. In a strict physical sense, however, it is incorrect, since the term pressure is defined as a scalar quantity, which implies that it is the same in all directions. This is the case only in gases and fluids, whereas mechanical stresses in soils are vectors and are different in different directions.

tyres running in arable fields the mean ground pressure is often slightly higher than the tyre inflation pressure, but the divergence may be great.

To measure the actual ground pressure of a flexible tyre with lugs directly in the contact area when a machine is moving in an arable field is difficult. Therefore, very few measurements of that kind have been made. Most ground pressure values reported in literature are approximate mean values for entire contact areas, obtained by dividing wheel loads by ground contact areas. However, it is difficult to measure the ground contact areas of the tyres when a machine is moving in the field. Therefore, such measurements are usually made under machines at standstill, either under field conditions or on hard surfaces. An implicit assumption often is that the areas remain practically unchanged when the machines are moving. However, when a contact area is measured on a hard surface, it must be observed that it increases under field conditions, and more so the softer the soil. When a deep rut is formed, it is often presumed that the contact area approaches its maximally possible value. This is sometimes thought to be the product of the width of the tyre and a length of the contact area equal to the radius of the wheel. Because of the difficulties to measure the ground pressure of a moving wheel directly in the contact area, an often used alternative in soil compaction studies is to measure the vertical, normal stress induced at a shallow depth in the soil when the wheel passes. This can be made by stress transducers installed in beforehand some cm below soil surface. The results can provide approximate information on the ground contact area and on the mean and maximum ground pressure.

Theoretical considerations indicate that an extremely soft tyre when moving on a hard surface must generate a ground pressure close to the tyre inflation pressure. For a normal tyre running on a hard surface, the walls of the tyre contribute more or less to the ground pressure depending on their stiffness. Measurements indicate that a traditional agricultural tyre when carrying the load for which it is designed and having the inflation pressure recommended at a low travelling speed often exerts a mean ground pressure that is about 30% higher than the inflation pressure (Tijink, 1994, Döll, 1999). For a tyre with a stiff carcass or pronounced lugs, the difference may be greater.

In a soft soil, the ground pressure may be limited by the bearing capacity of the soil. Then the tyre sinks (a rut is formed), and this results in a larger contact area and a lower ground pressure than on a hard surface. At the same time, the soil under the rut becomes compacted and its bearing capacity increases. The wheel stops sinking when the increasing bearing capacity matches the decreasing ground pressure. If the soil was initially very soft, the resulting ground pressure may even be considerably lower than the tyre inflation pressure. In such a soil a stiff rubber tyre behaves nearly like a rigid wheel.

In a medium soft soil where shallow ruts are formed, the contact area is somewhat larger and the ground pressure somewhat lower than on a hard surface. Under such conditions, a mean ground pressure of the same magnitude as the tyre inflation pressure has often been obtained (Trautner, 2003; Anselmsson, 2003). However, the maximum ground pressure within the ground contact area may be much higher than the mean pressure.

Measurements of ground pressure distribution within the contact areas of various wheels show that the distribution is usually very uneven (Tijink, 1994; Trautner, 2003; Keller, 2004). This can result in greater soil compaction, particularly in the upper soil layers, than would have been the case with a uniform distribution. The stiffness of the tyre carcass and the tread pattern largely influence the ground pressure distribution. When a stiff tyre, over-inflated with regard to the load, runs on a relatively hard soil (where almost no rut is formed), there is a concentration to the centre of the contact area (Döll, 1999; Way et al., 2000; Keller, 2004), where it can be twice the mean ground pressure. If the tyre is softer and is under-inflated with regard to the load, the ground pressure tends to be highest near the edge of the contact area, where it can be considerably higher than the average. If the soil is soft and a rut is formed, the ground pressure again tends to be concentrated in the centre of the contact area. Under normal field conditions, maximum vertical, normal stresses measured by stress transducers 10 cm below the soil surface have often been about 50% higher than the tyre inflation pressure (Keller, 2004). However, for tyres with pronounced lugs, the stresses under the lugs may be raised much more than that, particularly in hard soils (Febo, 1999).

2.2. Stress propagation in the soil

Since the 1950s, theoretical models have been used to predict stress propagation under wheels or tracks with different dimensions and loads and under various soil and moisture conditions. Many models of various types have been developed (Gupta & Raper, 1994; Horn et al., 1998; Defossez & Richard, 2002). Examples of results obtained by the classical pseudo-analytical model of Söhne (1953) are shown in Fig. 5. This figure shows stresses induced by various wheels in sections of the soil profile perpendicular to the wheel tracks. The curve systems look like sections through bulbs and are often referred to as stress bulbs.

Stress bulbs such as those in Fig. 5 can only show one of the stress components in the soil, in this case the major principal stress (Box 2). The vertical normal stress and the mean normal stress

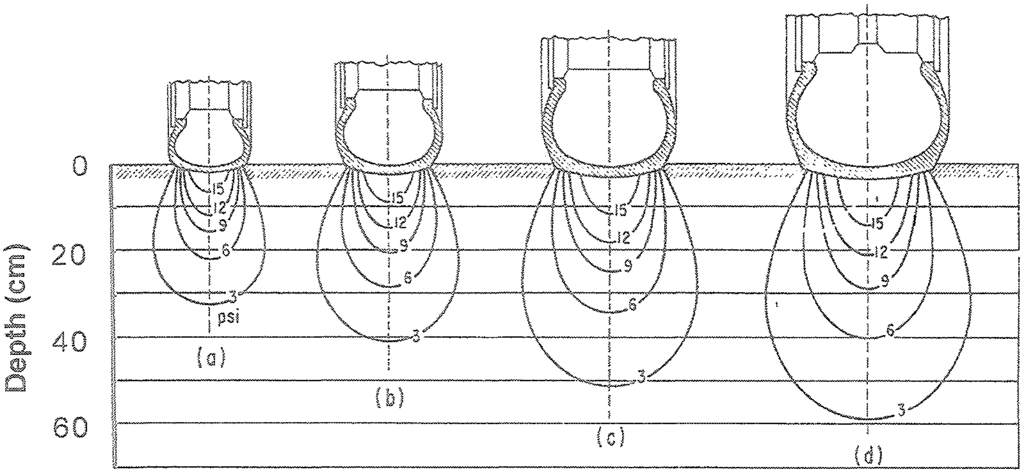


Fig. 5. Predicted major principal stress at different depths in the soil under wheels loaded by (from left to right) 300, 500, 750 and 1000 kg and having matching dimensions, so that the ground pressure in all cases is 90 kPa (=12 psi). The figure shows the stresses in vertical sections through the soil perpendicular to the direction of travel and through the centre of the ground contact area. (After Söhne, 1958.)

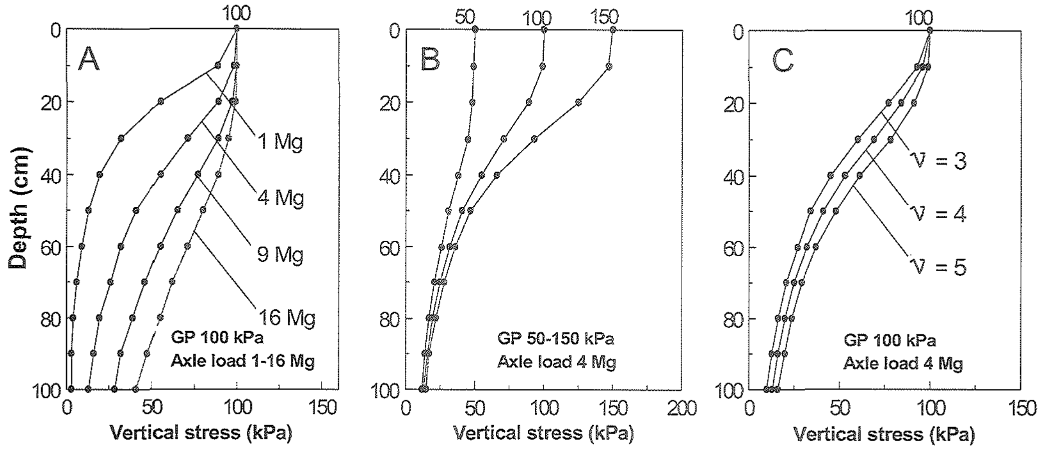


Fig. 6. Vertical normal stress at different depths in the soil under the centre of circular, uniformly loaded ground contact areas as predicted by the model of Olsen (1994).
A. Comparison between four contact areas (wheels) loaded by 0.5, 2, 4.5 and 8 Mg, i.e. axle loads of 1, 4, 9 and 16 Mg. In all cases, the ground pressure (GP) is 100 kPa.
B. Comparison between three areas (wheels) with ground pressures of 50, 100 and 150 kPa. The wheel load is 2 Mg in all cases, i.e. the axle load is 4 Mg.
C. Effects of different values of the so-called concentration factor (ν). This factor is often assumed to be lowest (about 3) in dry soils and highest (5 or more) in wet soils.

are often closely related to the major principal stress and have sometimes been used as alternatives. None of these components provides complete information on the total stress situation in the soil. Nevertheless, they are often useful for predictions of the magnitude of machinery-induced soil compaction, since field and laboratory measurements as well as observations of the extension of compacted zones under wheel tracks (Richard et al., 1999) show that they often lead to satisfactory predictions of the compaction. However, particularly close to the soil surface, shear stresses induced by draught forces of the wheels may be equally important or even more important than the normal stresses (Wiermann et al., 1999).

Fig. 6 shows vertical, normal stress as a function of depth in the soil under various wheels as predicted by a model of pseudo-analytical type described by Olsen (1994). For each wheel, the stress under the centre of the ground contact area is shown, and it can be seen that this stress gradually decreases by depth. The wheels are assumed to be single mounted and to have circular ground contact areas with uniform ground pressure distribution.

In Fig. 6A wheels with different loads are compared. The sizes of the wheels are chosen in such a way that the ground pressure in all cases is the same (100 kPa). Under the smallest wheel with the smallest load the stress decreases much more rapidly than under the larger wheels with higher load. The depth at which a certain stress is induced is proportional to the diameter of the ground contact area. This also means that it is proportional to the square root of the load. For example, a stress of 60 kPa is induced at 20, 40, 60 and 80 cm depth, respectively, at axle loads of 1, 4, 9 and 16 Mg (=1^2, 2^2, 3^2 and 4^2, respectively). Consequently, the increasing axle loads of the farm vehicles (Fig. 7) give rise to increas-

Fig. 7. Farm machines with high wheel loads are increasingly used, particularly for harvest and transport purposes. They induce high stresses to depths much greater than normal tillage depth. The sugar beet harvester in this figure has a wheel load of about 10 Mg when it is fully loaded, and measurements in farm fields have shown (Fig. 16) that such a wheel load may cause compaction to depths greater than 70 cm. (Photo Thomas Keller.)

ing stresses in the subsoil.

In Fig. 6B wheels with the same load but with different ground pressures (i.e. with different ground contact areas) are compared. A low ground pressure implies that the load is supported by a large, low-pressure tyre, a high ground pressure that it is supported by a smaller, high-pressure tyre. Throughout the plough layer, the stresses are close to the ground pressure of the tyres and the differences between the wheels are large. The differences decrease with depth and at depths greater than 50 cm they are small. However, at higher wheel loads than that in Fig. 6B, sizable influences of the ground pressure extend to greater depths.

The stress propagation in the soil under a wheel does not only depend on the load and on the ground pressure (and thus on the dimensions, stiffness and inflation pressure of the tyre) but also on the soil properties. The common conception is that the stresses are most concentrated under the ground contact area in a wet soil. In a dry soil it is thought to be spread horizontally to a greater extent, and therefore to decrease more rapidly by depth. In pseudo-analytical stress-propagation models this is handled by a so-called concentration factor. Fig. 6C shows the influence of this factor on the propagation of stresses towards depth. In a soil with a concentration factor of 5 (which is often supposed to be the case in a wet soil), a certain stress extends deeper than in a soil with a concentration factor of 3 (which is often supposed to be the case in a dry soil). This means that compaction may penetrate deeper in wet than in dry soil not only as a consequence of greater soil compactibility but also of deeper stress propagation.

Opposite to this conception, measurements by Trautner (2003) in various soils showed that vertical normal stresses and resulting compaction effects in the subsoil at depths >50 cm were often greater in dry soils than in wet. He suggested this was an effect of the aggregate structure of real soils, a factor so far unconsidered in the models, where soils have been assumed to be homogeneous. Furthermore, these and other measurements made in normal fields have shown a great variability in stresses, also a likely effect of soil aggregate structure. On the basis of comprehensive measurements by Keller (2004) it may be concluded that stresses under wheels are often largely affected by the uneven ground pressure distribution. These results call upon extended studies of the effects of soil moisture and structure, and of the ground pressure distribution, on stress propagation and compaction, particularly in the subsoil. They indicate that some stochastic element is required in the models.

The examples in Fig. 6 show that, within common ranges of wheel loads and ground pressures of agricultural machines, stresses in the plough layer mainly depend on the ground pressure, and consequently to a great extent on the tyre design and inflation pressure. For stresses in the upper part of the subsoil, the ground pressure and the wheel load are often about equally decisive. In deep subsoil layers, the stresses mainly depend on the wheel load. However, the depth to which the mean ground pressure and the ground pressure distribution are significant factors increases with increasing wheel load (and increasing ground contact area). With the highest wheel loads used today (>10 Mg) stresses near the ground pressure arise even in deep subsoil layers.

With respect to stresses at some depth in the subsoil it is rather unimportant, whether a certain load is carried by a single relatively wide wheel or by two narrow dual-mounted wheels placed close together, provided the ground pressure is the same. In deep subsoil layers, such dual-mounted wheels interact and the stresses are determined by the total load on the two wheels (which in most cases means half the axle load) rather than by the load on the individual wheels. Therefore, the axle load rather than the wheel load has often been quoted as a factor of major importance for the depth of compaction. However, the interaction is of importance within the depth of interest only as long as the ratio between the width (perpendicular to the direction of travelling) and the length of the ground contact area of each wheel is small. If the wheels are wide and the width/length ratio is near 1 or higher, the interaction between the two wheels becomes negligible within the depth of interest (Keller, 2004). In this case, it is misleading to use the axle load instead of the wheel load as decisive for the depth of stress propagation. The same is true if the load on the axle is non-symmetric. However, axle or wheel load do not only influence the depth of soil compaction, the track width is also influenced. When ground pressure and wheel diameter of heavy vehicles are the same, the depth of soil compaction may not be appreciably affected, but the width of the track, and consequently also the area affected, increases proportionally to the wheel load.

If two wheels follow each other in a tandem axle arrangement, their ground contact areas are positioned further apart than in the case of dual mounted wheels. Then a very great depth must be reached until they start interacting. However, now two wheels run in the same track and this leads to more compaction than if only one of them had run there (Chapter 3). Consequently, for equal risk of subsoil compaction, the load on a tandem axle unit should be slightly less than twice the load on a single axle.

2.3. Tracked vehicles

The mean ground pressure under the tracks of a tracked vehicle is usually low. However, when driving on fairly firm agricultural soil, the ground pressure has been shown to be concentrated under the supporting roadwheels and rollers, whereas it is very low in the zones in between. Furthermore, stresses are repeated and applied for a longer time under a track than under a wheel, and as shown by Danfors (1974) a vehicle with steel tracks may induce vibrations in the soil. Therefore, a tracked vehicle may induce more soil compaction than the mean ground pressure indicates. However, when driving on very soft soil (wet or recently loosened) where marked ruts are formed, it is likely that there are less pronounced stress peaks under the tracks. Then the track area contributes more uniformly in supporting the load and in ensuring trafficability.

The heterogeneity of the stress distribution under a track depends on its construction, on soil conditions and on the distribution of the load along the track. The latter is influenced by the existence of a drawbar pull. Unfortunately, stresses and compaction induced by tracked vehicles in various soils have been insufficiently studied to facilitate general conclusions. Only some examples can be given.

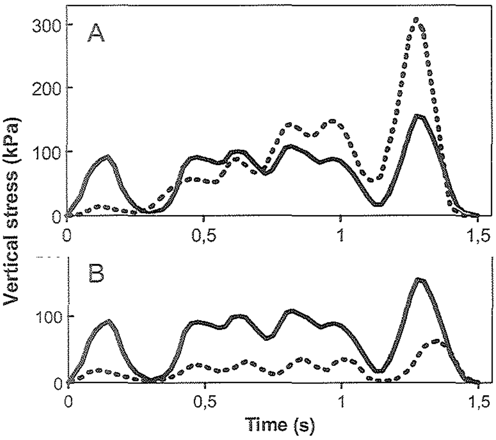


Fig. 8. A. Vertical normal stress at a depth of 0.1 m under the centre line of one of the tracks during the passage of a 18.5 Mg tractor equipped with rubber tracks with four supporting rollers between the front and rear roadwheels. The mean ground pressure was 43 kPa. The measurements were made on a moist sandy loam when ploughing with a 12-furrow plough with the tractor running 'on land'. A stress peak is obtained each time a roadwheel or roller passes the stress transducer. The attack point of the draught force of the plough was either in its original, relatively high position (dashed line) or in a lower position (solid line).
B. Stress under the centre of the track (solid line) and under its edge (dashed line) when the attack point was in the lower position. (After Keller et al., 2002.)

Fig. 8 shows the distribution of the vertical normal stress at a depth of 0.1 m (nearly equal to the ground pressure) in a sandy loam soil under one of the tracks of a heavy rubber-tracked tractor pulling a mouldboard plough (Keller et al., 2002). Pronounced stress peaks occurred under each supporting roadwheel and roller (Fig. 8A). The stress was higher under the centre line of the track than near the edge (Fig. 8B). Measurements were first made with the same settings of tractor and plough as those used till then by the driver. In this case, the stress was concentrated to the rear part of the track, and the maximum stress was about seven times the mean value. A situation similar to this is likely to be common. Guided by these measurements the attack point of the draft force was then lowered to get the tractor better balanced. Then the difference between the front and rear ends of the track as well as the maximum stress was considerably reduced. Now, this tractor caused less compaction than a considerably lighter wheel tractor.

Keller & Arvidsson (2004a) measured

the stress in a clay loam soil under two 6-row sugar beet harvesters, one weighing 26.5 Mg with four wheels, the other weighing 53.7 Mg with two rubber tracks and one pair of dual-mounted wheels. At the side where measurements were made the lighter harvester had a 650/85 R38 front wheel (inflation pressure 180 kPa, load 10.1 Mg) and a 750/45-30.5 rear wheel (160 kPa, 4.5 Mg). The heavier harvester had a rubber track (ground contact area 2.6 m^2, load 16.6 Mg) at the front and dual mounted 900/60 R32 rear wheels (190 kPa, total load 10.3 Mg). Thanks to the better running gear, the heavier harvester induced a somewhat less maximum stress at 0.3 m depth than the lighter harvester. It also caused somewhat less vertical displacement in the subsoil (cf. Chapter 3.3).

Using pneumatic stress sensors, Marsili & Servadio (1996) measured stresses induced at 10 and 15 cm depth by two 3.5 Mg tractors, one with metal tracks and one with rubber tracks. No implement was attached. The soil had been ploughed to 40 cm depth. The stress distribution was more uniform than that shown in Fig. 8. Possible reasons are a looser soil, no draught forces and another type of stress transducers. The stress was more uniform under the metal tracks than under the rubber tracks, perhaps because the former had a larger number of supporting wheels. After four passes in the same tracks, there was a tendency that the metal tracks had caused less compaction than the rubber tracks. Using similar methods, Marsili et al. (1998) compared two heavier tractors, one with metal tracks and one with rubber tracks, when driving without any implement in a relatively dry lucerne field on a clay soil. At 13 cm depth, the stresses were relatively uniform and similar for both tractors. The compaction effect was small and somewhat less for the metal-tracked tractor than for the rubber-tracked. The authors suggested this might be caused by relatively wide lugs on the rubber tracks as compared to narrow grousers on the metal tracks.

In a clay soil, Servadio et al. (2001) compared the compaction effects of one and four passes by two heavy tractors of similar weight, one with rubber-tracks and one with wheels. In the plough layer, the track zones became more compacted by the tracked tractor than by the wheeled tractor, even though the mean ground pressure must have been much lower.

A factor of importance when comparing the compaction effects of tracked and wheeled vehicles is the track width. Even though the compaction effects within the tracks of a tracked vehicle may be similar to that of a wheeled vehicle, the track width is usually smaller, and consequently also the proportion of the field area affected. This is an advantage in many situations.

Chapter 3
Extent and persistence of compaction in arable soils

Summary

The term *compaction* is used here to denote a decrease in volume of a soil element or in thickness of a soil layer under the influence of external mechanical forces. For the resulting state, the term *compactness* is used. Compaction implies that the pore volume decreases and the bulk density increases. In laboratory experiments, the bulk density of an originally loose soil usually increases linearly with the logarithm of the applied stress. A moist soil is usually more susceptible to compaction than a dry soil. In an annually ploughed field, the plough layer runs through an annual cycle of loosening and compaction. Mouldboard ploughing to a depth of 20-25 cm usually increases the thickness of the plough layer by 6-7 cm. Within a few weeks, natural settling reduces its thickness to some extent, often by about 2 cm, but after that the settling rate declines. In early spring, the plough layer of an autumn ploughed field that is subsequently untrafficked is still some centimetres thicker than before ploughing. In seedbed preparation, the wheels of tractors and other machines compact the central and deeper parts of the plough layer, and only a shallow surface layer remains loose. The net effect is a reduction in thickness of the plough layer to nearly the same value as before the ploughing.

To characterize the state of compactness of the plough layer some relative bulk density value is more suitable than the bulk density itself. One such parameter is the 'degree of compactness', which has been used in experimental work for many years. It is defined as the bulk density of a soil as a percentage of its bulk density after a standardized compaction treatment with a uniaxial stress of 200 kPa. The mean degree of compactness of the plough layer induced by machinery traffic increases with soil water content at time of traffic, with number of wheel passes and with weight, wheel equipment and ground pressure of the machines.

Maximum depth of compaction in the subsoil is largely determined by the wheel load. Compaction has often been observed to more than 40 cm depth at wheel loads over 3 Mg, to more than 50 cm depth at loads over 4 Mg and to nearly 1 m depth at higher loads. Even in the subsoil, repeated heavy traffic causes cumulative compaction effects.

Compaction effects are counteracted by cycles of drying/wetting and freezing/thawing, by biological activity, and in the plough layer by tillage operations. Since both intensity and frequency of all these processes decrease with depth, compaction effects are much more persistent in the subsoil than in the plough layer. In coarse-textured soils, compaction effects in the plough layer of annually ploughed fields may be nearly completely alleviated within one year, but in clay soils residual effects may persist for up to five years. In unploughed soils and below the ploughing depth, compaction effects are much more persistent. At depths >40 cm (in sandy soils >30 cm) the effects are at least partly permanent.

3.1. Relationships between stress and compaction

When the volume of a soil element or the thickness of a soil layer is reduced under the influence of external mechanical forces, applied for instance by wheels or tillage tools, the soil is said to be *compacted* (Box 3), while when the soil volume or the thickness of the layer is increased the soil is said to be *loosened*. Thus, *compaction and loosening are processes* that change the state of the soil, in this case its *state of compactness*.

Compaction occurs when the compactive stress induced in a soil exceeds its strength. The higher the stress and the wetter the soil at time of traffic (up to a certain limit), the more intensive the compaction. A loose soil is less resistant (more susceptible to compaction) than an already compacted soil. Therefore, the first pass by a wheel on a recently loosened soil causes a large reduction in soil volume or in thickness of the loosened layer (= large compaction), the next pass a smaller reduction, and so on. Usually the reduction continues up to a large number of passes (Ljungars, 1977; McKyes, 1985; Etana & Håkansson, 1996). At repeated passes in the same track in an originally loose soil, each doubling of the number of passes often causes about the same compaction, or in mathematical terms: the cumulative compaction effects are proportional to the logarithm of the number of passes. This does not necessarily mean that the first pass is the most detrimental. On the contrary, moderate recompaction often improves the properties of a recently loosened soil.

Before the effects of machinery traffic in the field are discussed, some typical results of compaction experiments in the laboratory are shown. Fig. 9A shows in a slightly simplified way the changes in bulk

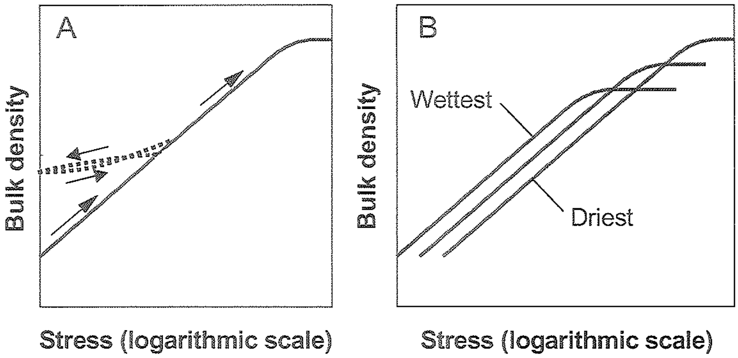


Fig. 9. Slightly simplified results of laboratory experiments where a moist and originally loose arable soil is exposed to a stress that is gradually increased in small steps of short duration.
A. The bulk density increases linearly with the logarithm of the stress, mainly due to loss of air-filled pores. If the stress increase is interrupted and the soil unloaded, the density only decreases slightly (the dashed line). If the stress is then increased again, the density increases slowly until both the stress and the density reach the values before the unloading, but after that the density increases again as if no unloading had occurred.
B. Compaction curves for the same soil at three water contents. The curves are parallel within the range of water contents typical for most field operations. When most air filled pores have disappeared the density increase ceases. The wetter the soil the lower both the density and stress at which this occurs.

Box 3

Definition of soil compaction and compactness

In this book, the term soil *compaction* is used to denote a decrease in volume of a soil element or in depth of a soil layer under the influence of an external, mechanical stress, mainly by expelling air. Thus, the term is used for a decrease in volume in a soil where the pore system is partially filled with air. One part of the volume decrease occurs very quickly (instantly) as soon as the stress is applied, another part is more lengthy. In field soils, the first part is relatively independent of soil texture, whereas the latter part is greater in clay soils than in sandy soils (Eriksson, 1982).

As defined here, the term compaction denotes *a process* in the soil. Its magnitude can be characterized by the absolute or relative *decrease* in volume of the soil element or in depth of the soil layer regarded, by the *decrease* in porosity, void ratio or specific volume of the soil or by the *increase* in its bulk density. When talking about the resulting state of the soil, the term *compactness* is used. This can be characterized by the absolute or relative porosity, void ratio, specific volume or bulk density (Box 5 and Box 11). By this terminology it is possible to clearly distinguish between the *active process,* by which the stress is induced in the soil (for instance the application of traffic by a certain vehicle), the *reactive process* in the soil, viz. the compaction, and the *resulting state*, the compactness.

When the pore system of a soil that is exposed to mechanical stress is completely filled with water (except for the possible occurrence of a small amount of entrapped air), the process of volume decrease that may be induced due to drainage of water is usually called *consolidation* and not compaction. In this case, water rather than air has to be expelled. Consolidation is a much slower process than compaction, and it is of much greater interest in various geotechnical applications than in agriculture.

density (this and some other soil physical terms are defined in Box 5) when an originally loose soil is exposed to a mechanical stress in such a way that the stress is gradually increased in small steps, each one of short duration (though usually much longer duration than the stresses applied by the wheels of normal field vehicles). Measurements in various kinds of soils have resulted in curves of this type. Within certain limits, the bulk density usually increases proportionally to the logarithm of the stress, mainly due to loss of air-filled pores.

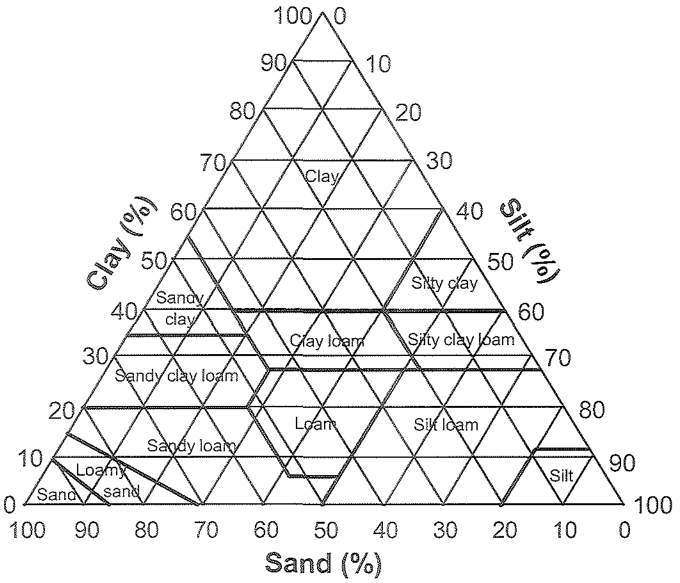
In laboratory experiments of this kind, the same stress increment usually causes a greater density increase in clay soils than in sandy soils (see Box 4 regarding soil classification). This means that the slope of the curve is greater for clay than for sand and that the *compression index*, which is defined as the change in bulk density caused by an increase in the logarithm of the stress by 1 unit, is higher in a clay or clay loam than in a coarse-textured soil (Larson et al., 1980). However, this result seems not to be directly applicable to field traffic. Arvidsson (1998b) computed a field compression index on the basis of the increase in bulk density of the plough layer in various soils generated by identical tractor traffic, and found no increase of this index with the clay content. A likely major reason is that the loading time is much shorter for machinery traffic in the field than in traditional laboratory experiments. Then only the instantaneous part of the compaction process may be accomplished (cf. Box 3) and this part may not differ between soils.

The bulk density obtained in a laboratory experiment at a certain stress also de-

Box 4

Classification of soils according to their texture

The solid material in soils consists of mineral particles of various sizes and organic material. The properties of a soil are largely dependent on the particle size distribution (texture) of the mineral fraction and the content of organic material. Various systems are used for textural classification of soils. Since most arable soils only have a small content of gravel and stones, systems for textural classification of such soils usually disregard the content of mineral particles >2 mm. In the American classification system, which is used in this book, particles <2 mm are divided into three size classes: clay <0.002 mm, silt 0.002-0.05 mm and sand 0.05-2 mm. On the basis of the content of particles in each of these classes (percentage by weight) the soils are divided into textural classes as shown in the diagram below.



pends on the wetness of the soil. Within the range of stresses and soil water contents typical for most agricultural field operations, the bulk density obtained increases with soil water content. Fig. 9B shows results for the same soil at different water contents. A series of parallel curves is obtained. As long as the volume of air-filled pores is sufficient (>6%, Perdok et al., 2002), the soil can be compacted by short-term loading. During this process air is expelled, and the bulk density increases linearly with the logarithm of the stress. When no air-filled pores remain (except a small percentage of pores with entrapped air), the compaction process ceases. The reason is that water is much more difficult to expel than air (Box 3). A counteracting pressure is then induced in the water-filled pores, which prevents further compaction.

The higher the water content, the lower the air content of the soil and therefore, when the compaction ceases, the lower both the bulk density and the stress. However, this does not mean that it would be appropriate in practice to try to avoid compaction by applying traffic when soils are very wet. The consequence would then be great wheel slip, deep ruts and intensive kneading of the soils, and this would lead to destructive effects on soil aggregate structure (see Box 5 regarding soil structure) that might be more detrimental than pure compaction, at least in the short term.

The dashed curve in Fig. 9A shows what happens in case the stress increase is interrupted and the soil is unloaded when a certain stress level is reached. The resulting relaxation is characterized by a slight increase in soil volume (soil rebound) and a corresponding slight decrease in bulk density. If the stress is subsequently increased again, the increase in bulk density is small until the same stress and bulk density as before the unloading are reached. After that the density increases as if the stress increase had never been interrupted. However, the above description is a simplification. In reality, when the same stress as before the unloading is again reached the bulk density has increased slightly, and additional cycles of repeated unloading and loading up to the same stress cause small cumulative compaction effects (e.g. O´Sullivan & Robertson, 1996; O´Sullivan et al., 1999a). Accordingly, Eriksson (1982) obtained a somewhat larger compaction effect of many short loading pulses than of continuous loading with the same total loading time. Laboratory measurements also show that the application of a shear stress in addition to a normal stress often increases the intensity of compaction (O´Sullivan et al., 1999b).

It has often been assumed that these laboratory findings can be directly applied to field conditions. This would imply that if a soil has been pre-compacted by a certain stress, it can only be further compacted to a small extent until this stress is exceeded. The stress at this point is called the precompression stress. However, like all mechanical properties of a soil even the precompression stress changes when the water content changes. Furthermore, recent studies have shown that it is less well-defined in normal field soils than in homogenized and initially loose laboratory samples (Trautner, 2003; Arvidsson & Keller, 2004; Keller et al., 2004), possibly because the structure (aggregates, cracks, etc.) makes these soils more heterogeneous. Therefore, the precompression stress seems not to be a very practical limit of tolerable stress.

Even in other respects the situation when a soil is loaded by machinery traffic in the field is more complicated than in a compaction experiment in the laboratory. Therefore, the results are usually not as simple and clear as those shown in Fig. 9. This is demonstrated for example by the fact that the number of passes by a vehicle is one of the most important factors for the amount of compaction of an initially loose soil (Ljungars, 1977; Wiermann et al., 1999). A major reason for this seems to be that the wheels usually apply stresses of such short duration that the compaction process remains uncompleted. Another reason is probably that the direction of the stress system acting on a soil element changes continuously when a wheel moves, whereas in most types of laboratory experiments the direction is constant. In addition, the first pass by a wheel compacts the soil and increases its strength, and therefore at the next pass the ground contact area is smaller and the mean ground pressure higher. At each pass, new portions of the soil may also be affected by the peak stresses that occur within the ground contact areas of the wheels, for instance under the lugs. Furthermore, field traffic often causes large shear stresses in the soil particularly at excessive wheel slip, and increased slip may lead to considerably increased compaction of superficial soil layers (McKyes, 1985).

Box 5

Definition of some soil physical terms

Some soil physical terms, in the way they are used in this book, are defined below. The definitions are illustrated by a figure showing the volumetric relationships in a medium-textured arable soil that has been water saturated and subsequently drained.

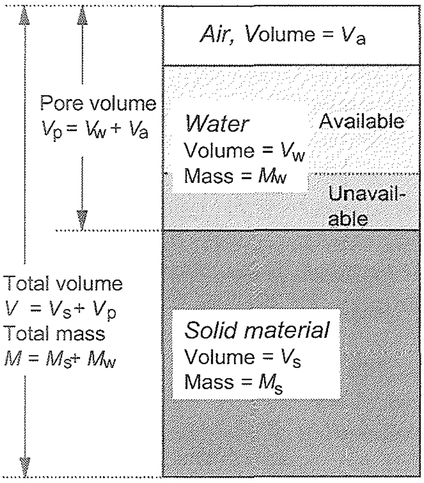
A soil consists of three components (phases), solid material, water and air. The solid material is composed of mineral particles of various sizes (Box 4) and organic material. The voids (pores) between the solid particles are filled with water and air in varying proportions. The proportion of pores in the total volume varies largely depending on soil composition and compactness, and ranges from >95% in some organic soils to <30% in some coarse glacial till soils. Some of the water that can be retained in the pores is available to plants, but a smaller or larger part is too strongly retained and is unavailable. Compaction or loosening of the soil changes the total soil volume without changing the volume of solids. In a clay soil, the total volume decreases (the soil shrinks) when the soil dries, but then the soil swells to its original volume when it is re-wetted.

Bulk density is the mass of the soil per unit of its total volume. *Wet* bulk density ($\rho_w = M/V = (M_s+M_w)/V$) includes the mass of both solid material and water; the mass of soil air, M_a, is very small and is usually disregarded. *Dry* bulk density ($\rho_d = M_s/V$) only includes the mass of the solid material. When the term bulk density is used without further specification, it usually refers to the dry bulk density.

Particle density ($\rho_s = M_s/V_s$) is the mean density of the solid particles, i.e. the mass of solid material per unit volume of the solid phase.

Porosity ($n = V_p/V = (V_w+V_a)/V$) is the proportion of pores in the total soil volume, often given as a percentage. Sometimes the air-filled porosity (V_a/V) or the water-filled porosity (V_w/V) is specified, i.e. the proportion of the total soil volume filled with air or water.

Materiality ($m = V_s/V = 1 - n$) is the proportion of solid material in the total soil volume.



Void ratio ($e = V_p/V_s$) is the pore volume per unit volume of solid material.

Specific volume ($v = V/V_s = 1 + e$) is the total soil volume per unit volume of solid material.

Soil structure is the way in which the individual (primary) soil particles are located relative to each other and linked together. Various types of structure can be distinguished. *Aggregate structure* implies that the primary particles are bound to each other into larger (secondary) units, aggregates, and that the bonds between the particles in the aggregates are much stronger than the bonds between the aggregates. Clay soils often manifest a pronounced aggregate structure. The stronger the bonds within the aggregates, while the bonds between the aggregates are still weak, the more stable the aggregate structure. If the bonds between the primary particles are strong but no clearly distinguishable aggregates exist, the structure is *massive*. Compaction of a fine-textured soil often leads to a massive structure. If the bonds between the primary particles are very weak and no pronounced aggregates can be distinguished, the soil has a *single-grain structure*. Coarse sandy soils often have this type of structure.

3.2. Extent of compaction in the plough layer

3.2.1. Changes in thickness of the plough layer during the year

On average, each surface element in an arable field is affected several times per year by loaded wheels that have the potential to compact the soil (Chapter 1). A large part of the field traffic is concentrated to short periods at seedbed preparation and sowing and at harvest. However, in traditional tillage systems, the upper soil layer is also loosened annually by the tillage operations.

Fig. 10 shows normal changes in mean thickness of the plough layer throughout the year in a Swedish arable field where mouldboard ploughing is carried out each autumn, some weeks before the soil freezes in the winter, and an annual crop is sown after seedbed preparation in spring. The diagram is based on periodic determinations by Andersson & Håkansson (1966) of the mean height position of the soil surface relative to the base of the plough layer in fields with traditional annual mouldboard ploughing (20-25 cm deep) and shallow seedbed preparation (4-6 cm deep). Similar results have been reported from other countries, for instance from the Netherlands (Kuipers & van Ouwerkerk, 1963; Poesse & van Ouwerkerk, 1967) and from Minnesota, U.S.A. (Allmaras et al., 1966).

Fig. 10 shows that a large part of the loosening effect obtained by ploughing in the previous autumn still persists after frost melting in early spring, as manifested by a great thickness of the plough layer. Measurements in Sweden (Andersson & Håkansson, 1966) and Canada (Kay et al., 1985) show that freezing in the winter causes no net effect on the mean thickness of the layer nor on the bulk density of the soil. During traditional seedbed preparation and sowing in spring when using several separate operations and a wheel track distribution of random type, most of the field area is covered by tracks of tractors and other machines (Fig. 2). This causes compaction of the central and deeper parts of the plough layer and a considerable decrease in its mean thickness, usually by at least 3 cm. Only the harrowed surface layer remains loose. The magnitude of the decrease in plough layer thickness during seedbed preparation depends on many factors, such as texture, moisture conditions and initial compactness of the soil (the latter depends on previous ploughing and subsequent settling), number of field operations and working width, weight, wheel equipment and tyre inflation pressure of tractors and other machines.

During the first few weeks after sowing, the thickness of the plough layer decreases slightly, usually by about 1 cm, mainly because the harrowed surface layer settles. After that, in coarse- and medium-textured soils, the thickness usually does not change very much until harvest time. However, in clay and clay loam and in organic soils the thickness may continue decreasing by 1 cm or more due to soil shrinkage in case the soil dries out. If so, however, when re-wetted the soil swells again to the same thickness as before the dry period.

At harvest time there is another period of heavy traffic, and if the plough layer is not very dry and firm it may be further compacted and its thickness may be reduced. When the field is ploughed in the autumn, the whole plough layer is loosened and its thickness is substantially increased. At a ploughing depth of 20-25 cm, the increase is usually about 7 cm but variations between 4 and 10 cm have been reported (Andersson & Håkansson, 1966; Poesse & van Ouwerkerk, 1967). The magnitude of the increase depends on

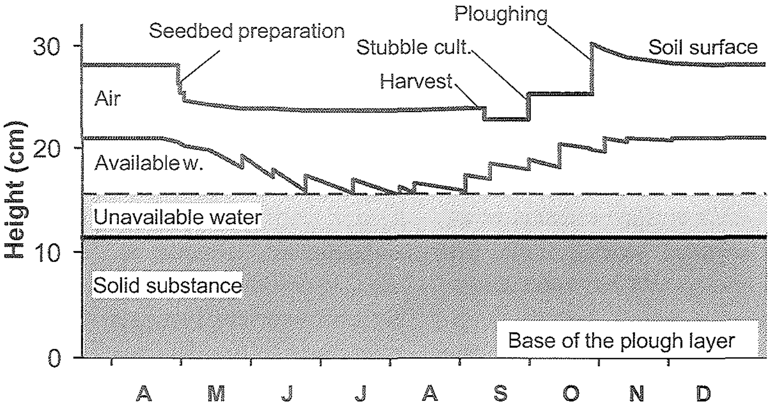


Fig. 10. Normal changes in the mean thickness of the plough layer throughout the year in a Swedish field with a spring-sown cereal crop where mouldboard ploughing has been made in the previous autumn. Just before sowing, a 4-6 cm deep seedbed is prepared by repeated harrowing. After harvest, shallow stubble cultivation and a new ploughing are carried out. The total thickness (volume) of the layer is divided into sub-volumes of solid material, unavailable water, plant available water and air. The moisture situation illustrated applies to a clay loam soil in a year with a relatively dry growing season and a wetter autumn. Water is supplied to the plough layer by small rain events, but during the growing season most plant available water in the plough layer is quickly taken up by the crop or evaporates. Changes in thickness of the plough layer similar to those shown in the diagram occur in all types of soils, but the changes are often somewhat smaller in coarse sandy soils than in other soils. (After Andersson & Håkansson, 1966.)

factors such as ploughing technique and moisture conditions, and tends to be less on coarse sandy soils than on other soils. If stubble cultivation is carried out between harvest and ploughing, as illustrated in Fig. 10, some of the increase occurs on that occasion.

During the first few weeks after ploughing the loose soil settles by a couple of centimetres under the influence of natural factors (Fig. 10), and by the beginning of winter it has about the same thickness as it had in early spring or at the same time in the previous year. However, the magnitude of the settling may vary. Under Swedish conditions, where the plough layer is usually frozen during a relatively long period in the winter, the settling of the plough layer from ploughing time to early spring usually seems to be smaller and less variable (Andersson & Håkansson, 1966) than in regions with a shorter frost period and more rainfall on unfrozen soil in the winter, such as in the Netherlands (Poesse and van Ouwerkerk, 1967).

Fig. 10 is based on measurements in fields where primary tillage was performed by mouldboard plough, but the results would have been similar if a layer containing the same quantity of soil had been loosened by a chisel plough or a disc plough. However, when comparative measurements have been carried out it has turned out that the amount of soil loosened by the latter implements is usually much less than assumed (e.g. Arvidsson et al., 2004) and the increase in thickness is likely to be correspondingly smaller.

Fig. 10 indicates that the state of compactness of the central and deeper parts of the plough layer does not change very much during the growing season if this is relatively short. This is further exemplified in Fig. 11, which shows changes in mean thickness of the plough layer from early spring until harvest time in a field trial with spring sown cereals. The field was ploughed in the previous autumn and the plough layer was compacted or loosened to various extent immediately before sowing. This resulted in great differences in thickness of the plough layer at sowing. In all treatments, the thickness decreased slightly during the first few weeks after sowing, mainly because the 5 cm thick and originally loose seedbed settled by about 1 cm due to rainfall and other natural influences. Most of the differences in thickness between treatments persisted until harvest. This means that the state of compactness generated in the central and deeper parts of the plough layer at the time of seedbed preparation persisted nearly unaltered throughout the growing season and influenced crop growth all the time until harvest. Results similar to those in Fig. 11 were obtained in several Swedish field trials with spring-sown crops on various soils (Håkansson, 1966). Similar results were also obtained in some trials with autumn-sown crops, where differences in thickness of the plough layer were established at seedbed preparation in the early autumn. Most of these differences persisted until harvest time about eleven months later (I. Håkansson, unpublished data). However, since the time from sowing to harvest is longer for autumn-sown than for spring-sown crops, it is reasonable to expect greater changes in some years, particularly those with high rainfall.

Results similar to those in Fig. 11 have been obtained in several other parts of the world as well. For instance, in sandy loam soils in a dry region in Nigeria, differences in dry bulk density in the plough layer generated by tractor traffic before sowing of pearl millet or cowpea were nearly unaltered at harvest time (Mamman & Ohu, 1997; Dauda & Samari, 2002). However, in very wet regions the changes are possibly greater.

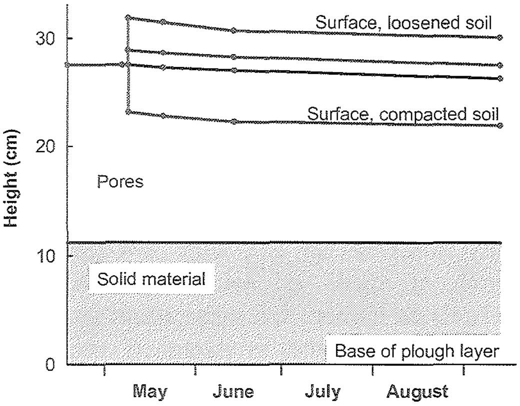


Fig. 11. Changes in the mean thickness of the plough layer throughout the growing season in a trial in an autumn ploughed field with fine sandy loam. Various compaction and loosening treatments were carried out immediately before sowing of cereals in spring. This resulted in differences in thickness of the plough layer (and consequently, in its state of compactness) and most of the differences persisted until harvest. The decrease in thickness of the plough layer during the first few weeks after sowing was mainly caused by settling of the shallow seedbed and was approximately equally large in all treatments. (After Håkansson, 1966.)

3.2.2. Effects of machinery traffic on the state of compactness of the plough layer

In Chapter 5.2 it is shown that ploughing or other deep primary tillage usually loosens a soil too intensively and that a moderate recompaction improves crop growth. Therefore, during seedbed preparation in a ploughed field there should be an endeavour to recompact the loosened layer throughout the field area as uniformly as possible and to a state of compactness as near the optimal as possible, i.e. to the state that results in the highest crop yield. When seedbed preparation is carried out under suitable moisture conditions by several operations in different directions, it is usually beneficial to use wide low-pressure tyres or dual- or even triple-mounted wheels on tractors and other machines. The soil is then brought to a state of compactness near the optimal in a large part of the field area, whereas sub-areas with over-compacted or uncompacted soil are small (cf. Fig. 2 and Chapter 8.2.1). The use of single-mounted, narrow wheels leaves the soil in a large part of the field area uncompacted, yet the soil may be over-compacted in many wheel tracks, especially in areas where multiple wheel passes are common such as in the headlands.

Heavy machines, for instance heavy harvesters, manure spreaders and other transport vehicles, often compact the soil in the wheel tracks to such an extent that subsequent loosening by ploughing or other deep tillage is necessary. This occurs most often in humid regions and when high-pressure tyres are used. Under such conditions, soil compaction may be the major constraint on the use of reduced tillage or direct drilling.

All over the world, many one-year field trials have been carried out for studies of soil and crop responses to machinery traffic during seedbed preparation and sowing in ploughed fields. The parameter most frequently used to characterize the effects of traffic on soils has been the bulk density. However, as further discussed in Chapter 5.2, the state of compactness should preferably be characterized by some relative bulk density value rather than by the bulk density itself. The reason is that a suitably chosen relative bulk density value can be the same for all soils when the state of compactness is comparable (for instance when properties are optimal for crop growth), whereas the bulk density itself differs substantially.

Relative bulk density values have been used for instance by Riley (1988), Carter (1990) and da Silva et al. (1994, 1997). The most extensive use of such a parameter in studies of soil and crop responses to machinery traffic has been in a large series of field trials in Sweden, where traffic of various intensities was applied during seedbed preparation. The results cited below originate mainly from these trials. Although many of them were carried out in the 1970s with smaller machines than those commonly used today, the results are still relevant.

To compare the effects of traffic on different soils and in different years, one-year trials with the same traffic treatments and the same crop (barley sown at the normal spring sowing time) were carried out during a series of years at many sites all over Sweden. In fields ploughed in the preceding autumn experimental traffic was applied at normal sowing time in spring by 2WD agricultural tractors. Immediately before seedbed preparation, at a soil water content slightly below field capacity, the tractors were run track by track over the experimental plots. The resulting state of compactness of the plough layer was characterized by a parameter named the 'degree of compactness' (Box 11). This was defined as the soil bulk density in the field as a percentage of the bulk density of the same soil after a standardized compaction treatment in the laboratory using a uniaxial stress of 200 kPa (Håkansson, 1990). Fig. 12 shows the mean degree of compactness (*D*) in the plough layer (more exactly in the layer between harrowing depth and ploughing depth, i.e. from about 5 to 25 cm depth) according to measurements carried out in each trial soon after sowing. It also shows a schematic average response curve for grain yield of the barley crop. (Even

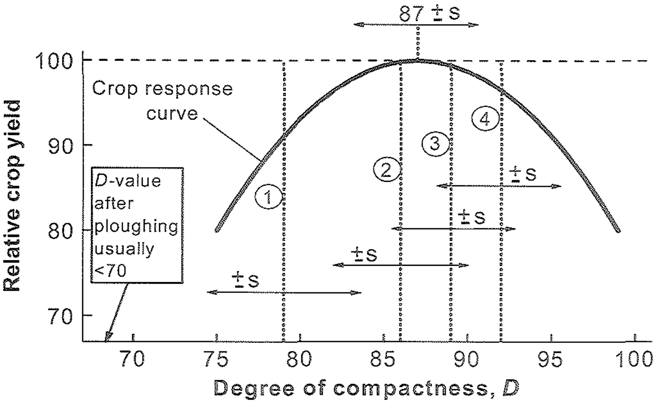


Fig. 12. Degree of compactness (*D*) in the central and deeper parts of the plough layer (about 5-25 cm depth) in autumn-ploughed fields after application of traffic by 2WD tractors of various weights and ground pressures on moist soil in spring. The diagram shows mean values and standard deviations (±s)after similar treatments in about 100 field trials in a large range of soils all over Sweden. The treatments were: 1) no compaction, 2) one pass, track by track, by a 2 Mg tractor with a mean tyre inflation pressure about 70 kPa, 3) one pass, track by track, by a 3-3.5 Mg tractor with a mean tyre inflation pressure about 140 kPa, 4) four passes by a 3-3.5 Mg tractor with a mean tyre inflation pressure about 180 kPa. The position of the mean response curve for grain yield of barley is indicated, as is the *D*-value usually produced by ploughing.

though the response curve varied between individual trials, the crop yield was on average highest at the same *D*-value, about 87, in all types of soils. Crop responses are further discussed in Chapter 5.2.)

Figure 12 shows that the mean *D*-value in the autumn ploughed fields uncompacted in spring (treatment 1) was lower than the mean optimal *D*-value for the barley crop. Therefore, crop yield usually increased when the soil was moderately compacted. After one pass by a very light tractor with a low ground pressure (treatment 2; mean tractor weight 1.94 Mg, mean inflation pressure in rear wheels 62 kPa, in front wheels 83 kPa) the *D*-value was on average slightly below the optimal.

After one pass by a somewhat heavier tractor with intermediate ground pressure (treatment 3; mean tractor weight 3.2 Mg, mean inflation pressure in rear wheels 126 kPa, in front wheels 159 kPa) the mean *D*-value was slightly higher than the optimal. After four passes by a tractor with increased ground pressure (treatment 4; mean tractor weight 3.2 Mg, mean inflation pressure in rear wheels 157 kPa, in front wheels 205 kPa), the mean *D*-value was clearly above the optimal, and this usually influenced crop yields negatively. However, the standard deviations show that the *D*-values for all treatments varied considerably between individual trials, due to a number of reasons. In treatment 1, the most important reason was the differences between sites and years in amount of soil settling after ploughing. In treatments 2-4, the main reason was variations in compaction effects between sites and years because of differences in moisture conditions and initial structure of the soils at time of traffic. It was also impossible to acquire tractors with exactly the same weight, tyre equipment, inflation pressure and speed at all sites. Furthermore, both low organic matter content and low clay content in the soils tended to increase the *D*-values in these treatments (Arvidsson, 1998b).

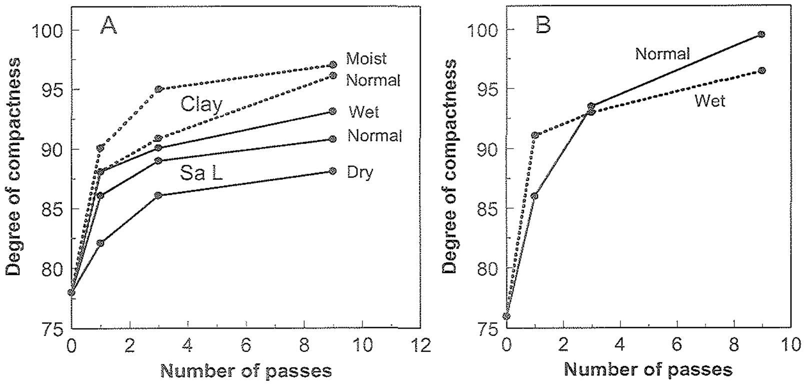


Fig. 13. Mean degree of compactness of the plough layer (about 25 cm deep) after 0 to 9 passes by various vehicles in autumn ploughed fields at time of spring sowing in Sweden. The traffic was applied track by track under moisture conditions varying from wet to dry compared to normal moisture conditions during spring sowing in Northern Europe. (Normal conditions mean a water content slightly below field capacity.)
A. Traffic on a clay soil (Clay) and on a fine sandy loam (Sa L) with a 4 Mg 2WD tractor (rear axle load 3.0 Mg; 12.4 x 36" bias tyres; inflation pressure 110 kPa). (After Ljungars, 1977.)
B. Traffic on a fine sandy loam with a 9.9 Mg wheel loader (17.5 x 25" bias tyres; inflation pressure 250 kPa). Mean values for loads of 0 and 1.5 Mg in the scoop. (After Etana & Håkansson, 1996.)

In other Swedish investigations, the degree of compactness of the plough layer (about 25 cm deep) was measured after a wider range of traffic treatments in soils with various textures and water contents. These measurements were also carried out in autumn-ploughed fields in spring, and the experimental traffic was applied track by track by the vehicles. Ljungars (1977) used relatively light tractors in a comprehensive series of measurements, while Etana & Håkansson (1996) used heavier vehicles of various kinds. Fig. 13 shows some examples of the results, chosen to illustrate the effects of soil water content and number of passes by the vehicles, since these two factors turned out to be the most decisive for the degree of compactness obtained. Wheel load, wheel equipment (single or dual wheels) and inflation pressure were factors of intermediate importance; driving speed and slip (draught force) were of minor importance. Some potentially important factors, such as tyre type (radial or bias) and stiffness of the carcass were not studied in these measurements.

The investigations by Ljungars (1977) exemplified in Fig. 13A showed that the increase in the degree of compactness of an initially loose soil induced by machinery traffic is often approximately proportional to the logarithm of the number of passes. Similar results have been obtained in several other studies. For instance, in investigations in Canada bulk density of the plough layer increased approximately linearly with the logarithm of the product of ground pressure and number of passes (McKyes, 1985). More recently, both Mosaddeghi et al. (2000) and Canillas & Salokhe (2001) showed that machinery-induced compaction of the plough layer is largely influenced by soil water content and number of passes by the vehicles, with wheel loads and ground pressure being other relatively important factors. However, the short-term loading caused by machinery traffic can only increase soil compactness as long as there are air-filled pores in the soil. Fig. 13B shows a case where the wettest soil had a rather low air content and could only be compacted by machinery traffic to a degree of compactness of about 97. Therefore, after 9 passes the degree of compactness was lower under 'wet' than under 'normal' conditions (cf. Fig. 9B). Under wet conditions repeated passes caused kneading of the soil rather than compaction.

In the experiment in Fig. 13A the degree of compactness after similar tractor traffic was higher in the clay soil than in the sandy loam. This must not be interpreted such that the same traffic treatment always results in a higher degree of compactness in clay soils than in coarse-textured soils, since opposite results have been obtained in other measurements. Therefore, the results of laboratory experiments mentioned in Section 3.1 showing that a certain stress increment led to more compaction (a higher compression index) in clay soils than in coarse-textured soils seem not to apply to machinery traffic under normal field conditions. Using results of the trials presented in Fig. 12, Arvidsson (1998b) showed that the same traffic treatments (the same number of passes by similar tractors with similar ground pressure) did not increase the bulk density of the ploughed layer more in fine-textured than in coarse-textured soils. The result was rather the opposite.

A possible major reason for the discrepancy between field and laboratory determinations is that the loading time is much shorter during field traffic than in most laboratory experiments carried out so far. This reduces the compaction, and more so in fine-textured than in coarse-textured soils (Box 3). When stress is applied to a sandy soil most of the compaction occurs instantaneously, whereas in a clay soil a greater part occurs slowly and is uncompleted after short-time loading. A low air content in some clay soils may contribute.

3.3. Extent of compaction in the subsoil

When traffic is applied on the soil surface by a machine with a high axle load equipped with tyres with an inflation pressure ≥150 kPa, compaction often occurs not only in the plough layer but also in the subsoil. Danfors (1974) showed that such traffic at various sites caused subsoil compaction that was more intensive and extended deeper the higher the axle load was. His results agreed reasonably well with theoretical predictions of stresses under loaded wheels, such as those shown in Figs. 5 and 6, and they led to a recommendation for Swedish conditions to limit the axle load of farm machines to 6 Mg to avoid compaction at depths greater than 40 cm (Håkansson & Danfors, 1981). However, even in the subsoil the stresses exerted and the extent of compaction induced depend on the ground pressure (Abu-Hamdeh, 2003), but the influence of the ground pressure decreases with depth and is less than in the topsoil.

In an investigation by Danfors (1994), subsoil compaction caused by several passes by vehicles with axle loads about 10 Mg decreased when the tyre inflation pressure was reduced from 150 to 50 kPa, but relatively less in the 40-50 cm layer than in the 30-40 cm layer. Arvidsson et al. (2002) showed that reduction of the tyre inflation pressure at wheel loads of 8.3 Mg from 220 to 90 kPa and at wheel loads of 12.1 Mg from 220 to 140 kPa reduced vertical stresses and displacement considerably at 30 cm depth. However, the reduction was less at 50 cm depth and very small at 70 cm depth. Unfortunately, when high-pressure tyres on a vehicle are replaced by low-pressure tyres or dual wheels, the wheel tracks also become wider. Therefore, at the

Table 2. Dry bulk density and relative shear strength (untrafficked control treatment = 100) in various subsoil layers in Swedish field trials where traffic by a dump truck with a total weight of 26 Mg and a tyre inflation pressure of 300 kPa (Fig. 33) was applied four times track by track in 1977 (After Etana & Håkansson, 1994)

	Dry bulk density 1978 (Mg m^{-3})		Relative shear strength[a], 35-45 cm		
Treatment	30-45 cm	45-60 cm	1978	1982	1988
Untrafficked	1.47	1.42	100	100	100
Trafficked	1.53	1.44	119	118	117
Significance[b]	*	n.s.	***	***	***

[a] Measured by a shear vane tester (Box 10). Penetrometer measurements in 1988 showed the same relative difference in strength of the subsoil as the shear vane tester.

[b] n.s. = not significant; * = significant ($p<0.05$); *** = highly significant ($p<0.001$).

same time as compaction effects under the central parts of the tracks are mitigated a larger part of the field area is affected, and this reduces the beneficial effect of the low-pressure tyres to some extent.

Table 2 shows the results of measurements in Swedish field trials where traffic was applied on one occasion by a loaded dump truck with a total weight of 26 Mg, 10 Mg on the front axle and 16 Mg on the rear tandem axle unit, and a tyre inflation pressure of 300 kPa. One year after this traffic, statistically significant compaction effects were observed to a depth of about 50 cm. Ten years later, virtually no alleviation of the compaction effects in the subsoil was observed. Similar results have been reported from various countries, for instance Minnesota, U.S.A. (Voorhees et al., 1986), Denmark (Schønning & Rasmussen, 1994), Finland (Alakukku, 1996) and Jordan (Abu-Hamdeh, 2003).

By comparing various investigations, it can be shown that an increase in the axle load increases the maximum depth in the subsoil to which compaction occurs. Theoretical stress distribution models, such as those used in Figs. 5 and 6, indicate that at the same ground pressure and approximately circular ground contact areas, a certain stress penetrates to a depth proportional to the diameter of the ground contact area. Under such conditions, maximum depth of compaction in soils where all layers are approximately equally susceptible may be expected to increase with the diameter of the ground contact area. Since the latter is proportional to the square root of the load on the area, the maximum depth of subsoil compaction may also be expected to increase about linearly with the square root of the wheel load. Unless dual-mounted wide tyres are used (cf. Chapter 2.2), this also applies to the axle load.

Fig. 14 shows results derived from a literature review of investigations from all over the world on compaction effects induced by vehicular traffic in various soil layers. The maximum observed compaction depth is shown as a function of the axle load, with the latter presented on a square root scale. A straight line with the equation $z = 22\, x^{1/2}$, where z is the depth in cm and x is the axle load in Mg, appears to be a depth limit for the compaction. However, in many investigations no significant compaction effects in the subsoil or a relatively shallow maximum compaction depth have been reported (e.g. Gysi et al., 2000; Berli et al., 2004; Schäfer-Landefeld et al., 2004). There may have been several reasons for this. In some cases the soil may have been too dry and hard at time of traffic and with a high pre-compression stress. There may also have been hard layers of pedogenic origin. In other cases, particularly when traffic intensity has been low and compaction effects small, sampling may have been too limited to make it possible to reveal the effects with statistical significance. Depth and intensity of compaction are also influenced by factors such as wheel dimensions, ground pressure and travelling speed.

It can be concluded that traffic by vehicles with high axle loads on moist soils may cause compaction to great depth in the subsoil, where the effects are very persistent. Vehicles with traditional wheel equipment have frequently been observed to cause compaction to more than 30 cm depth at axle loads ≥4 Mg, to more than 50 cm depth at axle loads ≥9 Mg and to more than 70 cm depth at axle loads ≥16 Mg. Furthermore, it will be indicated below that dry conditions do not always protect deep subsoil layers from compaction. When driving in the open furrow during mouldboard ploughing or when deep ruts are formed, the furrow or rut depth must be added to the depths mentioned here. Furthermore, as discussed in Chapter 2.2, when wide low-pressure tyres are dual-mounted or when the load on an axle is non-symmetrical it is misleading to use the load per axle instead of the load per individual wheel as a factor decisive for stresses and compaction in the subsoil.

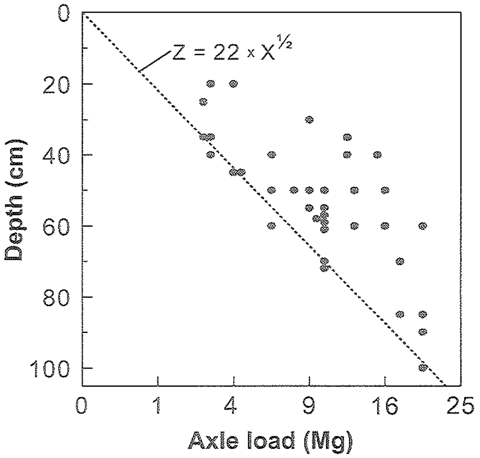


Fig. 14. Maximum observed compaction depth as a function of vehicle axle load according to investigations carried out in various parts of the world. The results agree with theoretical predictions which indicate that when other factors are similar, the depth of compaction may be expected to increase with the square root of the axle load. The diagram is based on data presented in literature reviews by Håkansson & Reeder (1994) and Alakukku (1997).

As shown in Section 3.2.2, repeated machinery traffic usually causes cumulative compaction effects in the topsoil. The same seems to apply to the subsoil. Etana & Håkansson (1994) showed that four passes by a 26 Mg vehicle caused about four times greater subsoil compaction than one pass. Similar results were obtained by Alakukku (1996) and Arvidsson (2001). Meek et al. (1988) recorded cumulative compaction effects to a depth of 65 cm when applying up to 10 passes by a 6 Mg tractor and Botta et al. (2004) recorded cumulative effects in the 30-60 cm layer when applying up to 8 passes by a 3.9 Mg tractor. In studies by Jakobsen & Greacen (1985), the compaction effects in the subsoil increased approximately with the logarithm of the number of passes when up to 27 passes by a 26 Mg vehicle were applied on a soil where no heavy traffic had previously been applied. Thus, available information indicates that cumulative compaction effects in the subsoil may be expected to usually occur up to a very large number of passes. Fig. 15 shows the results of measurements in soil profiles from a military training ground, trafficked by heavy military vehicles for many years. The figure shows the macropore volume (the volume of pores with equivalent diameter >0.03 mm) as a percen-

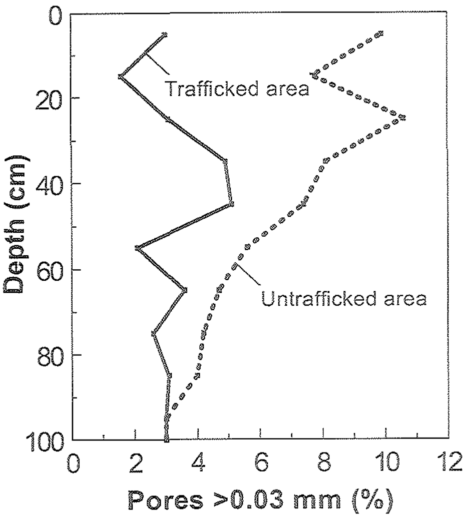


Fig. 15. Volume of coarse pores (as a percentage of the total soil volume) as a function of depth in parts of a military training ground on a clay soil where traffic had been applied for many years by military vehicles weighing up to 50 Mg and in adjacent untrafficked parts of the ground. (After Eriksson, 1976.)

tage of the total soil volume at various depths. In the trafficked area, the macropore volume was reduced to very small values throughout the soil profile, indicating that important soil functions such as gas exchange, water infiltration and drainage were severely impaired (cf. Chapter 4).

Arvidsson (1998a) measured the depth and extent of compaction caused by traffic by heavy sugar beet harvesters. Sensitive displacement sensors were installed at three depths in the soil and the vertical displacement of the sensors was recorded when the wheels of the harvester passed straight over them. A persistent downward movement of a sensor implies that the soil layer under the sensor becomes compacted, although the displacement may also to some extent be caused by sideward movement within this layer.

Fig. 16 shows results obtained at a site with sandy soil. The harvester had two axles. It weighed 20 Mg when empty and 35 Mg when fully loaded. The load was slightly higher on the front than on the rear axle. Tyre inflation pressures were 220 kPa (front) and 180 kPa (rear). Each time a wheel passed, the sensors were displaced downwards. Some of the displacement was elastic and the sensors moved upward again when the wheel had passed, but some of it was persistent (plastic). Repeated wheel passes caused cumulative plastic displacement. In agreement with predictions of stress distributions (cf. Fig. 6), the front axle caused more displacement than the rear axle because of its higher load. Displacement occurred at all depths, indicating that compaction occurred to depths greater than 70 cm, probably to nearly 90 cm. The displacement was greater when the harvester was fully loaded (Fig. 16A) than when it was empty (Fig. 16B).

Using the same method and the same depths of the sensors as in Fig. 16, Keller & Arvidsson (2004a) measured soil displacement caused by two six-row sugar beet harvesters, one weighing 26.5 Mg with four wheels, the other weighing 53.7 Mg with two rubber tracks and one pair of dual-mounted wheels (cf. Chapter 2.3). Thanks to the better running gear, the displacement in the subsoil at depths of 0.3, 0.5 and 0.7 m was somewhat less under the heavier harvester than under the lighter one.

Using the same method, Trautner (2003) measured soil displacement caused by wheel loads from 2 to 7 Mg at five sites with various soils. The measurements were carried out at a series of soil water contents. The highest loads usually caused soil displacement at all depths, even when the topsoil and upper part of the subsoil had dried out to the wilting point and the precompression stress was extremely high. In fact, the displacement at 70 cm depth was usually greatest when the soil was driest. A possible reason is that heterogeneities such

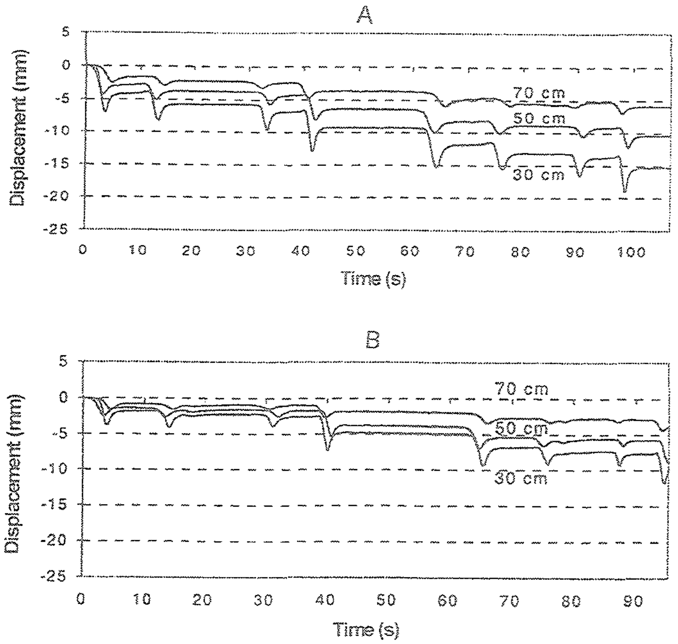


Fig. 16. Vertical displacement at three depths in a sandy soil under the centre line of one of the wheel tracks of a six-row sugar beet harvester with two axles (from Arvidsson, 1998a). Displacement sensors were placed at 30, 50 and 70 cm depth. The harvester passed four times (forwards, backwards, forwards, backwards) in the same tracks. It was either fully loaded (A) or empty (B) with total weights of 35 and 20 Mg, respectively.

as hard clods or cracks in the upper soil layers led to stress transmission to great depth without reduction, instead of the gradual reduction and lateral spreading assumed in the theoretical models described above (Fig. 6). These results show that dry conditions do not necessarily protect subsoils from compaction. They also show that further studies are required concerning the influence of soil moisture and structure on stress transmission and subsoil compaction in various soils. Nearly all studies carried out so far have been made under relatively wet conditions, simply because it has been assumed that no compaction occurs under dry conditions.

During traditional mouldboard ploughing the tractor wheels run in the open furrow, and this is often the most important cause of subsoil compaction. These wheels apply stresses in the upper part of the subsoil that are usually higher than any other machinery-induced stresses in these layers (Tijink & van der Linden, 2000) and they often lead to formation of so-called plough pans. From this point of view, a mouldboard ploughing technique with the tractor running on land or the use of some alternative method of primary tillage or zero-tillage is a great advantage. This has often been shown to lead to improved structure of a previous plough pan within some years (e.g. Rydberg, 1987; Tessier et al., 1997).

3.4. Persistence of compaction effects

Several processes, such as wetting/drying, freezing/thawing, various biological activities and (in the plough layer) tillage, contribute towards alleviating the effects of soil compaction. Both drying and freezing cause crack formation and disintegration of large clods near the soil surface into smaller aggregates. Cracks and aggregates are usually more stable at higher clay content, but they are also more indispensable for the function of the soil. Roots and microbial activities contribute towards stabilizing crack and aggregate surfaces, and both roots and soil animals may generate relatively stable cylindrical channels in the soil. However, the intensity of all processes that alleviate compaction decreases rapidly with depth. For example, under the climatic conditions in Northern Europe, thin superficial layers of bare soils may freeze and thaw 30 times per winter, sometimes with a minimum temperature considerably below that in the air. On the other hand, layers at depths >35 cm never freeze more than once per winter and the minimum temperature just reaches a couple of degrees below the freezing point (Box 6). Likewise, drying and wetting cycles are much more frequent and intense near the soil surface than at greater depth. Furthermore, only the upper soil layers are loosened by tillage. Therefore, the persistence of compaction effects increases rapidly with depth. To a depth of 5 cm or slightly more, the natural processes seem to alleviate most of the compaction effects in all agricultural soils within a year, even when no tillage is carried out. In contrast, in deep subsoil layers compaction effects seem to be permanent. In intermediate layers the persistence depends on several factors such as soil texture, climate, tillage methods and cropping system.

3.4.1. Plough layer compaction

If the mean bulk density or the mean degree of compactness (cf. Boxes 5 and 11) are used as the sole parameter to characterize compaction effects in the plough layer, one ploughing might seem to completely alleviate the effects. Indeed, this may actually be the case in soils with very low clay content but not in soils with higher clay content.

After ploughing, the mean bulk density of the plough layer of any soil, and consequently also the mean degree of compactness, may be similar, regardless of whether the soil was compacted before the ploughing or not. In a clay soil, however, compaction before ploughing leads to more coherent and less fractured furrow slices (if the soil is wet) or to larger and more massive clods (if the soil is dry). This is illustrated in Fig. 17, which shows the soil surface soon after ploughing in an experimental plot intensively trafficked by a tractor and trailer before ploughing and in an adjacent uncompacted control plot. In field trials in Sweden (Arvidsson & Håkansson, 1994), plough layer compaction often led to substantial crop yield losses in subsequent years. (These results are presented in Chapter 5.3). After a five-year period with annual ploughing, however, crop yields were no longer reduced. For at least one year during this period, nearly all soil in the plough layer must have been located in the upper 6-8 cm soil layer, where natural alleviating processes are intensive. Unpublished results from the Ukraine (cited by Håkansson & Medvedev, 1995) indicate that it may take six years under Ukrainian conditions until the effects of plough layer compaction have disappeared. In coarse-textured soils, crop responses indicate that one single ploughing in combination with the natural processes during one winter alleviate nearly all effects of machinery-induced compaction. No report has been found that indicates the existence of completely permanent compaction effects in annually ploughed soil layers, irrespective of soil texture. However, the possibility of permanent effects when a virgin soil is taken under cultivation for the first time cannot be excluded. There may also be long-term indirect effects of annually re-

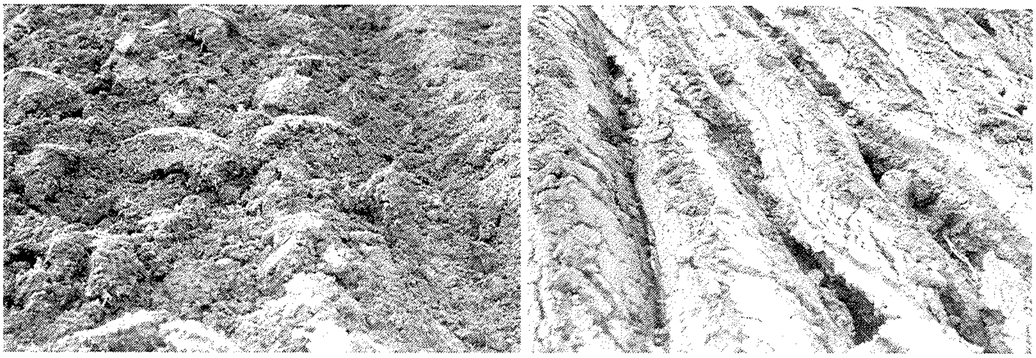


Fig. 17. The soil surface in a field trial on a Swedish clay loam soil soon after autumn ploughing. To the left an uncompacted control plot, to the right a plot trafficked just before ploughing with a traffic intensity of 350 Mgkm ha^{-1} by a relatively light tractor and trailer.

peated soil compaction.

In soils that are not regularly loosened, compaction effects persist longer than in annually ploughed soils. If a system with relatively deep annual ploughing is replaced by a system with only shallow tillage or zero-tillage, the layer that is no longer regularly loosened will often become very dense. During the first years without loosening, repeated machinery traffic will cause cumulative compaction effects in this layer. However, as further discussed in Chapter 5.4, this may partly be compensated for by improved stability of the macropore system and after some years a dynamic equilibrium is likely to be reached between repeated compaction effects and natural alleviating effects.

3.4.2. Subsoil compaction

A literature review by Håkansson & Reeder (1994) shows that subsoil compaction is much more persistent than plough layer compaction. This applies to all types of soils in all regions, including swelling/shrinking clay soils where deep desiccation cracks appear regularly and soils in regions with annual freezing. It is obvious that freezing influences soil structure much less in the subsoil than in the surface layer. One example is given in Table 2. Blake et al. (1976) provide an example from a clay loam soil in southwestern Minnesota, USA. They compacted the subsoil to a depth of at least 60 cm by applying four passes by a loaded roller in the bottom of each plough furrow. Ten years later they found virtually no alleviation of compaction effects in the subsoil (below 25 cm depth), in spite of soil freezing each winter, usually to more than 60 cm depth.

In regions without freezing, compaction effects in the subsoil are likely to be even more persistent than in regions where the soils freeze. In a sandy clay loam in a tropical area in Pakistan, Ishaq et al. (2001a) studied the effects of artificial compaction of the soil layer below 15 cm depth. One and a half years and three crops later, considerable compaction effects still persisted in this layer, although the data indicated that they were partially alleviated. Particularly in coarse-textured soils that are not disturbed by tillage operations, compaction effects are likely to be even more persistent. Jakobsen (1983) reported from a forest site in Australia that in tracks caused by trans-

Box 6

Soil freezing - depth, frequency and frost action

In clay soil regions with cold winters, every farmer knows that freezing can drastically improve the structure of the surface layer. Freezing has not such a favourable effect in coarse-textured soils, or in deeper layers of any soil. In fine-sandy and silty soils in particular, freezing may even influence the structure negatively. Reasons for these dissimilarities are differences in frost structure in different soils and differences in intensity and frequency of freezing at various depths. The effects of freezing on soils have been illustrated for instance by Andersson (1961), Czeratzki (1971) and Kay et al. (1985).

In a *coarse sandy soil,* all pores are relatively coarse. When such a soil freezes, the water freezes in the individual pores without appreciably influencing the structure. Provided that the groundwater level is not very shallow, the upward transport of water to the freezing front is usually small, and therefore there is a very limited frost heave. However, if the ground water level is shallow or some water infiltrates, accumulation of ice and more pronounced frost heave may occur.

In a *heavy clay soil,* most intra-aggregate pores are very small and retain water strongly. In these pores, the freezing point is depressed and at normal freezing temperatures the water in these pores remains unfrozen. Instead, water starts freezing in cracks and other macropores where the freezing point is less depressed. This induces water movement from the small pores into the coarse ones, where clear ice lenses develop, while the aggregates dry and shrink. As freezing proceeds, the ice lenses extend and form a network of ice-filled cracks in the soil. In the surface layer, where the freezing is rapid and intensive, a dense pattern of thin ice-lenses is formed. In the upper 2-5 cm layer of a bare soil, there may be 20-30 cycles of freezeing/thawing per winter, some of them with very low minimum temperatures. This results in disintegration of coarse aggregates and clods, and after winter, this layer is often dominated by aggregates in the 0.5-5 mm range. Only in the case of very shallow groundwater or some water infiltration does a substantial enrichment of water in the frozen layer occur. Therefore, there is usually only moderate frost heave in these soils.

In *fine-sandy or silty soils,* the frost structure is sometimes intermediate between that in coarse sandy soils and clay soils. However, in these soils the potential often exists for substantial, long-distance capillary water transport from below up to the freezing front, and sometimes this leads to the formation of very thick ice layers. This results in an extensive enrichment of water in the frozen layer and substantial frost heave. Thawing, which proceeds from above while deeper layers are still frozen and impermeable, then leads to super-saturation of the upper soil layer and to deterioration rather than improvement of soil structure.

The number of freeze/thaw cycles decreases rapidly with depth. At depths greater than 30-35 cm, the soils in areas with normal snow cover never freeze more than once per winter under Scandinavian conditions (Andersson, 1964). At these depths, the minimum temperature is seldom lower than -2°C. Therefore, at depths >35 cm, freezing has only minor effects on soil structure. This conclusion was drawn from the measurements summarized in Section 3.4.2, which showed that compaction effects at these depths persisted nearly unaltered after many years, even in clay soils that had frozen to 70 cm depth or deeper in some winters. At depths >35 cm, water depletion by plants seems to have greater effects on soil structure than freezing.

port vehicles 50 years earlier, compaction effects still persisted all the way from 2 to 50 cm depth.

In fine-textured soils in temperate regions ploughed to 20-25 cm depth, some alleviating effects have been shown to occur to a depth of 10-15 cm below ploughing depth, i.e. to about 35 cm below the soil surface (Rydberg, 1987; Tessier et al., 1997; Munkholm et al., 2005a). However, at depths >35-40 cm compaction effects seem to be at least partly permanent in all soils. This conclusion was drawn from investigations in many countries in areas with annual freezing. Table 2 shows results of field trials in Sweden, where traffic by vehicles with an axle load of 10 Mg was applied on one occasion. The year after traffic, compaction effects were recorded to a depth of about 50 cm, and eleven years later virtually no alleviation had occurred at depths >35 cm. In coarse-textured soils, compaction effects seem to be nearly permanent, or at least to persist for decades, even in layers immediately below the traditional ploughing depth, i.e. from a depth of 20-25 cm.

The fact that compaction effects in the subsoil are very persistent is further evidenced by observations in so-called basal till soils in areas of northern Europe or North America that were glaciated until about 10 000 years ago. During the glaciation, these areas were covered by up to 3000 m thick ice caps, and the soils were exposed to stresses up to 30 MPa. As summarized by Håkansson & Reeder (1994), no exact information seems to be available on the minimum depth at which compaction effects of this heavy loading still persist, but in coarse-textured till soils it is likely to be from about 50 cm depth. This indicates that completely permanent compaction effects may exist from this depth, at least in coarse-textured soils.

When regarded in a more normal human time perspective, it can be concluded that compaction effects are nearly permanent at depths >40 cm in all types of soils, and in non-swelling soils or in regions where the subsoil does not freeze even at a shallower depth. This makes subsoil compaction a serious threat to long-term soil productivity, unless measures can be taken to alleviate its effects. However, this is often difficult or even impossible.

It seems to be impossible to completely alleviate machinery-induced compaction effects in the subsoil by mechanical loosening (Box 7). Such operations are also expensive and often difficult, particularly in stony soils. In humid regions, soils are often too wet for deep tillage when there are no crops in the fields. Furthermore, many trials have indicated that any mechanical disturbance both destroys some existing macropores and makes the subsoil more susceptible to compaction by subsequent traffic. Therefore, deep loosening sometimes makes more harm than good, and if carried out once it must often be repeated periodically. Consequently, as discussed by Håkansson & Petelkau (1994), the strategy should be to minimize subsoil compaction rather than to try to alleviate its effects by deep loosening after it has occurred.

A possible measure to reduce the effects of subsoil compaction is to grow so-called pioneer plants with roots having a special ability to penetrate dense soil layers. Such plants can form new root channels through a compacted layer, but they cannot effect a general loosening of the layer. However, even a relatively sparse system of new root channels may sometimes be of importance, since the roots of subsequent crops can utilize these channels to reach underlaying layers. A plant often mentioned as a potential pioneer plant is lucern, partly because it is a perennial (e.g. Mitchell et al., 1995; Löfkvist, 2005). Common annual crops show no dramatic differences in this respect, and growing of special crops only for this purpose may not be economically fea-

Box 7

Subsoil loosening

Trials in various countries show that mechanical loosening can seldom completely alleviate the effects of machinery-induced subsoil compaction (Werner, 1989; Kooistra & Boersma, 1994). Where dense subsoil layers are of pedogenic origin, the prospect for positive effects of subsoil loosening are better, and under such conditions the loosening effects can be more positive and long-lasting.

Loosening of subsoils is energy-consuming and expensive and is often technically difficult, particularly in stony soils. Furthermore, during periods when there are no crops in the field, soils in humid regions are often too wet to be actually loosened by deep ripping. Even if a subsoil is dense, it usually contains some continuous and stable macropores, many of which actually become destroyed by the subsoiling and replaced by new and unstabilized coarse pores. Any disturbance also reduces the strength of the soil, and this makes the soil more susceptible to compaction, at least temporarily (Lebert, 1992). Therefore, a few years after deep tillage, the subsoil in many trials has been found to be as dense as before the loosening (e.g. Evans et al., 1996) and in some cases with a less favourable structure than before the loosening (e.g. Kooistra & Boersma, 1994; Munkholm et al., 2005a, b).

Large and persistent positive crop response to subsoil loosening has been reported from some trials (e.g. Nitant & Singh, 1995; Varsa et al., 1997; Canarache et al., 2000). However, more often there has only been a small crop response, either positive or negative (e.g. Håkansson, 1976a; Larney & Fortune, 1986; Pittelkow et al., 1988; Evans et al., 1996). This has been the case even when the loosening has been carried out under suitable conditions (when the soil has been relatively dry). Particularly when carried out under wet conditions, subsoil loosening has often caused more harm than good (Zaidel´man, 1990; Alakukku & Elonen, 1997; Munkholm et al., 2005b). On average, the effects have been small and have often not justified the cost. The best possible technique certainly improves the results (Spoor & Godwin, 1978; Böttcher & Lehfeldt, 1990, cited by Håkansson & Petelkau, 1994), but a prerequisite for a positive outcome seems to be that heavy machinery traffic afterwards is substantially reduced during a long period (Schulte-Karring & Haubold-Rosar, 1993). A crop with an abundant root system during this period will help stabilizing the effects. Likewise, if mouldboard ploughing with tractor wheels running in the open furrow is replaced by on-land ploughing or other tillage systems where the tractors run on the soil surface, the effects of subsoiling will persist longer (Ehlers et al., 1994; Tessier et al., 1997; Munkholm et al., 2005a, b). Likewise, Busscher et al. (2002) found that the loosening effects persisted longer in a controlled traffic system than those previously found in a system with a random type of machinery traffic, and that the recompaction effect then largely depended on the total amount of rainfall at the site. Furthermore, Svantesson (2005) reported that the effects of subsoil loosening in a clay soil became more persistent when calcium oxide was injected into the loosened layer.

Unfortunately, experimental activities on subsoil loosening have been rather limited in many countries during recent years. Results of older trials may no longer be applicable, since the subsoil was then probably less compacted and in less need of loosening than it is today. Furthermore, recompaction probably now occurs more quickly than before, and this makes the loosening effect less persistent. Therefore, new trials are desirable.

sible, particularly if they have to be grown for more than one year. Therefore, the possibilities to use this method to alleviate subsoil compaction are limited. However, if subsoil loosening is carried out immediately before, or still better after the establishment of a suitable perennial crop like lucern, the roots of this crop may contribute in stabilizing and prolonging the effect of the loosening (Löfkvist, 2005).

Chapter 4
Effects of compaction on some soil properties and processes

Summary

Compaction affects nearly all physical, chemical and biological properties and processes in a soil to a greater or lesser extent. Compaction implies a decrease in total pore volume, but it is mainly the volume of coarse pores, such as cracks and other large voids between aggregates and clods, worm channels and root channels that is affected. The continuity and stability of the macropore system is also strongly impaired. This may very negatively affect soil aeration, as well as infiltration, transport and drainage of water. From a crop production point of view, increased resistance to root growth and hampered soil aeration are usually the most detrimental effects. This may reduce the growth rate of roots, and vital root functions such as uptake of water and nutrients may be seriously impaired. Seedbed quality and crop establishment may also be negatively affected. As further discussed in Chapter 6, the conditions for the soil microflora and fauna are affected to a greater or lesser extent. On the other hand, in very loose soil the contact between roots and soil may be too poor and unsaturated hydraulic conductivity and transport of water and nutrients to the roots suppressed.

4.1. Pore volume and pore size distribution

When a soil is compacted, virtually all soil properties and processes, physical as well as chemical and biological, are affected to a greater or lesser extent. This influences many fundamental plant growth factors. It primarily affects several basic physical properties, such as pore volume, pore size distribution and continuity and stability of the macropore system. These changes, in turn, affect the storage and transport of water, air and heat in the soil. They also influence root growth and function, both directly and indirectly, as well as the habitable pore space and other properties of importance for various soil organisms. In this chapter, the effects of soil compaction on soil properties and processes are discussed mainly from a crop production point of view and in a short-term perspective. Environmental effects and more long-term effects are discussed in Chapter 6.

Since compaction implies that the total volume of a soil element or the total depth of a soil layer decreases, while the volume of the solid substance is unaltered, only the pore volume decreases. However, pores of various sizes are affected differently. The decrease in volume particularly affects the coarsest pores (the macropores) such as cracks and other large voids between clods and aggregates. Vertical, cylindrical pores, such as worm channels and root channels, may also be affected, even though they are generally considered to be more resistant than other macropores. Furthermore, compaction does not only reduce the volume of macropores in a soil, it also strongly impairs the continuity and stability of the

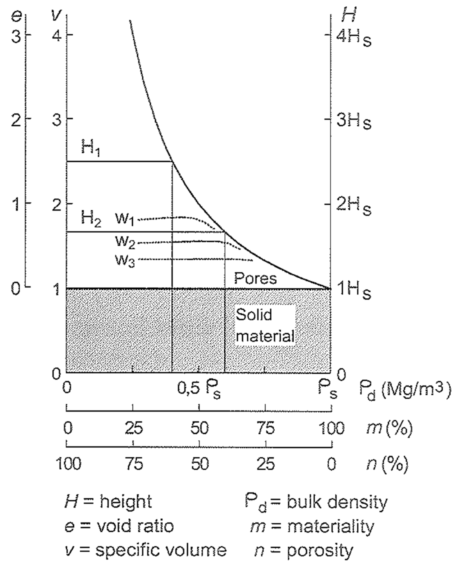
Box 8

Influence of compaction on volumetric relationships and pore size in soils

The figure below shows how compaction and loosening influence the volumetric relationships in a soil layer, e.g. a plough layer, and the interrelations between various parameters used to characterize these relationships (after Håkansson et al., 1988). It also illustrates how compaction and loosening usually influence the water retaining properties of a soil.

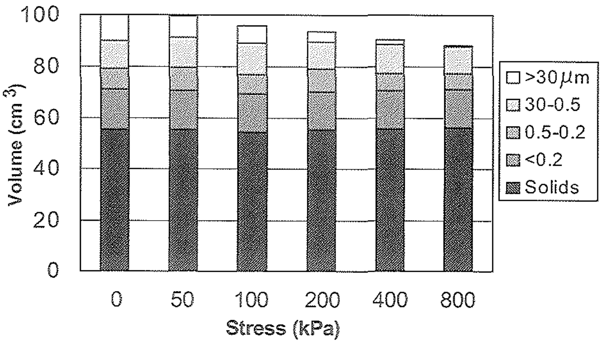
The quantity (volume) of solid material in the layer is assumed to be constant. If this material could be compressed to a nonporous rock, its height would be H_s. Then it would have a porosity $n = 0$, materiality $m = 100$, specific volume $v = 1$, void ratio $e = 0$ and dry bulk density $\rho_d = \rho_s$. (These terms are defined in Box 5.) The actual depth of the layer depends on the type of soil and its state of compactness. The curve shows the relationships between the depth of the layer and the other parameters. The unshaded area under the curve represents the pores.

For a given soil, only a limited section of the curve is applicable under normal field conditions, and this section varies between soils. An example is shown for a mineral soil with a depth varying between $H_1 = 2.5\ H_s$ when the layer is very loose and $H_2 = 1.67\ H_s$ when it is intensively compacted. Corresponding porosities are 60% and 40%, respectively. This applies to a soil with relatively low porosity, specific volume and void ratio, and relatively high bulk density and materiality. Many coarse- and medium-textured soils with low organic matter content have a range of variation similar to that in the example. Clay soils usually have a range of variation somewhat further to the left in the figure. Organic soils have a much smaller amount of solids, and consequently a low H_s and a range of variation much further to the left, some of them with m-values below 10%.



The unshaded area below the dashed curves w_1, w_2 and w_3 represents the water-filled pore space for the soil in the example at three matric water tensions and illustrates how the state of compactness of a soil usually influences the water retaining properties. 1 is a low tension (<100 hPa corresponding to a drainage depth <1 m), 2 is an intermediate tension (about 250 hPa) and 3 is a high tension (about 1.5 MPa, i.e. near the wilting point). The rest of the pore space is air-filled. The quantity of water retained in an arable soil (i.e. the gravimetric water content) at matric tensions ≥200 hPa is usually only marginally affected when the soil is compacted or loosened by normal field operations. This water is mainly held in so-called textural pores, which are nearly unaffected by usual compaction/loosening processes (Dexter, 2004). (In Fig. 10 it was assumed that this is the case even at field capacity, which is not exactly true.) On the contrary, the volume of coarse, so-called structural pores, water-filled only at matric tensions lower than 100 hPa, decreases greatly when a soil is compacted (Fig. 18) and increases correspondingly when it is loosened. Pores drained between 100 and 200 hPa are affected at intensive compaction. The diagram shows that the air-filled pore space at low matric tensions usually becomes critically low when a soil is compacted. Investigations by Perdok et al. (2002) confirm the general trends concerning the effects of soil compactness on water retention shown here, but they also show that the way by which a certain state of compactness is reached may slightly influence the water retention at high tensions and strongly at low tensions.

Fig. 18. Volumes of solid material and pores of various sizes in core samples extracted from the subsoil in a clay soil and exposed to various uniaxial stresses from 0 to 800 kPa. All samples initially had a volume of 100 cm^3. (After Eriksson et al., 1974).



macropore system. When the macropore volume is reduced to values as low as those shown in Fig. 15, most of the remaining macropores are quite isolated.

Effects of compaction on pore size distribution and continuity in various soils have been studied in numerous investigations, mainly by classical methods such as determination of water characteristic curves, hydraulic conductivity, infiltration rate, air permeability or gas diffusivity. More recently, new methods such as studies of fractal dimensions of pore distribution patterns (Lipiec et al., 1998) or distribution of stained pores after infiltration of coloured water (Kulli et al., 2003) have also been used.

The pore size distribution in a soil is usually determined by measuring the water retention properties. When water is extracted from a soil and replaced by air, it is extracted most easily from the coarsest pores. Therefore, the more intensively a soil is drained, i.e. the higher the water tension, the more and the finer pores get drained. Many investigations of this kind have been carried out in various soils to determine the effects of compaction on the pore size distribution. A typical example is presented in Fig. 18, which shows the volume of pores of different sizes in a clay soil exposed to different uniaxial stresses. Pores with an equivalent diameter >30 µm (>0.03 mm) gradually disappeared when the stress increased. At the highest stresses the volume of pores <30 µm also decreased to some extent. Conversely, it has also been shown that loosening of a soil primarily increases the volume of the coarsest pores (Box 8).

4.2. Hydraulic conductivity, infiltration and drainage

The coarsest pores in a soil are responsible for most of the transport of water and gases, and therefore compaction often affects saturated hydraulic conductivity, water infiltration, drainage and soil aeration very negatively. Fig. 19 is a drastic example from a long-term field trial in a Swedish heavy clay soil showing the influence of machinery traffic on water infiltration rate. In some of the plots, all implements had been pulled by cable and winch over twenty years (Box 18). In these plots, the infiltration rate was high, and it remained high even after 30 minutes, when nearly 200 mm of water had infiltrated. In plots where tractors had been used for the field operations, the infiltration rate was already low at the beginning and it decreased to nearly zero within some minutes. The decrease was most rapid in plots where single wheels had been used. With such a low infiltration rate, surface water is quickly formed at rainfall, even in small rain events. In surrounding farm fields with similar clay soils, this is regarded as a serious problem in mechanized agriculture. Even though the effects of compaction on water infiltration and drainage are less dramatic on lighter soils, large detrimental effects may occur

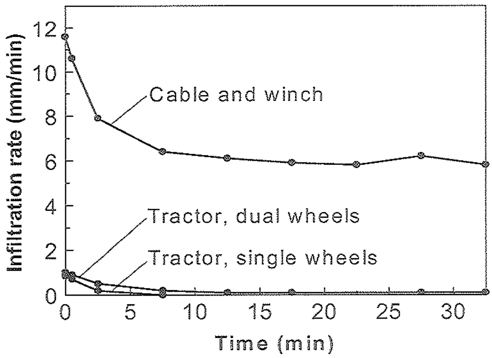


Fig. 19. Infiltration rate in a field trial on a heavy clay soil where all field operations throughout a twenty-year period had been carried out by tractors with single wheels, by tractors with dual rear wheels, or by pulling the implements over the experimental plots by cable and winch (Box 18). In the latter plots, no traffic-induced soil compaction had occurred. (After Håkansson et al., 1985.)

on most soils.

The differences in infiltration rate shown in Fig. 19 mainly depended on compaction of the plough layer and uppermost part of the subsoil, since in these trials only rather light machines had been used. However, traffic by heavier vehicles as well as tractor traffic in the open furrow at mouldboard ploughing may cause compaction even in deeper layers. Since compaction mainly affects the coarsest pores and also impairs the continuity of the macropore system, saturated hydraulic conductivity can decrease drastically even when bulk density is only slightly increased. This is illustrated for instance by Voorhees et al. (1986) and Arvidsson (2001). The latter measurements were made in a series of trials where traffic had been applied by a 35 Mg sugar beet harvester that caused compaction to more than 70 cm depth. (This was shown by the displacement measurements exemplified in Fig. 16.) Using core samples from these trials, it was shown that the saturated hydraulic conductivity in the subsoil was reduced by up to 90%, in spite of relatively small increases in bulk density (Table 3). The effects were similar one and four years after the traffic application.

4.3. Root growth and function

With respect to crop production, the influences of compaction on various plant growth factors are of special interest.

The two factors usually identified as the most critical in excessively compacted soils are the mechanical resistance to root growth (the penetration resistance) and the gas exchange between soil and atmosphere

Table 3. Dry bulk density and saturated hydraulic conductivity in soil samples acquired in 1996 and 1999 at 30-35 and 50-55 cm depth in a Swedish field trial on a loam soil, where 4 passes track by track had been applied in 1995 by a sugar beet harvester with an axle load of nearly 20 Mg (From Arvidsson, 2001)

	Bulk density ($Mg\ m^{-3}$)				Hydraulic conductivity ($mm\ h^{-1}$)			
	30-35 cm		50-55 cm		30-35 cm		50-55 cm	
Treatment	1996	1999	1996	1999	1996	1999	1996	1999
Without traffic	1.68	1.76	1.60	1.66	7.4	2.3	80.6	23.8
With traffic	1.74	1.78	1.69	1.70	0.8	0.33	5.7	4.7
Significance[a]	**	ns	ns	¶	ns	*	¶	*

[a] ns = not significant; ¶ = significant ($p<0.1$); * = significant ($p<0.05$); ** = significant ($p<0.01$).

(soil aeration). Both of these factors may limit the uptake of water and nutrients by the crops. Too high penetration resistance impedes root growth, and poor aeration may lead to oxygen deficiency that damages the roots or impairs their functions. However, the incidence of such effects also depends on other factors. For example, soil aeration becomes critical mainly when the growing season is wet, penetration resistance when it is dry.

4.3.1. Soil aeration

Oxygen deficiency in the soil affects plant growth in a very complex way (Gliński & Stępniewski, 1985). Only roots with adequate oxygen supply and respiration can maintain normal growth and functions. The oxygen supply also influences the production of various growth-regulating substances in the roots and the transport of such substances to above-ground parts of the plants. In poorly aerated soils, microbial activity or chemical reactions may result in unfavourable transformations of some plant nutrients or the production of various substances that are toxic to plants, such as hydrogen sulphide or high concentration of aluminium ions.

Gas exchange in soils occurs both by diffusion and by mass flow, even though the former is usually considered to be the most important. Consequently, the gas exchange depends both on gas diffusion coefficient and on air permeability. When a soil is compacted, usually both the gas diffusion coefficient (Fig. 20) and the air permeability (Table 4; Peng et al., 2004) are drastically decreased. In compacted and wet soil, the oxygen content in the soil air often decreases considerably. Sometimes it is reduced to 10% or lower, i.e. to a much lower content than in the atmosphere, while at the same time the CO_2 content may increase to 10%.

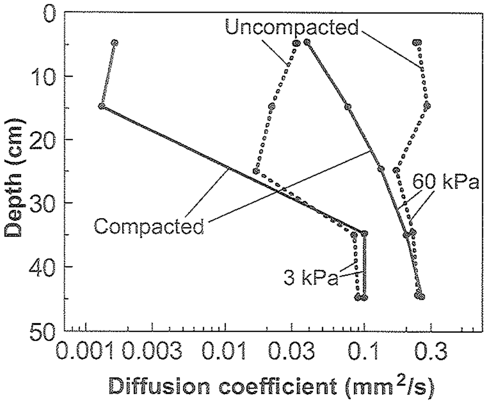


Fig. 20. Gas diffusion coefficient at various depths in a Swedish clay soil after traffic (one pass track by track) in spring in an autumn-ploughed field by a 3.3 Mg tractor with standard tyres (inflation pressure front 200 kPa, rear 120 kPa). The diffusion coefficient was determined in the laboratory in core samples from compacted and uncompacted plots at water tensions of 3 and 60 kPa (corresponding to drainage depths of 30 and 600 cm under the sampling depth). Since the tractor was light, it caused statistically significant compaction effects only in the 20 cm deep plough layer. (After McAfee et al., 1989.)

Gas exchange in a soil is largely determined by the air-filled porosity. The minimum air-filled porosity required for adequate aeration differs and depends on soil texture and structure. It also depends on the rate of oxygen consumption, which is governed by factors such as temperature and content of readily decomposable organic matter. Surprisingly, however, the same air-filled porosity (about 10%) has often been shown to be a critical limit in annually tilled layers of most arable soils (Stępniewski et al., 1994). Below this limit the oxygen supply often becomes critically low. The reason is that recently disturbed soils usually only contain entrapped air when the air-filled porosity is 6% or lower. Therefore, to obtain adequate air permeability or gas diffusion, the air-filled porosi-

Table 4. Air permeability (mm s^{-1}) at various depths in a Swedish clay soil after compaction treatment in an autumn-ploughed field in spring by a 3.3 Mg tractor with standard tyres (one pass track by track). The measurements were made in the field at the beginning and end of the growing season for cereals (After McAfee et al., 1989)

Depth (cm)	Date	Uncompacted	Compacted	Significance[a]
0-5	30 May	64	30	*
	2 September	12	10	ns
10-15	30 May	32	0.2	*
	2 September	12	1.6	*
25-30	30 May	1.6	0.4	*
	2 September	1.6	2.4	ns

[a] ns = not significant; * = significant ($p<0.05$)

ty must be a few percent higher than that (Perdok et al., 2002). However, in many clay soils the continuity of the air-filled macropore system is better than in other soils, and then the critical limit of air-filled porosity may be lower than 10% (e.g. McAfee et al., 1989), sometimes much lower (e.g. Håkansson, 1965). In sandy soils as well as in some organic soils, the continuity of the macropore system is poorer and the critical limit higher (Boone & Veen, 1994). Measurements by Lindström (1990) in a coarse sandy loam indicated that the critical limit in this soil was even over 20%. At the same air-filled porosity, the continuity of the air-filled pores is usually better in undisturbed soil layers (in the subsoil or in a topsoil layer that has not been tilled for some years) than in annually tilled layers. This improves the aeration and reduces the critical limit of air-filled porosity, presumably more so in fine-textured soils than in coarse-textured.

4.3.2. Penetration resistance

If a soil layer has a well-developed system of continuous and vertically directed coarse pores such as desiccation cracks, old earthworm channels or root channels to a great depth, plant roots can grow in these pores without encountering mechanical resistance. Therefore, the rooting depth of annual crops is usually greatest in soils where such a macropore system exists throughout the potential root zone (Box 9). However, in most traditionally managed arable soils there is at least one layer with a less developed or less continuous macropore system. Through such a layer, few or none of the roots can find unbroken macropores where they can grow at their maximum elongation rate. Instead, many roots must penetrate a macroscopically more homogeneous soil, where mechanical resistance may retard the growth. Some soils are massive and have virtually no continuous macropores at all, and if the penetration resistance in the soil mass is high, the root system will be sparse and shallow.

Compaction reduces both the total volume and the continuity of the macropore system, and therefore it also reduces the growth rate of roots. However, its effects are not exclusively negative, since at least some of the roots must have more intimate contact with the soil than they get in wide macropores. It has been shown that the uptake of both water and nutrients is impaired when the root area in close contact with the soil is too small (Section 4.7). Therefore, even in soils with an abundant

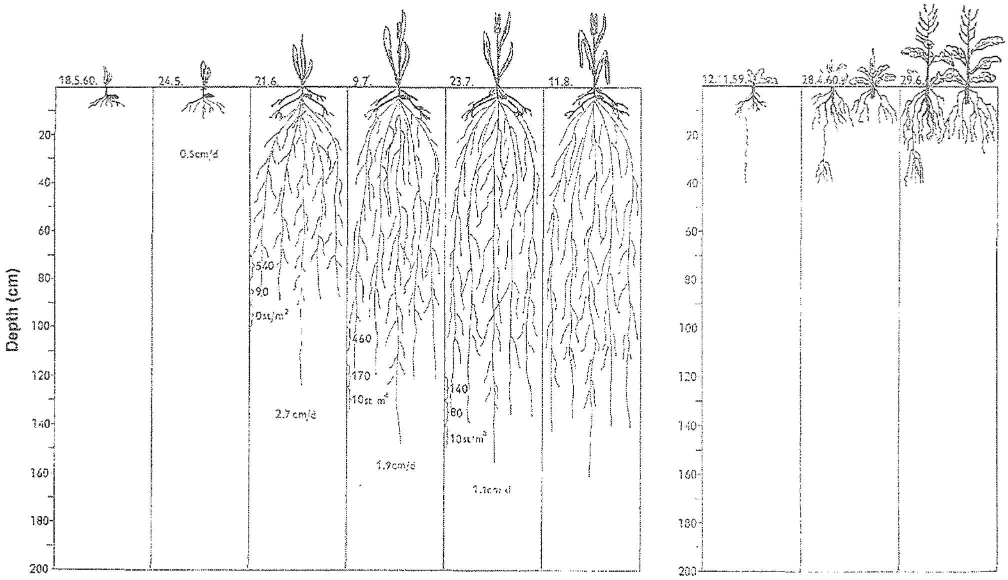
Box 9 Root growth and rooting depth

When conditions are suitable (suitable temperature, well-aerated soil, low mechanical resistance, adequate supply of water and nutrients), roots of most agricultural crops in temperate regions can grow downwards at a rate of 2-3 cm per day (1 mm per hour). In spring-sown small grain cereals, the root zone can be deepened by this rate until the time when straw elongation ceases, provided the penetration resistance is low or the soil has an extensive system of continuous macropores (cracks, bio-pores, etc.) to great depth. An efficient rooting depth of 1.2-1.4 m is then reached, but after that the rooting depth usually increases only slightly. Such a root development is common in clay soils rich in macropores. However, root density usually decreases with depth, and between the macropores, growth of lateral roots may be limited by mechanical resistance. Autumn-sown cereals have a longer period of root growth than spring-sown cereals, and even though the growth may be interrupted in the winter, final rooting depth may be considerably deeper (Wiklert, 1961). The latter applies also to other crops with a long period of vegetative growth. For instance, sugar-beet roots can reach a depth of more than 2 m (Biancardi et al., 1998; Draycott and Christenson, 2003). Roots of crops grown in a warmer climate may have a greater growth rate. Coelho et al. (2000) reported a growth rate of 3.5 cm per day for cotton roots.

The figure to the left shows an example of root development of a spring-sown cereal crop in a clay soil with a well-developed macropore system to great depth. In such a soil, most plant available water throughout the root zone is usually accessible to the crop in a dry period.

In soils with too sparse a system of interconnected macropores, the deepening of the root system may be limited by mechanical resistance. At a resistance of 1.5 MPa as measured by a penetrometer (Box 10), the growth rate is often appreciably reduced (Fig. 21). In many soils, root growth completely ceases at a resistance of 3-3.5 MPa. When the roots have to grow through a soil with no visible macropores, growth may cease already at 2.5 MPa. This is the case in many sandy soils, particularly in soils with a large amount of particles >0.1 mm (Heinonen, 1985). Root development may then stop a few cm below ploughing depth. The figure to the right illustrates a situation in which only a few roots found a possibility to grow more than 3-5 cm below ploughing depth.

Sometimes, factors other than the penetration resistance cause a shallow rooting depth (Heinonen, 1985). The most common seem to be oxygen deficiency and too low a pH-value. A drought barrier and a low nutrient content have also been mentioned as possible reasons, but seem to be rare.



Root system of annual crops on some occasions during the growing season in two soils. Left: Spring-sown barley sown on May 5, 1960, in a clay soil with macropores to great depth. Right: Autumn-sown rape seed sown in August 1959 in a sandy loam with single-grain structure in the subsoil. (From Wiklert, 1961.)

and continuous system of coarse pores, at least some lateral roots must be able to penetrate the more homogeneous soil mass in between the coarse pores. Consequently, even in a soil with an extensive macropore system, the penetration resistance in the soil mass between these pores should not be too high.

The penetration resistance is usually measured by penetrometer (Box 10). Such measurements result in useful relative values of the resistance to root growth and many investigations show that the growth rate decreases when the penetration resistance increases (Fig. 21). Boone et al. (1994) reported that a penetration resistance of 3 MPa is a critical limit in many soils, above which root growth is very slow, and that the growth rate is already significantly reduced at 1.5 MPa. Similar values are reported for instance by Pabin et al. (1998). Petelkau (1986) reports a considerable reduction in the rate by which the root system is deepened when the penetration resistance increases in the 0.1-0.8 MPa range. However, the critical limit of the penetration resistance also depends on the type of soil and its structure (Fig. 21). Thus, it is relatively high in clay soils with a well-developed macropore system and relatively low in sandy soils with few continuous macropores. To some extent the critical limit also depends on the type of roots.

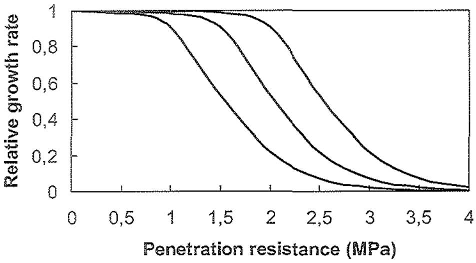


Fig. 21. Relative growth rate of roots as a function of the penetration resistance in the soil (after Stenitzer & Murer, 2000). The curve in the middle may be regarded as a normal curve applicable to crops with roots of average firmness growing in a soil with a moderate frequency of continuous macropores. The curve to the left applies to crops with soft roots or to soils with very few macropores. The curve to the right applies to crops with very stiff roots or to soils with a high frequency of continuous macropores. It is assumed that the supply of water and nutrients is adequate. In case of poor water supply, all curves are displaced to the left.

4.4. Soil structure and seedbed quality

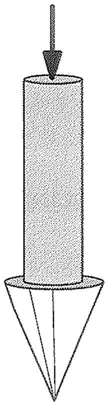
As shown for instance in Fig. 17, compaction makes the soil more massive. From a soil management point of view, this has the most detrimental consequences in clay soils. If the surface layer is compacted shortly before or during seedbed preparation, so that there is no time for natural weathering, seedbed quality may be severely affected. The seedbed may then tend to be too shallow and/or to get a too coarse structure, particularly when seedbed preparation is carried out under unsuitable moisture conditions (in too wet or too dry soil). To produce an adequate seedbed it may be necessary to increase the number of tillage operations. This leads to extra tractor traffic and increased compaction of the layers underneath. Alternatively, it may be necessary to accept a poor seedbed and an increased risk of unsatisfactory crop establishment. These problems are greatest for crops requiring a shallow, high-quality seedbed, such as sugar beet and some vegetables.

When carrying out shallow seedbed preparation in a soil with a dry surface layer, the machinery traffic may not cause compaction in the seedbed itself. Compaction may be limited to the layers underneath, whereas the wheels may cause positive effects on seedbed quality by crushing large clods in the superficial layer.

Seedbed quality and state of compact-

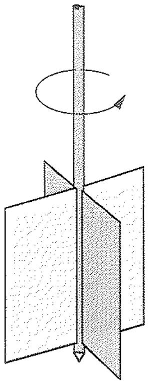
Box 10

The penetrometer and the shear vane tester



A *penetrometer* is an instrument often used in studies of mechanical resistance to root growth in soils. It consists of a shaft with a tip, the size and shape of which can be selected depending on the objective of the study and the strength of the soil. In root studies, the tip is usually a cone with an angle of 30°. In field studies, the diameter of the cone base is often 10-15 mm, in laboratory studies it is often much less. The penetrometer is steadily pushed through the soil, while measuring the force required to push it. To minimize the friction between the shaft and the soil, the shaft is narrower than the base of the cone. Therefore, the force required to push the penetrometer mainly depends on the properties of the soil around the tip. However, the deeper the penetrometer is pushed into the soil, the larger the friction between the shaft and the soil. To eliminate this problem, efforts have been made to introduce penetrometers that measure the force at the cone base rather than at the upper end of the shaft, but these efforts have not yet been very successful. The resistance is usually specified in kPa or MPa as the force per unit area of the cone base.

A penetrometer does not exactly measure the resistance that a root has to overcome to be able to elongate in the soil. One of the reasons is that the penetrometer is forced to move in a straight line, whereas a root can deflect and follow weak zones or macropores. Therefore, a penetrometer only provides a relative and approximate measure of the mechanical resistance to root growth. Furthermore, the values obtained must be evaluated with regard to soil texture and structure (Fig. 21), and they are largely dependent on the water content. An instrument that simultaneously measures penetration resistance and water content in the soil was presented by Vaz et al. (2001).



A *shear vane tester* is another instrument sometimes used for similar purposes. A simple shear vane tester consists of a shaft with radially attached vanes. It is pushed into the soil until the vanes have reached the intended depth. Then it is slowly turned by a torque wrench and the maximum torque required to turn it is measured. The torque is usually highest just as the tester has started turning, and after that the torque decreases. From the maximum torque and the dimensions of the instrument, the shear strength of the soil can be calculated.

When comparing strength values obtained by a penetrometer and a shear vane tester of this kind in soils with various treatments, both methods have often resulted in similar relative differences between the treatments.

ness of the basal layer underneath can be controlled more or less independently of each other by choice of machines and times and procedures of operations. Therefore, it is necessary both in experimental work and in practice to clearly distinguish between effects of machinery traffic on the seedbed and on the basal layer. Whereas seedbed quality is crucial for crop establishment, the state of compactness of the basal layer is important during the rest of the growing season. In practical farming, timeliness of sowing and seedbed quality are often more important factors than the state of compactness of the soil. Therefore, time and methods of seedbed preparation and sowing should usually be chosen without great attention to compaction effects in the basal layers. However, this is possible only with machines equipped in such a way that intolerable compaction effects are avoided.

4.5. Soil biological effects

It may be assumed that compaction or loosening to a greater or lesser extent affects all biological processes in a soil. This applies to many vital processes, such as decomposition of organic material and mineralization of plant nutrients. It may also apply to soil-borne pests and root diseases as well as to growth of weeds. In addition, the environmental impact of crop production may be affected in various ways. The effects of compaction and loosening on all these processes, however, are still poorly known. Some effects of this kind are discussed in Chapter 6.

4.6. Effects on soil trafficability

In recently loosened soils the trafficability is usually poor and machinery traffic generates deep tracks. There is a large rolling resistance to the wheels, a high energy requirement for the movement of the machines and a low drawbar pull of the tractors. In these respects, soil compaction improves the conditions. This is one of the advantages of a so-called controlled traffic system (Taylor 1994; Section 7.5.5). In such a system, all machinery traffic is concentrated to the same tracks (tramlines) for a shorter or longer period, whereas the rest of the field area is untrafficked. Once a system of compacted tracks has been established, it often offers considerably improved trafficability.

4.7. Effects of intensive loosening

Even though mechanical loosening of a soil is often essential, it usually has some negative consequences as well. All tillage operations destabilize the soil structure and make soils more susceptible to compaction (cf. Box 7). Furthermore, when the soil is very loose, the root-to-soil contact is poor (Kooistra et al., 1992; Lipiec et al., 1993), and when it is dry the unsaturated hydraulic conductivity (capillary conductivity) is very low (Kemper et al., 1971; Lipiec & Tarkiewicz, 1988). Under dry conditions in particular, this may lead to impaired plant uptake of both water and nutrients, especially of the least mobile elements (Veen et al., 1992). However, the reasons for negative effects on plant growth of a too loose soil are still poorly investigated. Critical limits have not yet been established but are probably variable. For instance, the detrimental effects of very low unsaturated hydraulic conductivity probably increase with increasing demand for water, i.e. with higher potential evaporation. This may be the reason why the optimal degree of compactness with respect to crop growth tends to be higher under dry conditions than under wet.

The state of compactness also influences the thermal properties of a soil. The thermal conductivity is lower in a loose soil than in a dense one, and therefore the temperature variations at the soil surface are greater, particularly if the soil is bare. In field trials, the author has often observed that a frosty night soon after crop emergence causes more pronounced frost damage to the crop in uncompacted plots than in compacted. Similar observations have been reported by many farmers, particularly in organic soils.

Chapter 5
Effects of compaction on crop growth and yield

Summary

The effects of soil compaction are not always detrimental. After mouldboard ploughing or other deep tillage, the tilled layer is usually too loose, and a moderate recompaction improves crop growth. The highest crop yield is obtained when the plough layer has a certain bulk density or porosity, but there are large differences between soils in optimal bulk density. These differences can be eliminated by the use of relative density values for characterization of the state of compactness. When a parameter of this type named 'degree of compactness' was applied in a series of field trials with the same crop, the mean optimal value was virtually the same in all soils. However, the optimal value depended to some extent on the type of crop grown and on the moisture conditions during the growing season.

The residual effects of machinery traffic applied before autumn ploughing were studied in long-term field trials in Sweden. The traffic was applied by light tractors and trailers, and compaction was mainly limited to the plough layer. Crop responses were negative and increased with soil wetness at time of traffic, with ground pressure of the tyres, with traffic intensity and with clay content of the soil. In clay soils, the effects persisted for a few years in spite of annual ploughing, but no effects persisted for more than five years. In coarse-textured soils, one ploughing and the weathering during one winter alleviated the effects.

In a series of long-term trials in several countries in Northern Europe and North America, traffic was applied on one occasion by vehicles with an axle load of 10 Mg. This led to compaction of the subsoil to a depth of about 50 cm. At depths grater than 40 cm, these effects appeared to be very persistent and caused nearly permanent negative crop responses in all types of soils. This shows that high mechanical stresses in the subsoil caused by heavy vehicles pose a serious threat to long-term soil productivity.

Compaction studies explain the results of trials in Northern Europe showing that crop responses to reduced tillage depth differ between soils. Machinery traffic causes cumulative compaction effects in deeper parts of the former plough layer. In sandy soils, this nearly always results in reduced crop yields. In fine-textured soils, on the other hand, the increase in soil density is largely compensated for by a gradual development of a continuous macropore system, and reduced tillage depth often results in increased yields.

Traffic in established crops not only causes soil compaction, but may also directly damage the plants, and this is often the most detrimental effect. Such traffic is of particular importance in ley crops, where intensive machinery traffic occurs at each harvest. Experimental traffic when harvesting ley crops has often caused drastic yield reductions at the subsequent cut, particularly when wheel slip has been extensive.

5.1. Various types of effect of machinery traffic

Machinery traffic in agricultural fields may influence the crops in several ways. Various individual effects have been studied in a wide range of soils all over the world for a long time. A very large number of one-year trials have been carried out to study crop responses to compaction induced by machinery traffic in ploughed fields at the time of seedbed preparation and sowing. A more limited number of long-term trials has been carried out to study residual effects of compaction that persist in the plough layer after reloosening by ploughing. Crop responses to subsoil compaction caused by heavy vehicles have been studied in many long-term trials in several countries. The effects of traffic in established crops, particularly harvest traffic in ley crops, have also been studied in many trials. In the latter case, direct damage to plants may be a more detrimental effect than soil compaction.

Most of the experimental work has been carried out within traditional tillage systems with ploughing to all annual crops, but some studies have been carried out in systems with reduced tillage. Examples of experimental results of various kinds are shown below. Many of them originate from trials in Sweden and other countries in humid temperate regions, since crop responses to machinery traffic have been most systematically studied in these regions.

5.2. Short-term effects of recompaction of a loosened plough layer

A large number of field trials, as well as practical experience all over the world, have shown that compaction of the plough layer is not always detrimental to crops. After mouldboard ploughing or other deep tillage, the tilled layer is usually too loose and a moderate recompaction during seedbed preparation and sowing improves crop growth and yield. As mentioned in Chapter 4, the main reason for this seems to be that the uptake of water and nutrients is impaired in a too loose soil. If the soil is not recompacted, the plough layer usually remains too loose throughout the growing season (Fig. 11). With traditional field traffic, however, the plough layer often becomes excessively compacted, which again reduces the yield.

5.2.1. How to characterize the state of compactness of the plough layer?

By tradition, the state of compactness of a soil layer is usually characterized by its dry bulk density, porosity or (less frequently) void ratio. It is unimportant which of these parameters is used since, for a given soil, if one of them is known the others can easily be calculated (Box 8). Some other parameters are sometimes used as supplements, such as the penetration resistance or the air-filled porosity at a certain moisture situation.

In an annually tilled layer of a specific soil, the bulk density (porosity, void ratio) may provide useful information on the function of the layer, since a change in bulk density affects the macropore system, and accordingly, some of the most important soil properties. Optimal conditions for crop growth occur at a certain bulk density, and both higher and lower density (lower and higher porosity or void ratio) lead to decreased yield. However, when the state of compactness is comparable, different soils have different bulk densities, and consequently the optimal bulk density with respect to crop growth also differs. Therefore, when comparing different soils in this respect, neither bulk density nor the other parameters mentioned are appropriate.

The influence of soil texture on optimal bulk density is exemplified by results from eastern Germany (Fig. 22). However, optimal values and critical limits may even differ between soils with the same particle size distribution but of different origins,

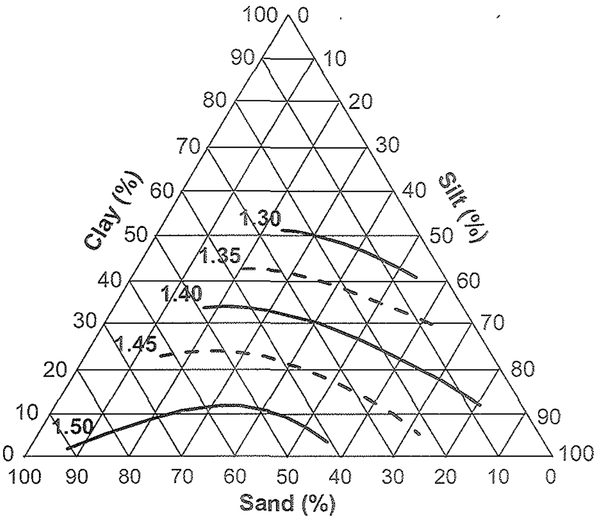


Fig. 22. The bulk density that is optimal with respect to crop growth differs between soils. This diagram shows the critical bulk density (Mg m^{-3}) in the plough layer in soils with different contents of sand, silt and clay, above which root growth and function may be substantially impeded. The diagram is based on trials in soils with relatively low organic matter content in eastern Germany. In heavy clay soils, the optimal bulk density is below 1.3 Mg m^{-3}, while in sandy soils it is over 1.5 Mg m^{-3} (after Petelkau, 1984.) In soils with higher organic matter content, the optimal bulk densities are lower than those shown in this diagram, and in organic soils they may be less than 0.4 Mg m^{-3}.

e.g. from various regions. This is because the soil textural classification is approximate and disregards factors such as mineralogy and particle shape. In addition, the optimal values are even more influenced by the organic matter content of the soil than by the texture of the mineral fraction. Therefore, the optimal bulk density may vary considerably even within an individual farm field.

When two soils have been treated similarly, one of them may have a much higher bulk density than the other. This does not necessarily mean that the former soil is more susceptible or sensitive to compaction than the latter soil in the sense that the function of the former soil is more negatively affected by mechanical stresses than the latter soil. For instance, the fact that increased organic matter content influences soil properties positively cannot be explained in this simple way, even though addition of organic matter to a soil has consistently been shown to reduce the bulk density at the same treatment (e.g. Arvidsson, 1998b; Díaz-Zorita & Grosso, 2000; Aragón et al., 2000; Barzegar et al., 2000). It must also be considered that the optimal bulk density is also reduced, and perhaps to the same extent.

To obtain a measure of the state of compactness of a soil that is more independent of soil type, several efforts have been made to relate the bulk density to a reference bulk density obtained by some standardized compaction treatment. For this purpose, various reference tests have been used. A Proctor test (compaction generated by the impact energy of a falling weight) was used by Pidgeon & Soane (1977), Carter (1990) and da Silva et al (1994). A specially designed uniaxial test with a stress of 200 kPa was introduced in Swedish experimental work many years ago

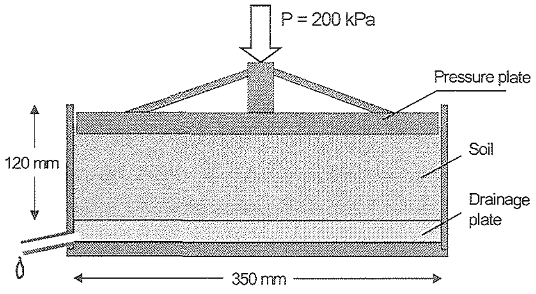
Box 11

Degree of compactness and other relative bulk density values

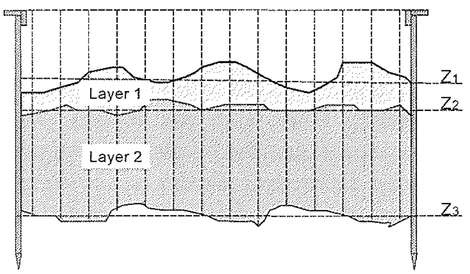
Many parameters have been used to characterize the state of compactness of soils, with bulk density and porosity being the most common. However, a bulk density or porosity that indicates a very loose state in one soil may indicate an extremely compacted state in another soil. For example, in a coarse glacial till soil, the bulk density of the plough layer may vary between 1.3 Mg m^{-3} when the soil is intensively loosened and 1.8 Mg m^{-3} when it is intensively compacted. Corresponding values for a sandy loam may be 1.1 and 1.6 Mg m^{-3}, for a heavy clay 1.0 and 1.4 Mg m^{-3} and for an organic soil 0.4 and 0.6 Mg m^{-3}.

To avoid this problem, efforts have been made to introduce some relative bulk density value to characterize the state of compactness. The 'degree of compactness' (*D*) is a parameter of this kind. This is used in this book, since most examples presented here originate from experimental work in Sweden, where this parameter was introduced in the 1960s (Eriksson et al., 1974). It is defined as the dry bulk density of the soil in the field as a percentage of the dry bulk density of the same soil after compaction in the laboratory in a standardized way. This method was described by Håkansson (1990), and a review of its usefulness was made by Håkansson & Lipiec (2000). In this case, the standardized compaction treatment used to obtain the reference value is a special, so-called drained, uniaxial compression test carried out in a large oedometer at a vertical, normal stress of 200 kPa. Loose soil is compacted to the maximum density obtainable with the stress applied. Thanks to very large samples, soil pretreatment can be minimized and the natural soil structure can be left almost intact. A similar reference test was used by da Silva et al. (1997). Pidgeon & Soane (1977), Carter (1990) and da Silva et al. (1994) used another type of test, a so-called Proctor test, where the soil is compacted by impact energy. For six Swedish soils, Håkansson (1990) found that a certain Proctor test resulted in between 7% and 17% higher bulk density than the test described here. In a similar study with six South African soils, Smith et al. (1997a, b) found corresponding values ranging between 10% and 18%. This shows that the choice of reference test (type and stress or energy level) is of importance. Unfortunately, no comparison has been made between various tests as regards their usefulness from a plant growth point of view, although this would be highly desirable (Håkansson & Lipiec, 2000).

Most examples of experimental results in this book concerning crop response to the degree of compactness originate from trials in which bulk density in field plots was determined by frame sampling (Andersson & Håkansson, 1967; Håkansson, 1990). This method involves hammering a steel frame (in this case usually with an area of 0.5 m^2) down through the layer of interest, after which the depth and quantity of soil is determined in the whole layer or in individual sub-layers. In swelling/shrinking soils, these determinations should be carried out at a standardized soil moisture situation, e.g. at field capacity.



The large oedometer used for determining the reference bulk density



The 0.5 m^2 steel frame used for determining bulk density in different topsoil layers.

Box 11 (Continued)

A degree of compactness, *D*, of 100 or higher in any soil indicates that it has been very intensively compacted. Immediately after ploughing or other relatively deep primary tillage, the *D*-value of the loosened layer is usually between 65 and 70. If the loosened soil is left to natural influences only, the soil gradually settles (Fig. 10) and *D* increases. Under Swedish conditions, the *D*-value in an autumn-ploughed field in the early spring is usually slightly below 80 (Fig. 12). If no machinery traffic is applied, this value persists almost unaltered throughout the summer (Fig. 11), but traditional machinery traffic during seedbed preparation increases the *D*-value more or less.

Up to now, this method to characterize the state of compactness has been used mainly in periodically loosened soil layers. A wide use in undisturbed soil layers seems to require some modifications of the procedure and some further investigations of its usefulness (Håkansson & Lipiec, 2000).

(Eriksson et al., 1974). This has been used when calculating the so-called 'degree of compactness' (*D*), which is defined as the dry bulk density of a soil as a percentage of the reference bulk density of the same soil determined by this test (Håkansson, 1990; Håkansson & Lipiec, 2000; Box 11).

A complication that must be considered in shrinking/swelling soils when characterizing the state of compactness by the bulk density itself or by any relative bulk density value, for instance the degree of compactness, is that the bulk density must be determined in a standardised soil moisture situation. An alternative might be to correct the bulk density to such a situation, but no method of that kind has been developed yet, and such methods would probably be dubious. So far, therefore, the former method must be used, with field capacity being the simplest and most useful soil moisture standard.

5.2.2. Crop response

Many field trials have been carried out all over the world to establish crop responses to machinery traffic during seedbed preparation and sowing in ploughed fields. Many of these trials are mainly of local interest, since the state of compactness has been characterized only by the bulk density or porosity. By using a relative bulk density value as discussed above, the results can be more easily generalized. The parameter of that kind used in the greatest number of trials seems to be the *degree of compactness* (Håkansson, 1990). This was used for instance by Eriksson et al. (1974), Riley (1988), Håkansson (1990) and Lipiec et al. (1991). The results presented in the present section are mainly based on Swedish trials where this parameter was used. (Climate, soils and crop production systems in Sweden and the surrounding countries are described in Box 12.)

These trials were generally established in autumn-ploughed fields. Compaction treatments were carried out immediately before sowing by one or more passes track by track by tractors of various sizes and with various wheel equipment. These were followed by shallow seedbed preparation with the aim to creating an adequate seedbed quality irrespective of the compaction treatment. Only trials where this resulted in a good and uniform crop establishment in all plots are utilized here. The degree of compactness (*D*) was determined in the layer between harrowing depth and sowing depth (about 5-25 cm depth) and *D*-values mentioned below apply only to this layer. The *D*-values shown in Fig. 12 originate from trials of this kind in spring-sown crops.

Fig. 23 summarizes the results of a large

Box 12

Climate, soils and crop production systems in Scandinavia

Most examples of experimental results presented in this book originate from Scandinavia. Therefore, soils, climatic conditions and crop production systems in this region are briefly described.

Most agricultural areas in Scandinavia are located between 55 and 66°N. The growing season is short, particularly in the northern parts. In most agricultural areas, normal mean temperature of the warmest month (July) is 16-17°C. Winter temperatures differ greatly, with mean temperature for January ranging from about -10°C in the northern parts to about 0°C in the south. The growing season (mean temperature above 3°C) lasts from early April to late October in southern parts and from mid May to late September in northern parts. Very long days in summer in northern parts (nearly midnight sun in late June) favour vegetative growth of grass. In the winter, soils in arable fields freeze to varying depth. Maximum freezing depth is usually 40 to 80 cm in central parts of Scandinavia. It is often less both in northern parts, where the protective snow cover is deeper and more stable, and in southern parts, where the temperature is higher. The snow cover usually lasts for several months in northern parts and some days or weeks in the south.

The climate is semi-humid to humid. It is wettest in the western parts of Norway, with an annual rainfall of 1,000 mm per year or more, and driest in eastern Sweden, with an annual rainfall about 550 mm. Annual potential evaporation is 450-500 mm in southern parts and somewhat less in the north. The weather is driest in spring and early summer, with a mean rainfall considerably lower than the potential evaporation. In late summer and autumn it is the reverse. Nearly every year, all soils are fully water saturated at the end of winter.

The arable soils vary considerably, but all of them are young. The whole area was glaciated during the lates glaciation, which ended about 14,000 years ago in southern parts and 9,000 years ago further north. In most areas, coarse and stony glacial till soils dominate in the landscape, but these are mainly used for forest production. Many arable soils are fresh-water or marine deposits with clay content in the plough layer ranging from 1 to 70%. Sandy soils dominate in southern parts, clay and clay loam soils in central parts and loam and silt loam soils in northern parts. Organic soils occur throughout the region.

The dominant crops are small grains, such as spring-sown barley, oats and wheat and autumn-sown wheat, rye and barley. Other important crops are oilseed rape, potato and sugar beet. Forage crops are grown on large areas, mainly clover-grass or grass ley grown in rotation with annual crops. In southern parts, some lucerne and silage maize is grown. The climate is too cool for grain maize.

For spring-sown crops, traditional tillage systems include 20-25 cm deep mouldboard ploughing in the autumn, sometimes preceded by stubble cultivation or followed by shallow harrowing. Shallow seedbed preparation and sowing are carried out as soon as soils have dried enough after snow melt and thawing. Even for autumn-sown crops, traditional tillage systems include mouldboard ploughing shortly after harvest of the preceding crop, followed by harrowing and sowing. Nowadays, some kind of reduced tillage is practised by many farmers for shorter or longer periods, usually stubble cultivation to about half the normal ploughing depth. This is particularly the case for autumn-sown crops. Direct drilling is still only practised to a small extent. However, partly for soil conservation or environmental reasons, spring-ploughing is gradually replacing autumn-ploughing on coarse-textured soils and various forms of conservation tillage or direct drilling is spreading in some areas.

series of trials in Sweden with different crops (Box 13). In the individual trials with spring barley, the highest crop yield was usually obtained at a *D*-value near 87. The more the *D*-value diverged from 87, the greater the number of trials where large yield decreases were obtained. In some cases the optimal *D*-value (D_{opt}) was as much as 8 units higher or lower (Fig. 24). For winter wheat and winter rye, the mean D_{opt} was about 3 units lower and for winter rape about 6 units lower than for spring barley (Fig. 23). The trials with autumn-sown cereals and rape were carried out side by side, and therefore both soil and weather conditions were similar. This makes a direct comparison between these two groups of crops possible.

In the trials with barley, D_{opt} was nearly independent of soil texture (Fig. 24), and this was exactly the objective of using the degree of compactness to characterize the state of the soil. If bulk density had been used directly, the optimal value would have varied considerably between soils.

Thus, the optimal degree of compactness turned out to be virtually independent of soil type. However, D_{opt} varied to some extent with other factors. Fig. 25 shows an example of results of Swedish field trials in spring barley with different moisture regimes. By irrigation and/or protection against rainfall during the first half of the growing season, the soil moisture content was kept as constant as possible at various levels. This and other similar trials showed that when this period was continuously wet, D_{opt} was lower than when it was continuously dry.

This means that in a drier climate the optimal degree of compactness is probably higher than in a wetter climate. This is supported for instance by results from the semi-arid zone in Nigeria, where the highest yields of rain-fed pearl millet or cowpea were obtained after 10 passes or more by a tractor in a ploughed field (Mamman & Ohu, 1997; Dauda & Samari, 2002). However, in the extensive series of field trials with rain-fed barley reported by Håkansson (1990), the effects on D_{opt} of the mean moisture conditions during the growing season were fairly inconsistent. The most likely reason is that the crop response was more influenced by the conditions

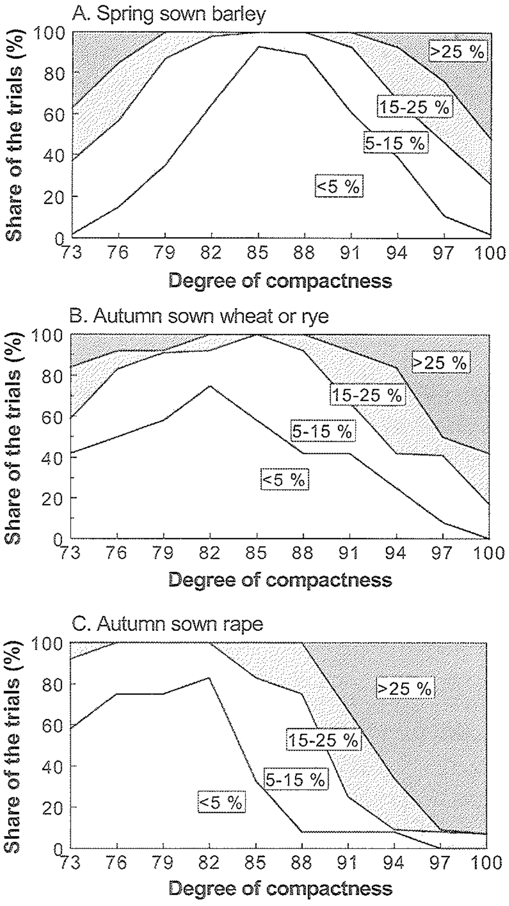


Fig. 23. Relative number of trials on different crops (cf. Box 13) with estimated yield reductions varying from <5% to >25% (relative to yield maximum in the individual trial) when the degree of compactness of the plough layer varied between 73 and 100. Trials with spring-sown barley (A), with autumn-sown wheat or rye (B) and with autumn-sown oilseed rape (C). (After Eriksson et al., 1974, with addition of later Swedish experimental results.)

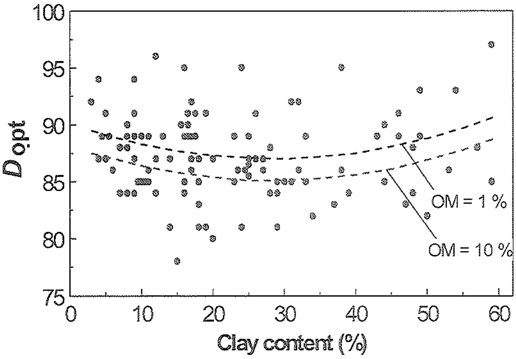


Fig. 24. Estimated optimal degree of compactness in the plough layer (D_{opt}) as a function of the clay content of the soil. Results of about 100 one-year field trials with spring-sown barley carried out all over Sweden during a ten-year period. Regression curves are shown for soils with organic matter contents (OM) of 1% and 10%. (After data from Håkansson, 1990).

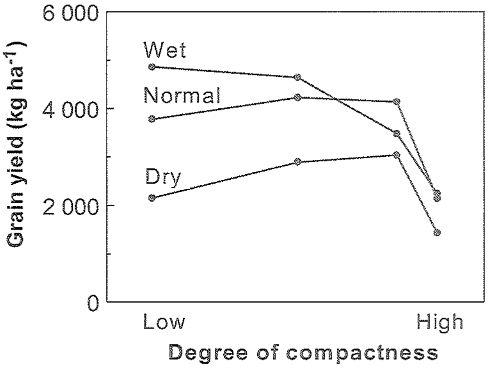


Fig. 25. Grain yield of barley as a function of the degree of compactness (*D*) of the plough layer in a field trial where the soil was constantly kept at different moisture regimes by irrigation and/or protection against rainfall during the first half of the growing season. When the soil was wet during this period, maximum yield was obtained at a much lower *D*-value than when it was dry. This trial was carried out before the method to determine the degree of compactness was fully established and therefore the exact *D*-values can not be shown. (After Edling & Fergedal, 1972.)

during some short critical period than by the mean conditions during the whole season. In any case, information on the variations between years is only of limited interest to farmers at sowing time, since at that time they do not know what weather conditions will occur during the forthcoming growing season. Consequently, they must aim at the *D*-value that is most likely to result in the highest yield. This is the *D*-value that, on average, has resulted in the highest yield in trials carried out during a series of years under conditions similar to those on their own farms.

Another factor that was thought to interact with the degree of compactness and to change the position of the D_{opt} is the nitrogen supply. Therefore, within the Swedish experimental programme, some trials were carried out with different rates of nitrogen fertilization. In these trials too, the crop was barley. There was a tendency for D_{opt} to be higher at 120 kg N ha^{-1} than at 60 kg N ha^{-1} (Fig. 26), but the difference was too small and uncertain to be of practical importance. It can be concluded that increased nitrogen fertilization is not a useful way to compensate for the negative effects of soil compaction under Swedish climatic conditions where the growing season is only seldom wet. However, one can speculate whether the interaction effect between soil compactness and nitrogen fertilization would have been larger in a region with a wetter growing season. Under wet conditions, nitrogen losses by denitrification may be greater, particularly in compacted soil (Section 6.5). This may increase the need for nitrogen fertilizer, and more so in compacted soil than in loose.

The results shown in Fig. 23 indicate some differences in optimal *D*-values between crops. The mean D_{opt} for the autumn-sown cereal crops (wheat and rye) was somewhat lower than for spring-sown barley. It is likely that this difference depends at least to some extent on the difference in climatic conditions between sea-

Box 13

Scientific names of crops mentioned in this book

In this book, only English common names of crops are used. The scientific names of crops mentioned are as follows:

Barley (two-rowed)	*Hordeum distichon* L.
Clover	Various *Trifolium* ssp, mainly red clover, *T. pratense* L. or white clover, *Trifolium repens* L.
Cotton	*Gossypium hirsutum* L.
Cowpea	*Vigna unguiculata* (L.) Walpers
Faba bean	*Vicia faba* L.
Forage grasses	Various species belonging to the *Poaceae* family
Italian ryegrass	*Lolium multiflorum* Lam.
Lucerne	*Medicago sativa* L.
Maize	*Zea mays* L.
Oats	*Avena sativa* L.
Pea	*Pisum sativum* L.
Pearl millet	*Pennisetum americanum* (L.) Leeke
Potato	*Solanum tuberosum* L.
Rape	*Brassica napus* L., *var. oleifera* Metzg. or *Brassica rapa* L., *var. oleifera* Metzg.
Rye	*Secale cereale* L.
Soya bean	*Glycine max* (L.) Merr.
Sugar beet	*Beta vulgaris* L.
Sugar cane	*Saccharum officinarum* L.
Wheat	*Triticum aestivum* L.

sons. Under Swedish conditions, wet periods with a risk of poor soil aeration are much more common in autumn and winter than in spring and summer. The longer growing season for an autumn-sown crop than for a spring-sown may contribute. A high penetration resistance in the soil may be less detrimental to plants with a long growing season, since even with a reduced growth rate the roots may still have time to reach deep layers. This would lead to a flatter crop response curve, and this is actually indicated in Fig. 23.

An appropriate comparison between crops concerning their response to the state of soil compactness can only be made if they are grown side by side in the same trials. The comparison between autumn-sown cereals and rape shown in Fig. 23 was carried out in that way. Similar comparisons have been made between some spring-sown crops (Håkansson, 1973; Eriksson et al., 1974). In those cases, the highest mean optimal *D*-values were obtained for wheat, barley and sugar beet and the lowest for potatoes (Fig. 27). Intermediate values were obtained for oats, peas, rape and faba beans. The difference between the extremes, however, was only a few *D*-units. Within the same crop there may be differences between cultivars, but these have only been studied in a few trials (Box 14). An interesting detail in these trials is that D_{opt} turned out to be higher for barley than for oats, whereas farmers usually argue that barley is more sensitive to compaction than oats. Farmers have often observed that barley develops a more yellowish colour than oats during the vegetative growth stage, when grown in excessively com-

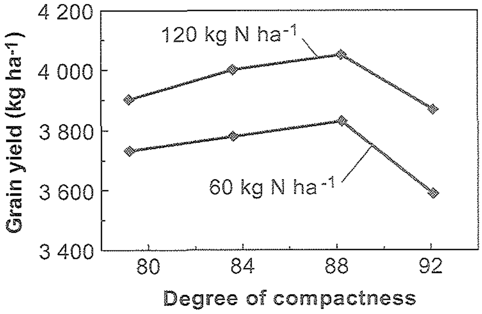


Fig. 26. Grain yield of barley as a function of the degree of compactness of the plough layer at different rates of nitrogen fertilization. Mean values of 11 trials in various soils, 1978-81. At 120 kg N ha^{-1} D_{opt} was slightly but not significantly higher than at 60 kg N ha^{-1}.

pacted soil. The same observation was made in the trials where these crops were grown side by side, but at harvest, oats still turned out to have the lowest D_{opt}.

Another important result is the position of D_{opt} for sugar beet. In the Swedish trials, which were carried out in such a way that crop establishment was good and uniform irrespective of the compaction treatment, D_{opt} was the same as for barley. In international literature, sugar beet is often described as more sensitive to compaction than cereal crops (e.g. Jaggard, 1977; Brereton et al., 1986). One factor contributing to this is that sugar beet is more sensitive to the quality of the seedbed and to the crop stand than cereals. In contrast to the Swedish trials, the trials by Brereton et al. (1986) were carried out in such a way that the traffic treatments not only affected the state of compactness of the underlying layer but also the quality of the seedbed and the crop establishment.

There may also be differences between cultivars in sensitivity to compaction and the results may eventually also depend on the method by which the sugar beet is harvested. There may be more fanging of the beet roots in compacted soils than in loose (Jaggard, 1977), and this may increase the losses at machine-harvesting. Furthermore, a comparison between crops with different lengths of growing season is complicated by differences in climatic conditions during the year. Thus, a sugar beet crop is influenced by weather and soil moisture conditions for a prolonged period after harvest of a cereal crop. This, rather than differences in sensitivity as such, may affect the results.

Another factor that may influence the optimal *D*-value is the availability of manganese to plants. In soils prone to manganese deficiency, a common observation in farm fields is that crops show less pronounced deficiency symptoms in wheel tracks of the machines than between these tracks. This is because the manganese in the looser and more well-aerated soil becomes more oxidized and less soluble. In some of the Swedish trials, the response of barley to the degree of compactness of the plough layer was studied in plots with and without manganese fertilizer applied by spraying with manganese sulphate after crop establishment. At sites where symptoms of manganese deficiency were visible in uncompacted and unfertilized plots, such symptoms were eliminated both by fertilization and by compaction. Without manganese fertilization, crop yields were low in uncompacted plots and D_{opt} was higher than normal. Fertilization increased yields more in uncompacted plots than in compacted and moved D_{opt} to its normal position. In some of these trials, there was a large and statistically significant interaction between compaction and manganese fertilization, but on average for the whole series of trials, which also included trials without manganese deficiency, the interaction was small and non-significant. This was also true in some trials where manganese deficiency symptoms were visible at an early stage, probably because availability of manganese may change during the growing season depending on weather fluctuations.

A summary of the influences of various factors on the position of the optimal *D*-

Box 14

Sensitivity of various cultivars to soil compaction

In some trials in Sweden in the 1970s, a comparison was made between different cultivars of oats and barley concerning their response to the degree of compactness, D, of the plough layer (I. Håkansson, unpublished results). An old cultivar of oats (Stormogul, rather different from the cultivars grown today) turned out to have a lower optimal D-value than the newer cultivars tested. This means that it was more vulnerable to compaction than the newer cultivars. No significant differences were found between the barley cultivars tested, but all of them were of similar type. It is tempting to hypothesize that the reason why the old cultivar of oats was more vulnerable was that it was introduced before field operations were mechanized. At that time the test fields had probably a looser soil than today. This hypothesis seems to be supported by the results presented in Fig. 27 showing that the crops with the highest optimal D-values are wheat, barley and sugar beet. Among the crops compared, these were the crops in which the most extensive breeding and variety testing programmes had been carried out prior to the trials. If this hypothesis is true, it would imply that part of the plant breeding efforts during several decades have inadvertently been spent on making the crops more tolerant to high soil density rather than on increasing their yield potential in looser soil. This would also mean that soil compaction is more detrimental than recent field trials indicate.

value according to results obtained in the Swedish trials is shown in Fig. 27.

5.2.3. Reasons for short-term effects

The reasons for impaired crop growth in excessively compacted soils have been studied in many investigations throughout the world. The results indicate that two factors are usually the most critical, namely the penetration resistance to root growth and the soil aeration. In Chapter 4, it was mentioned that a penetration resistance of 3 MPa as measured by a penetrometer is often a critical upper limit for root elongation and that an air-filled porosity of 10% is a critical lower limit for the oxygen supply in the tilled layer of most soils.

Fig. 28 shows how these limits depend on the degree of compactness and the moisture conditions in an annually tilled soil layer. In this figure, the moisture conditions are characterized by the matric water tension, which shows how strongly the water is retained in the soil. In a soil that is wetted and then drained to a depth of 1 m, the

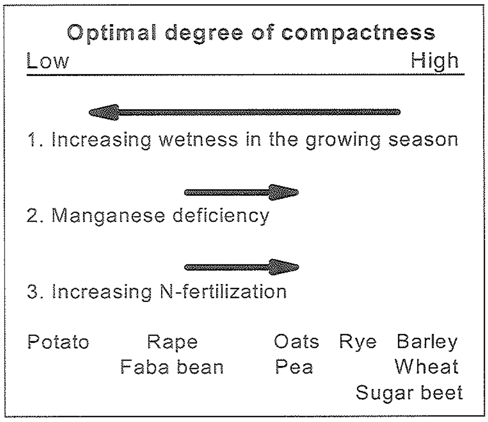


Fig. 27. Direction and mean relative magnitude of the movement of the optimal degree of compactness observed in Swedish field trials when 1) the growing season becomes wetter, 2) manganese deficiency appears and 3) the nitrogen fertilization rate is increased. At the bottom, the average relative position of the optimal D-value for various spring sown crops is shown. (However, it is possible that D_{opt} varies between varieties of the same crop; Box 14).

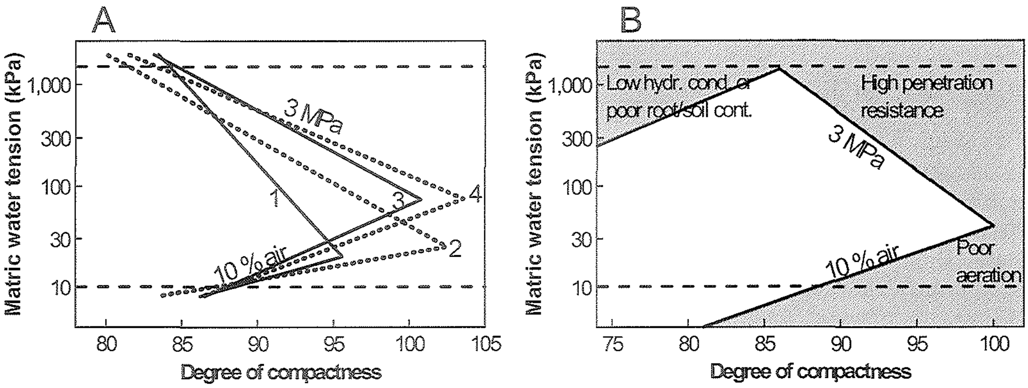


Fig. 28. A. Diagram showing the combinations of degree of compactness and matric water tension in the soil leading to an air-filled porosity of 10% (the lower branch of each V-shaped line) and a penetration resistance of 3 MPa (the upper branch of the same line) in four soils. 1 is a coarse sand, 2 a fine sand, 3 a silty soil and 4 a clay loam. (From Lipiec & Håkansson, 2000.)

B. Schematic diagram showing the combinations of degree of compactness and matric tension where the roots can elongate and function normally (in the unshaded area) or where they are severely hampered by oxygen deficiency (in the lower right-hand corner), by too high penetration resistance (in the upper right-hand corner) or by too poor capillary conductivity or root-to-soil contact (in the upper left-hand corner). (From Håkansson & Lipiec, 2000.)

matric tension in the surface layer is 10 kPa (=100 hPa or 100 cm water column). When the soil dries, the tension increases, and when all plant available water is taken up by the plants (when the wilting point is reached) the tension is 1500 kPa.

Fig. 28A shows the positions of the critical limits in four Polish soils with different texture. In all of them, the positions of the critical limits are similar. This is probably the main reason why the optimal degree of compactness is nearly independent of the type of soil. If bulk density or porosity had been used instead of degree of compactness to characterize the state of compactness, the position of the critical limits would have varied much more between soils.

Fig. 28B shows a schematic diagram of the normal positions of the critical limits in a soil layer and the main problems for the crops at different combinations of degree of compactness and soil moisture conditions. In situations represented by the unshaded area in the diagram, the roots can grow and their normal functions can be maintained. Under conditions represented by one of the shaded areas, root growth or functions are impeded, since a critical limit is exceeded. In the lower right-hand corner of the diagram oxygen supply is too poor for normal root functions, while in the upper right-hand corner the penetration resistance is too high for normal root elongation. This diagram of course over-simplifies the situation to some extent, since in reality there is a more gradual change from non-restrictive to restrictive conditions.

The reasons for hampered crop growth at too low a *D*-value are not yet very well known, and intensified investigations are required. However, crop responses in field trials have indicated that a low *D*-value is detrimental particularly under dry conditions. Therefore, problems arise mainly in the upper left-hand corner of the diagram (Fig. 28B). The basic reasons seem to be too low unsaturated hydraulic conductivity (capillary conductivity) and/or limited root-to-soil contact (Section 4.7), and both these factors may hamper the uptake of water and nutrients.

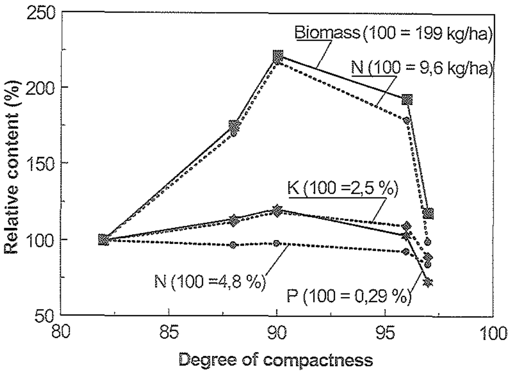


Fig. 29. Relative concentration of nitrogen (N), phosphorous (P) and potassium (K), as well as total content of biomass and nitrogen on May 22 in the above-ground parts of a barley crop sown on April 25 in a field trial where the plough layer had been compacted to various *D*-values ranging between 82 and 97 during seedbed preparation. The values for the uncompacted treatment to the left = 100. Concentrations of P and K were reduced both at the highest and lowest *D*-values, concentrations of N only slightly at the highest value. (After Arvidsson, 1997a).

Uptake of nutrients by the crop in soils with different *D*-values has been studied in some field trials. It has been shown that the uptake of many plant nutrients is hampered both when the *D*-value is too low and too high. An example is given in Fig. 29, which shows the content of nitrogen, phosphorous and potassium in a barley crop about three weeks after emergence. In the most compacted soil the concentration of all these elements in the crop was reduced, but in the loosest soil only the concentrations of phosphorous and potassium. The results can be explained as a combined effect of the growth and function of the root system and of the solubility, mineralization and mobility of the individual elements. The rate of mineralization of organic matter is of importance particularly for the supply of nitrogen to the crop. Nevens & Reheul (2003) observed a much lower content of mineral nitrogen in compacted soil than in uncompacted in early summer after heavy application of farmyard manure, and in forage maize this resulted in a larger reduction in nitrogen yield than in dry matter yield. In a pot experiment with wheat, Saqib et al. (2004) showed that compaction aggravated salinity problems in a clay loam soil.

Different crops are likely to respond somewhat differently to changes in individual growth factors, including any changes induced by compaction. In Fig. 27, it was shown that the mean optimal degree of compactness differs slightly between crops. However, the order of crops or differences between crops probably differ depending on which of the growth factors is the most limiting in the individual case. For example, on average for all Swedish trials, the optimal *D*-value was considerably lower for potatoes than for barley, but in some of the individual trials no difference was found.

Several other factors may also affect the crop responses to the state of compactness of a soil. For example, in the Swedish field trials, perennial weeds such as couch grass (*Elymus repens* L. Gould) were often observed to be more competitive in loose soils than in compacted. Consequently, this tended to move the optimal *D*-value upwards at sites with weed problems. Likewise, root diseases may be influenced by the state of compactness of the soil. *Aphanomyces* root rot is a severe disease in peas, particularly in compacted soils. Accordingly, Grath (1996) found that D_{opt} was much lower for peas than for barley at a site with heavy infestation, whereas both crops had the same D_{opt} at an adjacent site without such infestation. Furthermore, as discussed in Chapter 6, all biological processes in a soil, including denitrification, mineralization of plant nutrients and nitrogen fixation in leguminous crops, are influenced to a greater or lesser extent by the state of compactness, and this in turn influences crop growth.

5.3. Effects of compaction in the plough layer that persist after ploughing

5.3.1. Crop response

As discussed in Section 3.4.1 and illustrated in Fig. 17, compaction before ploughing may largely affect the structure of the ploughed soil. Although residual effects of compaction that persist after ploughing are often quite obvious, and can sometimes be observed after more than one ploughing, studies of crop responses to such effects have been very few. The study carried out in Sweden between 1963 and 1992 (Arvidsson & Håkansson, 1994) seems to be the most systematic to date. This comprised a series of 21 long-term field trials in various soils all over the country with a total of 259 location-years. The present section focusses on the results of this study.

In each trial, traffic was applied by tractors and trailers each autumn soon before annual autumn ploughing for a period of at least seven years. The vehicles used for the treatments were light (total weight about 9 Mg, axle load less than 4 Mg). Therefore, it may be assumed that the compaction effects were concentrated to the plough layer, while compaction of the subsoil was small. The traffic was usually applied when soils were wet and susceptible to compaction (mean soil moisture class according to Table 12 was 3.7). The vehicles had wheels of types traditionally used at the time the trials were initiated (in the 1960s and 1970s) which means that the ground pressure was relatively high. Efforts were made to minimize variations between sites and years in moisture conditions during experimental traffic and in vehicles and procedure used for the treatments, but some variations were unavoidable. Soon after compaction, the soils were ploughed to the normal depth (22-25 cm). During the rest of the year, all plots were uniformly treated in accordance with recommended agricultural practice using as light machines, as low ground pressures and as low traffic intensity as possible. The same crops as in the surrounding farm fields were usually grown. Barley, oats and wheat dominated but oilseed rape and sugar beet also occurred, and occasionally some other crops.

Fig. 30 shows crop responses in plots where the intensity of annual experimental traffic was about 350 Mgkm ha^{-1}. This is two to three times as much as the typical total annual traffic intensity in Swedish cereal fields, which is often about 150 Mgkm ha^{-1} (Table 1).

Fig. 30A shows the mean crop response in the whole series of trials during the initial seven-year period. It shows the crop yield relative to the yield in control plots without experimental traffic. The relative yield decreased gradually during the first four years, but after that it remained rather constant. This can be interpreted such that after a four-year period, there is a dynamic equilibrium between annual compaction effects and annual alleviating effects obtained by ploughing and natural factors (wetting/drying, freezing/thawing, biological activity). It can be concluded that one year of ploughing and natural weathering is usually insufficient to completely alleviate the effects of plough layer compaction. In another treatment included in most of the trials, a traffic intensity of about 120 Mgkm ha^{-1} was generated by the same vehicle. This resulted in a mean crop response approximately one third of that at 350 Mgkm ha^{-1}. Thus, within this intensity range, the crop response seems to be almost proportional to the traffic intensity.

When annual compaction treatments had been carried out for 7-10 years in each individual trial, the compaction treatments were terminated, and the residual effects were then studied for some years. The effects gradually decreased and five years after the last treatment no effects persisted (Fig.30C). This was the same amount of time required to reach an equilibrium stage after the annual compaction treatments were initiated (Fig. 30A). Thus under Scan-

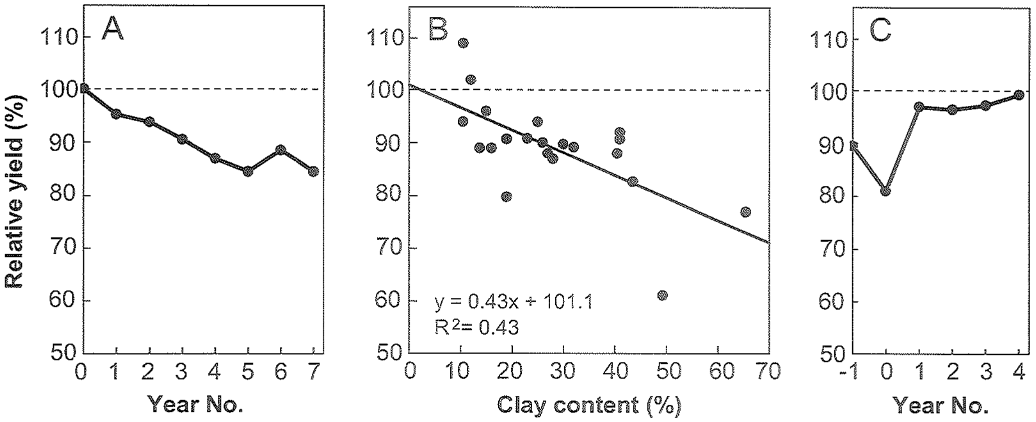


Fig. 30. Relative crop yield in a series of 21 long-term field trials in Sweden in which annual experimental traffic was applied soon before autumn ploughing by vehicles with an axle load <4 Mg. The traffic intensity was 350 Mgkm ha^{-1}, uniformly applied over the plots. Yield in plots without experimental traffic = 100. (After Arvidsson & Håkansson, 1994.)

A. Mean relative yield in compacted plots in the whole series of trials during the first seven years.

B. Mean relative yield from year 4 to the year after the last compaction treatment in each individual trial as a function of the clay content of the soil.

C. Mean relative yield in compacted plots in the whole series of trials after termination of the experimental traffic. Year No. 0 is the last year with annual compaction treatment.

dinavian climatic conditions, it takes about four years for the effects of compaction on one occasion to be fully alleviated in an annually ploughed soil. However, in a soil that is not ploughed annually the effects are probably more persistent.

There were great differences in mean crop response between sites. Nearly half the differences were explained by one single factor, viz., the clay content of the soil. Fig. 30B shows the relative yield decrease in compacted plots in the individual trials during the period from year No. 4 to the year after the last compaction treatment, i.e. during the period when the mean response in the whole series of trials was constant. The relative yield is plotted as a function of the clay content of the plough layer. The crop response was small in coarse-textured soils and increased linearly with the clay content. This means that compaction effects in the plough layer can be alleviated by one ploughing in combination with natural weathering during one winter in soils with a very low clay content, whereas in soils with a higher clay content, several years of annual ploughing and natural processes are required.

The crop response curves in Figs. 30A and 30C showing the mean values for the whole series of trials were relatively smooth, but in individual trials this was not the case. In the individual trials, the response varied strongly from year to year throughout the experimental period. These variations were probably caused by a great number of factors, and the same applies to the variations in Fig. 30B not explained by the clay content. No individual factor was found that significantly contributed to explaining the variations. Several climatic factors were probably of importance, such as frequency and intensity of freezing in the winter and moisture conditions throughout the year. Other factors of importance were probably the weed, pest and disease situa-

Table 5. Mean relative crop yield in years 4-7 (uncompacted treatment = 100) in two trials on clay soils where the plough layer was compacted annually during a seven-year period by traffic with tractor and trailer (axle load <4 Mg). Experimental traffic was applied in the autumn, soon before ploughing, by intensities of 120 and 350 Mgkm ha^{-1} at two soil moisture conditions (moist and wet). The tractor had traditional single-mounted tyres (inflation pressure about 100 kPa), the trailer had either high-pressure tyres (inflation pressure 300 kPa) or low-pressure tyres (inflation pressure 100 kPa). (After Arvidsson & Håkansson, 1994)

		Moisture conditions	
Traffic intensity	Tyres on the trailer	Moist[a]	Wet[a]
No traffic		--- 100 ---	
120 Mgkm ha^{-1}	Low-pressure (100 kPa)	96	89
350 Mgkm ha^{-1}	Low-pressure (100 kPa)	90	78
350 Mgkm ha^{-1}	High-pressure (300 kPa)	85	-[b]

[a] Soil moisture class according to Table 12 about 3 (moist) and 4.2 (wet).
[b] Sometimes too wet for traffic with high-pressure tyres.

tions. Soil factors such as sand/silt ratio, mineralogy and organic matter content may have caused some of the variations between sites. No significant differences in response between crops were observed. The relative crop response was virtually independent of the yield level, which means that the absolute yield decrease was proportional to the yield level.

In this series of trials, great efforts were made to minimize variations in experimental traffic between sites and years with respect to type, weight and wheel equipment of the vehicles used, as well as traffic intensity and soil wetness at time of traffic. Some variations in these factors were still unavoidable, but they could not explain the variations in crop response. However, in addition to the traffic intensity, soil moisture conditions at time of traffic and wheel equipment of the trailer were also varied at two of the sites. Both these factors turned out to be very important (Table 5). Traffic on a wet soil caused more than twice as large a yield reduction as traffic on a moist soil. High-pressure tyres on the trailer caused a 50% greater yield reduction than low-pressure tyres. The results of the trials presented in this section are summarized in a schematic way in Fig. 31.

Results similar to those obtained in Sweden have been obtained in annually ploughed chernozem soils in the Ukraine (V.W. Medvedev, personal communication,1994). The residual effects after ten passes by a T-150 K tractor (4WD, 8 Mg) were studied for several years in several crops, including winter wheat, maize, sugar beet, barley and peas. After 5-6 years, significant effects were no longer observed. Studies by Roger-Estrade et al. (2004) in silt loam and silty clay loam soils in France showed that some effects of compaction still persisted in deeper parts of the plough layer after one ploughing and one winter, but in annually ploughed fields no effects persisted for many years. One important reason is that after a few years, all soil in the plough layer has on some occasion been situated near the soil surface where the alleviating processes are intensive. In Denmark, Munkholm & Schønning (2004) found no residual effect on the structure of the 0-4 cm layer in a sandy loam soil (clay content 13%) one year after compaction by tractor traffic.

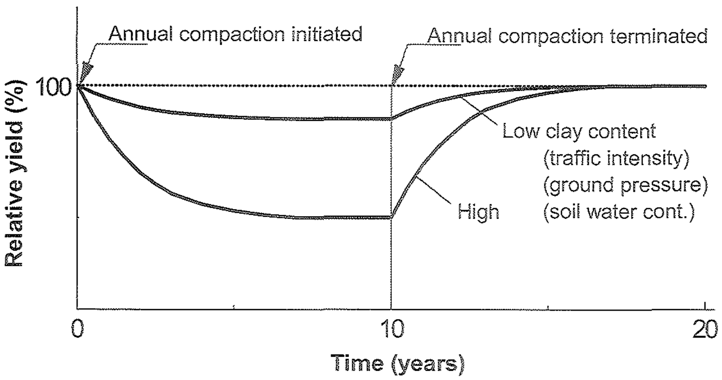


Fig. 31. Schematic diagram showing the residual effects on crop yield of annually repeated machinery traffic in an annually ploughed soil. It is assumed that the compaction is limited to the plough layer by using machines with low axle loads. The effects are larger in soils with high clay content than in soils with low clay content. At the same site, the effects are larger the higher the traffic intensity, the higher the ground pressure of the wheels and the higher the soil water content at time of traffic. If one of these factors is high and the other factors are intermediate, the crop yield reduction during the equilibrium phase under Swedish conditions is often 5-10%.

In a qualitative way, results such as those presented in Fig. 30 are probably applicable in any region. However, the magnitude of the effects are largely influenced by several factors, such as soil texture, climatic conditions and cropping system. Therefore, the effects can only be quantified in regions where a large amount of locally applicable results are available, and this is an unusual situation.

The need for recompaction of soils after loosening (Section 5.2) seems not to be influenced by the occurrence of residual effects of compaction of the type described in the present section. In some of the trials described in Fig. 30, a study was made regarding possible differences in need for recompaction during seedbed preparation between plots with and without compaction before ploughing. However, no significant differences were found (I. Håkansson, unpublished results). This indicates that the compaction effects described in Sections 5.2 and 5.3 can be regarded as additive.

5.3.2. Reasons for residual effects of plough layer compaction

The reasons for residual effects of compaction on crop growth in annually loosened soils are much more difficult to establish than the reasons for the short-term effects discussed in Section 5.2. From observations in the trials presented in Fig. 30, it was concluded that a great number of factors, both physical, chemical and biological, were of importance. The reasons for the effects at a certain site in the individual years could have been established only by monitoring a large number of growth factors throughout each growing season, and this was not feasible. Sometimes one factor must have been the most decisive, sometimes another, and the crop may have been affected only at a specific stage. Bulk density, porosity or degree of compactness (Box 11) during the growing season seemed to be of small value for explanation of the crop responses. Even though these parameters were sometimes affected by the pre-ploughing treatment

Table 6. Seedbed quality immediately after spring sowing in long-term trials where the plough layer had been compacted by machinery traffic soon before autumn ploughing. Mean values of determinations on 12 occasions at sites with clay or clay loam soils in the series of trials from which crop responses are shown in Fig. 30. (After Arvidsson & Håkansson, 1994)

	Depth (cm)	Aggregates <2 mm (%)			Water content (g 100 g^{-1})			
		Layer 1[a]	Layer 2	Layer 3	Layer 1[a]	Layer 2	Layer 3	Layer 4
Uncompacted	4.2	38.1	49.2	51.0	10.8	13.5	15.5	19.4
Compacted[b]	4.5	32.4	45.7	49.5	9.5	11.8	13.3	17.5
LSD[c]	n.s.	3.4	3.5	n.s.	0.8	1.0	1.1	1.0

[a] Layer 1 is the upper third of the loose, harrowed seedbed, layer 2 its middle third and layer 3 its deepest third, each of them is about 1.5 cm deep. Layer 4 is a 2 cm deep basal layer immediately below harrowing depth.

[b] 350 Mgkm ha^{-1} annually.

[c] LSD = least significant difference ($p=0.05$); n.s. = not significant.

(Arvidsson & Håkansson, 1994), they may often have been unaffected (Lal, 1996). Effects of the traffic on size distribution, density, strength and stability of the aggregates seem to be much more important, since they influence a large number of processes in the soil.

Clay soils have usually a distinct aggregate structure, but with great and important temporal and spatial variations. Coarse-textured soils, on the other hand, have a more diffuse and unstable structure and the variations are smaller and less important. It is difficult and labourious to measure the structural state of a soil. Therefore, in the trials a subjective characterization was usually the only possibility.

In clay and clay loam soils, a coarser or more massive structure was always observed in trafficked than in untrafficked plots immediately after ploughing (Fig. 17). A striking effect of this was that the seedbed quality was impaired. In most cases only simple, subjective observations of the seedbed quality could be made, but in some cases comprehensive measurements were made. They showed (Table 6) that the content of aggregates <2 mm was smaller in compacted plots than in uncompacted, and consequently the content of aggregates >2 mm was larger. Therefore, the seedbed was less protective against evaporation and the soil dried out faster. In the event of dry weather after sowing, this led to poorer crop establishment.

A general consequence of coarser soil structure is a reduced rooting depth and a less uniform root distribution and this may lead to reduced uptake of water and nutrients. Such an effect was observed by Arvidsson & Håkansson (1994). Coarser structure may also lead to impaired oxygen supply in the inner parts of the aggregates and may affect the biological activity and mineralization of plant nutrients in various ways. This may impair the availability of some plant nutrients and increase the losses of nitrogen by denitrification.

In many of the trials, perennial weeds grew much better in uncompacted plots than in compacted and competed more with the crop. At such sites, the machinery traffic led to less reduction in crop yield than it would have done had there been no perennial weeds. It is not clear whether the effects on the weeds mainly depended on direct damage to the weed plants or on impaired conditions for subsequent growth. In any case, machinery traffic appeared to be a rather efficient method for control of perennial weeds, but still not a recommendable one.

Another example of the complex and often unpredicted effects observed in these trials can be mentioned. Fig. 30B shows that compaction increased crop yield by 9% at a sandy loam site with a clay content of 11%. The yield increase was consistent and statistically significant when cereal crops were grown and unlikely to be caused by random errors. During the active experimental period no reason for this was found. However, at termination of the trial, it was found that the site was heavily infested by pathogenic nematodes and that the number of old cysts was larger in uncompacted than in compacted plots. Probably, the nematodes had been largely controlled by the experimental traffic, and therefore, caused less damage to the crops in compacted than in uncompacted plots. Then however, it was too late to prove that this actually had caused the positive effects.

5.4. Compaction effects at reduced tillage or direct drilling

Reduced tillage usually means a reduced depth of primary tillage, sometimes a reduced frequency of tillage. The extreme case is direct drilling, at which the only intentional disturbance of the soil is that caused by seed coulters in the superficial soil layer, sometimes only in narrow strips in the row zones. In systems with reduced tillage or direct drilling the total traffic intensity is usually reduced, but a considerable amount of traffic still occurs during the remaining field operations.

When traditional, relatively deep annual ploughing is replaced by a system with shallower tillage (using tine or disc implements or shallow mouldboard ploughing, but still to greater depth than the seedbed preparation) it may be assumed that the layer that is still tilled goes through an annual cycle of loosening during primary tillage and compaction during other field operations similar to that in traditional ploughing (Fig. 10). The magnitude of the changes in depth, however, may be assumed to be roughly proportional to the depth of the primary tillage irrespective of the implements used. However, no systematic studies seem to have been made on the effects of various implements and tillage depths in this respect.

Only rather few trials have been carried out concerning the need for recompaction in systems with reduced depth of primary tillage or with primary tillage by implements other than the mouldboard plough. However, it is reasonable to assume that the need for recompaction is similar irrespective of the implement used, provided that the loosened layer is equally deep. There is probably usually a need for recompaction even at reduced depth of primary tillage, provided this depth is greater than the sowing depth. These assumptions are supported by a Swedish trial where primary tillage had been carried out to different depths between 10 and 22 cm by various implements (Fig. 32). There was a significant ($p<0.01$) positive crop response to compaction during seedbed preparation, with no significant differences in response to compaction between the tillage depths.

If relatively deep ploughing is replaced by shallower primary tillage, the layer between the new, shallow tillage depth and the old and deeper one cannot remain for very long time in a state considerably looser than the optimal. Natural settling alone will cause the state of compactness of this layer to approach the optimal within a few years, and if normal machinery traffic is applied, a state of compactness over the optimal is usually obtained rather quickly. Compaction effects will be cumulative and more persistent than in annually loosened layers at the same depth. Comia et al. (1994) found a degree of compactness (*D*) of about 95 in such a layer in trials on a clay soil where reduced tillage depth had been practised during an eight-year period in previously ploughed fields. Etana et al. (1999) found similar values at three sites with clay and silt loam soils where such tillage had

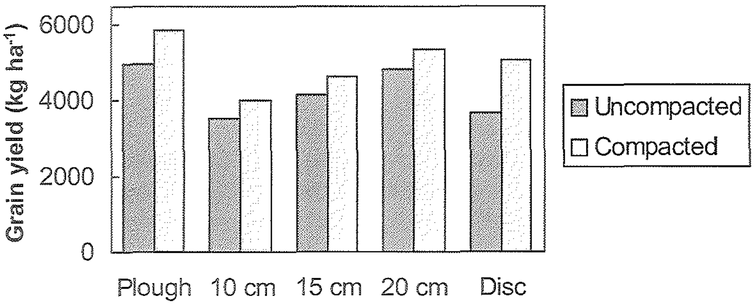


Fig. 32. Grain yield of barley in a Swedish clay loam soil with plots loosened in the previous autumn to about 22 cm depth by a mouldboard plough, to about 10, 15 or 20 cm depth by a field cultivator or to about 10 cm depth by a disc implement. During seedbed preparation in spring, half of each plot was uncompacted and the other half compacted using two passes track by track by a 4.9 Mg 4WD tractor with a tyre inflation pressure of 50 kPa. (After Arvidsson, 1997a.)

been practised for at least 15 years and at a site with sandy loam the *D*-value was over 100. However, at least until more extensive studies have been carried out, it may be assumed that the degree of compactness or other similar parameters provide less useful information on the function of soil layers that are not loosened regularly than on the function of annually loosened layers (Håkansson & Lipiec, 2000).

The degree of compactness was originally developed to characterize the state of compactness of annually disturbed soil layers and up to now it has mainly been used in such layers. Therefore, information is lacking on crop responses to the degree of compactness and on critical *D*-values in undisturbed layers. Nevertheless, it is reasonable to assume that the optimal *D*-value is the same as in annually loosened layers.

In undisturbed layers, natural processes result in a gradual improvement of shape, continuity and stability of the macropore system, particularly in clay soils. Such an improvement during the first years after reduction of the tillage depth was demonstrated for instance by Voorhees & Lindstrom (1984). This may compensate to a greater or lesser extent for the reduction in total pore volume, and is likely to gradually change the relationships between degree of compactness and crop yield. A *D*-value over the optimal will probably be less detrimental to the crops than in an annually loosened layer, which would make the response curve flatter. In the trials with reduced tillage depth on various soils where Comia et al. (1994) and Etana et al. (1999) found *D*-values of 95 or higher in the previously tilled layer, crop growth and yield were only slightly reduced.

Based on general knowledge of the properties of various soils, it may be assumed that improvements in the stability and continuity of the macropore system in layers that are no longer tilled are greater and more important in fine-textured (swelling/shrinking) soils than in coarse-textured (non-swelling) soils. Consequently, it may be expected that this compensates for a *D*-value over the optimal to a greater extent in clay soils than in sandy soils. In a clay soil, an untilled layer with a super-optimal *D*-value may still have adequate properties, whereas in a sandy soil compaction effects may accumulate without any improvement of the structure. Therefore, compaction is a more critical obstacle to reduced tillage in sandy soils than in clay soils. This is a likely reason why reduced tillage depth in Scandinavian trials has often resulted in as good or higher crop yield as traditional ploughing on clay soils but seldom on sandy soils (Box 15). A possible additional reason is that a low air-filled porosity in fine-textured soils at water contents around field capacity may restrict the achievement of very high *D*-values (≥ 98) in layers that are no longer loosened (cf. Fig. 13B), but this has not yet been shown.

The increased risk of excessive compaction of previously tilled layers at reduced tillage depth led to a hypothesis that it is more important to use machines with low ground pressure for reduced tillage than for traditional ploughing. Actually, this was the result in long-term Swedish trials where single wheels with standard tyres and dual wheels on the tractors were compared in systems with mouldboard ploughing and reduced tillage (Rydberg, 1992; Arvidsson et al., 1992). In these trials, dual wheels did not result in higher crop yields than single wheels in ploughed plots, whereas they increased the yield by 2-3% in plots with shallow tillage (Table 7). On the other hand, due to various processes, such as age hardening and reorientation of macropores, long-term reduced tillage depth causes a gradually increased strength of the soil in the layer that is no longer periodically disturbed. This counteracts an increased densification of the soil in this layer and possibly even in layers underneath (Wiermann et al., 2000).

Table 7. Relative crop yield in two long-term field trials on sandy loam soils in Sweden, where primary tillage was carried out in the autumn either by mouldboard ploughing to about 25 cm depth or by stubble cultivation to about 12 cm depth. (From Arvidsson et al., 1992.) The tractors used for all field operations throughout the experimental period were equipped either with single-mounted standard wheels or with dual wheels to achieve a reduced ground pressure. Mean results of two trials with a total of 28 harvest-years (annual ploughing, single standard wheels = 100)

Frequency of mouldboard ploughing	Single wheels	Dual wheels
Annually	100	99
One year out of five	93	95
Never	92	94

In Section 5.3 it was shown that residual effects of compaction in annually loosened soil layers persist for a longer time in fine-textured soils than in coarse-textured. In soil layers that are not loosened periodically, such as in the deeper part of the topsoil at reduced tillage depth or at direct drilling, as well as in the subsoil, the converse seems to be true. Therefore, in coarse-textured soils, abandonment of traditional ploughing is problematic, and if it is still done, it is particularly important to use running gear with low ground pressure on all machines. However, the differences between soils in this respect have not been sufficiently studied.

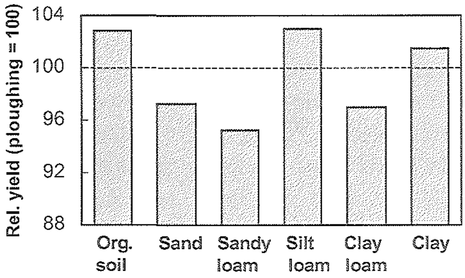
When direct drilling is used, nearly the whole previous plough layer may be excessively compacted. Often, only a very shallw layer is loosened by natural processes and by the coulters of the seed drill. Consequently, in many soils, particularly in coarse-textured soils, compaction is the major obstacle to direct drilling. Increased density of the previous plough layer in soils with direct drilling has been shown in many investigations. For instance, in three Danish soils with clay contents between 5 and 19%, the 4-18 cm layer was more dense and showed a reduced pore continuity during the growing season after 4-6 years of direct drilling than in ploughed control plots (Schønning & Rasmussen, 2000). However, at depths >24 cm there were tendencies for the opposite to occur. On a clay loam soil in Argentina, Botta et al. (2004) applied traffic by a 4 Mg tractor at intensities of 60-180 Mgkm ha^{-1} in a field where direct drilling had been practised for seven years in a wheat-soya bean double-cropping rotation. This caused compaction all the way to 60 cm depth and a yield decrease in next soya bean crop that increased with traffic intensity from 10 to 39%.

Box 15

Effects of reduced tillage in various soils in Northern Europe

Traditional tillage systems in Northern Europe include annual mouldboard ploughing, usually to a depth of 20-25 cm, and relatively intensive but shallow seedbed preparation. However, for soil conservation reasons or for cost reduction, many farmers have adopted various reduced tillage methods during recent decades. They may have reduced the ploughing depth occasionally or continuously, replaced mouldboard ploughing by shallower tillage with other implements or reduced the intensity of seedbed preparation. The most radical method, direct drilling, is only seldom used.

The most common reduced tillage system in Scandinavia at present is one in which mouldboard ploughing is replaced by cultivation with a field cultivator or chisel plough to about half the normal ploughing depth. Compared to traditional ploughing, this system has often resulted in similar or even higher crop yields in field trials on clay soils, but seldom on sandy soils. The mean results of Swedish field trials carried out on various soils over many years are shown in the figure below. A major reason for the difference in response between sandy and clay soils seems to be the development of the macro-structure in the soil layer between the previous tillage depth and the new and shallower tillage depth. In a clay soil, a system of stable and continuous macropores develops gradually in this layer and provides pathways for roots to the subsoil, even though the layer itself may become intensively compacted. In a sandy soil, on the other hand, compaction accumulates in this layer without the development of continuous macropores, and this may seriously hamper root growth. The positive results of reduced tillage in silt loam soils seems to have another reason. In these soils, hardening of the surface layer is a great problem, and this problem is reduced by the accumulation of crop residues and organic material at or near the soil surface.



Results of Swedish field trials where mouldboard ploughing to 20-25 cm depth was replaced by tillage with field cultivator to about half that depth. The figure shows mean relative crop yields in a comprehensive series of trials in soils of various textures (traditional ploughing = 100). (After Rydberg, 1992.)

5.5. Subsoil compaction

A series of 24 long-term field trials with subsoil compaction caused by heavy vehicles was carried out in an international cooperation in seven countries in northern Europe and North America (Håkansson, 1994). In this region, the soils usually freeze to relatively great depth each winter. Similar experimental traffic treatments were applied in all trials at a field capacity soil water content and on one occasion only. The treatments were 0, 1 and 4 passes track by track by vehicles with loads of 10 Mg on single axles or 16 Mg on tandem axle units (Fig. 33). Tyre inflation pressure was 250-300 kPa. After the experimental traffic, all plots in each individual trial were treated uniformly using vehicles with axle loads <5 Mg. Annual ploughing to a depth

Fig. 33. A series of 24 long-term trials with subsoil compaction was established around 1980 in several countries in northern Europe and North America. Experimental traffic was applied by vehicles with loads of 10 Mg on single axles or 16 Mg on tandem axle units. At many of the sites, a dump truck like that in this photo, with a load of 10 Mg on the front axle and 16 Mg on the rear tandem axle unit and a tyre inflation pressure of 250-300 kPa, was used for the traffic application. The traffic usually resulted in significant and very persistent compaction effects to about 50 cm depth (Table 2).

of 20-25 cm was performed in order to alleviate the compaction effects in the plough layer as quickly as possible. The same crops as in the surrounding farm fields were usually grown, mainly various small grains. In most trials, the experimental traffic caused significant compaction effects to a depth of about 50 cm (Section 3.3; Table 2) and repeated measurements in some of the trials showed that the effects in the subsoil persisted nearly unaltered after more than ten years (Etana & Håkansson, 1994; Alakukku & Ahokas, 1999).

Fig. 34 shows the mean crop response in the whole series of trials in plots with four passes track by track by the vehicles. During the first two years, crop yields were substantially reduced, presumably mainly because of compaction effects in the plough layer. It may be assumed, however, that most of the compaction effects in this layer disappeared within a three-year period (cf. Section 5.3), and that crop responses after that time may be regarded to be solely due to subsoil compaction. The mean yield reduction in year 4 and thereafter was 2.5%, with about the same reduction in fine-textured and coarse-textured soils. There was no indication of a decrease in response after the fourth year. Two trials in Finland (Alakukku, 2000) were still active after 17 years and the effects showed no tendency to diminish. Furthermore, in relative values, nitrogen yield in the grain harvested in the Finnish trials was reduced about twice as much as the grain yield.

In some of the American trials in the international series, traffic was applied with

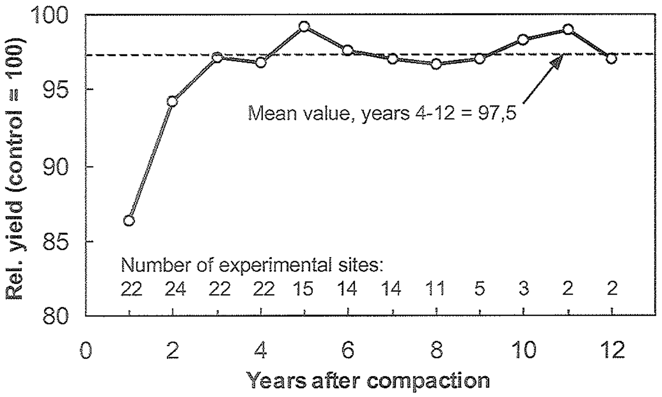


Fig. 34. Mean relative crop yield (untrafficked control plots = 100) in a series of 24 trials in 7 countries in northern Europe and North America. Traffic by vehicles with an axle load of 10 Mg (Fig. 33) was applied when the experiments were started and was not repeated. The crop response shown applies to plots where the entire plot area was covered by tracks of the vehicles four times (traffic intensity about 1200 Mgkm ha^{-1}). (After Håkansson & Reeder, 1994.)

axle loads of both 10 Mg and 18-20 Mg. The higher axle load caused compaction to greater depth than the lower load and crop responses were more negative (Lindstrom & Voorhees, 1994).

In addition to the trials mentioned above, other trials showing the effects of traffic by heavy vehicles have also been carried out, some of them in the same climatic zone. On a clay soil in Ohio, USA, a total of three passes under wet conditions by vehicles with axle loads of 10 and 20 Mg caused residual effects during four subsequent years on maize and soya bean yields similar to those shown in Fig. 34 (Lal, 1996). In Sweden, six trials with axle loads up to 20 Mg were initiated more recently, most of them on glacial till soils with a sandy loam texture (Arvidsson, 2001). In spite of clear compaction effects in the subsoil (Table 3), crop responses were negligible.

In other climatic zones, the incidence of subsoil compaction and its long-term effects on crop growth are less well known than in northern parts of Europe and North America. The effects may well be quite different from those in the latter region. Furthermore the effects may differ between irrigated and rain-fed crops. In irrigated cotton in Spain, Coelho et al. (2000) reported a decrease in seed cotton yield of 28% in the first year and 10% in the second year after intensive compaction of the 15-30 cm soil layer, even though some fine roots could penetrate the compacted layer and develop to great depth in the layers below. In a sandy loam soil in Pakistan, where the layer below 15 cm depth was intensively compacted (the 0-15 cm layer was uncompacted) yields of four crops in two subsequent years were between 38 and 8% lower than in the control plots (Ishaq et al., 2001a, b). In the first year, the root length density of wheat was significantly reduced in the compacted layer. In most cases, concentrations of plant nutrients in the harvested products were similar in both treatments, and consequently the total uptake of nutrients was reduced to about the same relative extent as the crop yield.

In the international series of trials with an axle load of 10 Mg, not only the crop response from year 4 onwards (-2.5%, Fig. 34) but also the increase in penetration resistance at 40 cm depth as measured in some of the trials (17%, Table 2) were nearly constant throughout the experimental period. Four passes by heavy vehicles caused about four times as great effects on both penetration resistance and crop yield as one pass (Håkansson & Reeder, 1994). Thus, the crop response increased proportionally to the increase in penetration resistance.

A reasonable interpretation of the experimental results is that impaired root growth was usually the most important reason for the crop yield reductions. Due to increased mechanical resistance, the root growth rate and the maximum depth reached by the root system during the growing season was probably usually reduced. This in turn reduced the quantity of soil water accessible to the plants and the water uptake during dry periods (Box 16). Such an effect was demonstrated by measurements of the cumulative reduction in water content during the growing season in various soil layers in trafficked and untrafficked plots in one of the trials (Voorhees et al., 1986; Håkansson & Voorhees, 1998; Fig. 35). In the 15-30 cm layer, there were no significant differences in water content between the treatments, since ploughing and natural factors had alleviated the compaction effects in that layer. However, the traffic had caused a significant increase in bulk density in the 30-60 cm layer (Voorhees et al., 1986). This resulted in fewer roots in the 60-90 cm layer and less water uptake from that layer. Similarly, Radford et al. (2001) showed that the depth of soil water extraction by a maize crop in a clay soil in Australia was reduced after traffic by a heavy vehicle. However, reduced water uptake is not the only reason for the negative crop response. The investigations by Alakukku (2000) show that the uptake of plant nutrients can also be hampered.

The mean crop response shown in Fig. 34 (-2.5%) was considerably smaller than the standard error in most individual location-years. Therefore, only the mean crop response in the whole series of trials was reasonably well established (Håkansson, 2000). It would have been very desirable to identify specific soils or conditions that result in greater or smaller effects than the average, but this would have required trials at a much larger number of sites. The group of sites was reasonably representative for the region as a whole (northern parts of Europe and North America), and therefore the mean results can be regarded as normal for the conditions in the region. It is possible that some of the trials in the group were carried out at sites where the traffic caused very little subsoil compaction or where subsoil compaction was harmless or even positive. However, the results at least indicate that positive effects of subsoil compaction similar to those obtained when a loosened plough layer is moderately recompacted are uncommon.

It is generally thought that problems with subsoil compaction do not exist in parts of the world with a drier climate, but the results presented by Trautner (2003) (cf. Section 3.3) as well as the results of trials in drier areas cited above indicate that this is not necessarily the case. Furthermore, it may be argued that subsoil compaction can be alleviated by subsoil loosening. However, many investigations show that deep loosening cannot completely alleviate the effects of machinery induced subsoil compaction in fields with normal machinery traffic (Box 7). In such fields, subsequent traffic often quickly re-compacts the loosened layer.

5.6. Effects of machinery traffic in established crops

Machinery traffic is sometimes applied in established crops, and this may result in direct damage to plants that is sometimes more detrimental than the compaction of the soil. Such traffic occurs for instance at post-emergence fertilizing, spraying or mechanical weeding of annual crops and at harvest of perennial crops. The extent of the direct damage depends on many factors,

Box 16

Water requirement and water uptake by crops

Water is a prerequisite for plant growth. In conditions of water shortage, the stomata on the leaves close, and this leads very quickly to shortage of carbon dioxide for photosynthesis. When stomata are open, water transpires and must be replaced by water taken up by the roots. The water requirement depends on the weather. When a crop is in its vegetative phase, is well supplied with water so that the stomata are continuously open and has a canopy that covers the soil surface (leaf area index >2), the water loss is of the same magnitude as the potential evaporation, i.e. the evaporation from a free water surface. Then there are only minor differences between crops. However, there are large differences between crops in the length of the period when these conditions occur, and consequently in total water requirement. For instance, it takes a longer time for sugar beet than for small grains to develop the canopy. On the other hand, sugar beet remains in the vegetative phase until harvesting time in late autumn, whereas cereals quite early enter the ripening phase, with a gradually decreasing water requirement.

In the temperate climate in northern Europe, the mean potential evaporation is 3-3.5 mm per day in spring and summer, and in hot and windy periods it may be twice as high. Consequently, in late spring and summer, the water consumption of a fully developed crop in the vegetative phase and well supplied with water is usually of this magnitude. This implies a mean water requirement of about 100 mm per month, although in late summer and autumn it is usually less. In dry and warm climatic zones, the potential evaporation and the water requirement of a crop may be more than three times as high.

Shortage of water leads to closing of the stomata. This reduces water loss and production of biomass in about the same proportions. Consequently, crop growth and yield are often proportional to the portion of the potential water requirement that can be supplied by rainfall or water uptake from the soil. In northern Europe, rainfall in May through July is usually considerably less than the water requirement of the crops. For full production, the deficit must be covered by uptake from the soil. Soils are usually fully water saturated in early spring, and in many soils the content of plant available water is then about 1.5 mm per cm soil depth or 150 mm to a depth of 1 m. In the event of dry weather immediately after crop establishment, the root zone of rainfed crops in such soils must be deepened by a rate of 2 cm per day to meet a water demand of 3 mm per day. In a climate with a higher demand, the root zone must be deepened still quicker. Accordingly, the most productive soils are those where roots can grow without limitations to a depth of 1 m or more. This is possible only in soils with a low penetration resistance or a continuous macropore system to great depth (Box 9). Otherwise, growth rate of roots or total possible rooting depth may reduce yields by making crops susceptible to drought. This may be aggravated by soil compaction. The amount of water accessible to the plants can be 200 mm or more in some soils, but in some coarse-textured soils, rooting depth is virtually limited to the topsoil (Box 9) and the amount of water accessible to the plants is as low as 30 mm. In the latter soils, crops often suffer from drought unless they are frequently irrigated.

such as the type of crop and its configuration and stage of development, the wheel track area, the positioning of the tracks relative to crop rows, the ground pressure and tread pattern of the tyres and the soil moisture conditions. Traffic in row zones

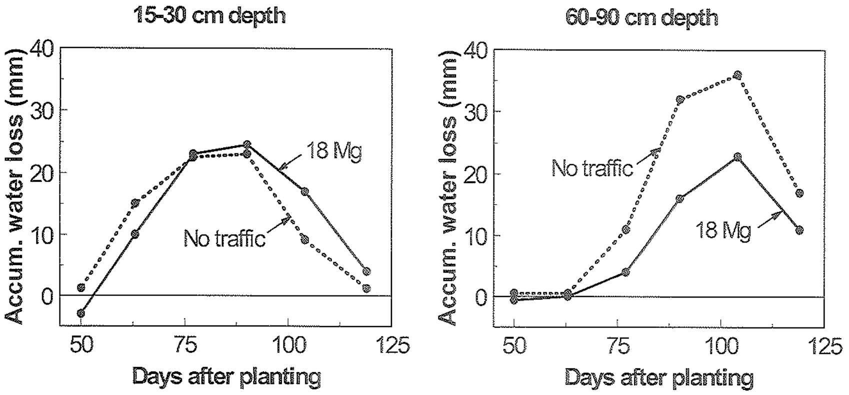


Fig. 35. Cumulative soil water loss in the 15-30 and 60-90 cm layers due to water uptake by a maize crop in a field trial on a clay loam soil in Minnesota, U.S.A. Results are shown for control plots without experimental traffic and for plots where four passes by a vehicle with an axle load of 18 Mg were applied in the previous year. (After Håkansson & Voorhees, 1998.)

causes more damage than traffic in inter-row zones, and wheel slip may increase the damage dramatically. On the other hand, in a perennial crop with a well-developed root system, soil compaction can be reduced to some extent by the reinforcement of the soil by roots. The latter of course particularly applies to sites with trees or shrubs, such as orchards, vineyards and forests (Cofie et al., 2000). In forestry, young trees may be broken (Wästerlund, 1988) and damage to tree roots may enable the entry of fungal diseases that spread to the trunk and impair the wood quality (Björkhem et al., 1974).

Leys or grassland for forage production (silage or hay) are major perennial crops in which machinery traffic is frequently repeated at harvest or other operations. This traffic is often applied in a random pattern directly onto the plants. Many field trials have been carried out to study the response of lucerne, clover and grass crops to such traffic. The situation may be similar in some other perennial crops, such as sugar cane. However, the latter crop is grown with a large row spacing, and it may be feasible to align most of the harvest traffic to inter-row zones. Traffic over or near the rows of sugar cane damages the stools, delays and impairs regrowth and reduces the number of ratoons (Braunack, 1995). However, the discussion below is limited to ley crops.

5.6.1. Traffic in ley crops

In a review of effects of machinery traffic in ley, Douglas (1994) showed that crop responses are often very negative, and yield losses of more than 20% are common. However, the effects are very complex and vary considerably depending on a large number of factors, such as age of the ley, plant species and development, number of cuts per year, traffic intensity, track distribution, wheel load, tyre dimensions, tread pattern, ground pressure and soil type. Soil moisture situation and wheel slip are factors of special importance.

When all influential factors are favourable, the traffic effects may not be dramatic. Table 8 shows mean effects in a series of 24 Swedish trials in clover/grass ley carried out in the period 1969-1978 on a wide range of soils varying from sand to clay loam (Håkansson et al., 1990). In these trials, experimental traffic was applied by light tractors and trailers (total weight about 8 Mg) soon after each harvest. In most trials, there were two or three cuts per year. Data in Table 8 include the yield at the first cut of the first-year ley, although there was no experimental traffic before this cut. Most of the experimental years were unusually dry, and on 61 out of 108 traffic occasions the soil was subjectively classified as drier or much drier than normal. Depth of the wheel tracks, wheel slip and visible damage to plants were then classified as very small. On 30 occasions, the soil had a 'normal' water content (which here means a water content somewhat below field capacity) and rut depth, wheel slip and plant damage were small. On 10 occasions, the soil was classified as slightly wetter than normal. Only on 7 occasions was the soil wet, the wheel slip large and the damage to plants classified as substantial or severe. Therefore, mean yield reductions in the whole series of trials were smaller than they would have been in wetter years. This conclusion was drawn since the reduction in dry matter yield at the succeeding cut was several times greater than the average (up to 50% yield reduction) when the traffic was applied under wet conditions and the wheel slip was large.

Crop responses and observations in these trials indicated that damage to the basal parts of the plants was a more detrimental effect of the traffic than soil compaction. The same conclusion was drawn from two trials in clover/grass or grass in Denmark (Rasmussen & Møller, 1981). Haass & Märtin (1975) applied traffic both over the rows and in inter-rows of a lucerne crop and found a considerably larger yield reduction in the former case. Håkansson (1976b) studied the response of a red clover/grass ley to the degree of compactness (*D*) of the plough layer produced by various intensities of pre-plant traffic. He found no indication of a difference in optimal *D*-value between this crop and barley but, as discussed in Section 5.2, it is likely that the ley crop has a flatter response curve because of its longer growing period. All these studies indicate that direct damage to plants is the most detrimental effect of machinery traffic in a ley crop, and crop responses in many trials are also far too large to be caused by soil compaction.

In the trials presented in Table 8, it was observed that a major consequence of the damage to plants when the traffic was applied under dry or normal conditions was a delay in regrowth. Therefore, the shorter the time to the next cut, i.e. the greater the number of cuts per year, the greater the relative yield decrease tended to be. Under such conditions, the yield decrease was mainly limited to the immediately succeeding cut, with only small cumulative effects. There was also a tendency for the effects to be alleviated over winter. Even in trials in clover or grass in Scotland (Frame, 1987) and Denmark (Rasmussen & Møller, (1981) and in irrigated lucerne in California, USA (Meek et al., 1988), there were no obvious cumulative effects when machinery traffic was repeated at each cut. However, in the trials in Table 8, when the damage to plants was severe (because of wet conditions) or when the crop was also stressed in some other way (e.g. by a harsh winter), the effects were more persistent and to some extent cumulative. Therefore, it is important to apply the traffic as gently as possible in leys, especially in cold and wet areas.

The moisture situation at the soil surface at time of traffic is a very important factor, since higher water content leads to increased damage to plants. However, wet conditions also lead to more intensive soil compaction and poor soil aeration during wet periods, and it is difficult to separate these two effects. In any case, investigations in different countries demonstrate a general trend of greater yield reductions the wetter the climate. In Ireland, zero traffic and low-ground-pressure traffic was compared with conventional traffic for harvest of grass crops at two sites with mean annual rainfall of 1341 mm and 763 mm (Fortune, 1999). Zero traffic led to up to 36% higher dry matter yield than conventional traffic at the former site but only 10% at the

Table 8. Mean decrease in dry matter yield (%) in 24 field trials in red clover/grass ley, carried out in 1969-1978 on a wide range of soils all over Sweden. (After Håkansson et al., 1990.) Traffic was applied soon after each cut by a rather light vehicle[a]. Normal traffic intensity means one pass by the vehicle per metre plot width, double intensity means two passes per metre plot width

		Traffic intensity after each cut	
Age of the ley	Number of trials	Normal[b]	Double[c]
First year	23	4	6
Second year	24	4	5
Third year	15	7	10
Fourth year	2	15	21

[a]Usually a 3 Mg tractor with inflation pressures about 180 kPa (front) and 120 kPa (rear) pulling a 5 Mg trailer with an inflation pressure about 250 kPa was used.
[b]About 80 Mgkm ha^{-1}.
[c]About 160 Mgkm ha^{-1}.

latter site. Low-ground-pressure traffic increased the yield to a lesser extent. In western Scotland, various traffic intensities caused a mean loss of dry matter yield of 17% compared to zero traffic (Frame, 1987). In eastern Scotland, conventional traffic caused 14% lower yield and low-pressure traffic 1% lower yield than zero traffic, and with lower nitrogen content (Douglas et al., 1992). In Norway, Myhr (1986) reported up to 14% yield losses caused by 'normal' intensity of traffic by light tractors, with a tendency to greater losses in northern Norway than in southern, in spite of fewer cuts per year in the former region. In Denmark, Rasmussen & Møller (1981) reported that 1-3 passes over entire plots by tractors and trailers with ground pressures between 70 and 220 kPa caused yield reductions between 21-57%. On a silty clay loam soil in Argentina, Jorajuria et al. (1997) studied the response of an Italian ryegrass/white clover crop to 1, 5 and 10 passes by tractors of different weights under wet conditions. In the wheel tracks, dry matter yield at the succeeding cut was reduced by 63-95% and for the entire plot area the yield was reduced by 18% on average for all treatments.

In the trials shown in Table 8, 'double' traffic intensity caused about 50% greater yield losses than 'normal' intensity. In the trials in Denmark by Rasmussen & Møller (1981), the effects of repeated traffic were slightly greater than that, whereas in the trial in Scotland by Frame (1987), they were slightly less. In the trials in Argentina (Jorajuria et al., 1997), even one pass by a light tractor was enough to severely damage the plants in the wheel tracks, and a heavier tractor or multiple passes could only cause a minor additional effect. However, measurements in the soil showed that both the heavier tractor and multiple passes caused more intensive and deeper soil compaction, and therefore potentially more persistent effects. These results indicate that in ley crops the traffic should normally be concentrated as much as possible to the same tracks.

The wheel equipment of the vehicles is a factor of great importance for the magnitude of the effects. However, observations in ley fields indicate that the most favourable types of tyres (dimensions, ground pressure, tread pattern, etc.) may depend on the conditions and differ between driven and free-rolling wheels. Under dry conditions, a small ground contact area is probably the best, under wet conditions a low ground pressure. However, the most important measure in all situations is to minimize the wheel slip. For instance, Armbruster (1989) showed that the yield reduction in tracks of tractor tyres increased nearly proportionally to the wheel slip. For tractor tyres with normal lug height, the yield reduction in the tracks at the succeeding cut was 47% when the wheel slip was 47%. For tyres with reduced lug height, the reduction was considerably less, since the damage to plants was then limited to a thinner layer. At a certain degree of wheel slip, special grassland tyres or low-pressure tyres also caused less yield reduction in the tracks. However, on a field scale, the relative track area and the wheel slip must also be considered, and both these factors may differ considerably between various tyres. To be able to quantify the effects of various wheel equipment under various conditions, local studies seem to be required.

The Swedish studies presented in Table 8 indicated that the yield loss at the succeeding cut was usually closely related to the damage to plants that could be observed by the naked eye. From a practical point of view, this means that traffic pattern, wheel equipment, etc. should always be adjusted to the prevailing conditions in such a way that visible damage to plants is minimized. An analogy can be drawn with results of Swedish trials with mechanical control of couch grass (*Elymus repens* L. Gould), a severe perennial weed in Scandinavia. In these trials, the control effects were closely related to the visible damage to the weed plants caused by the implements.

Machinery traffic may not only reduce the dry matter yield of ley crops, but sometimes also influence the botanical composition and the quality of the harvested product. However, traffic effects on the quality of the harvested product are probably very variable depending on local conditions. In trials in Scotland (Frame, 1987), the traffic caused some reduction in percentage of clover and a greater loss of crude protein than of dry matter. In some of the Swedish trials cited above, the percentage of clover was reduced to some extent, but the mean effect in the whole series of trials was rather small. The damage to plants caused by machinery traffic often delays the regrowth of the crop in track areas relative to inter-track areas. This increases the variability in stage of development of the crop within the field and may affect the quality of the harvested product.

Chapter 6

Ecological and environmental effects of compaction

Summary

As discussed in previous chapters, compaction affects virtually all soil properties and processes, and therefore, it may have substantial ecological and environmental consequences, most often of a negative character. Compaction reduces the saturated and near-saturated hydraulic conductivity, which often leads to reduced water infiltration and increased surface runoff and soil erosion. It decreases rooting depth and root density of crops, and this impairs the utilization of water and plant nutrients and increases the need for fertilizer and the risk of nutrient leaching. It has often been reported to negatively affect soil fauna, for instance to reduce the number of earthworms. Compaction also affects the rate of decomposition of organic material, mineralization of plant nutrients and emission of greenhouse gases. Since it reduces soil aeration, it increases the loss of nitrogen by denitrification. It may enhance some diseases on plant roots and strongly impair nitrogen fixation in leguminous crops. However, the biological or environmental consequences of compaction have not been studied sufficiently extensively to make it possible to quantify the effects in specific locations or larger regions. Only some examples of various effects can now be shown. Extended investigations on such effects should be strongly encouraged.

6.1. All soil properties and processes are affected

As indicated in previous chapters, compaction affects virtually all soil properties and processes. Therefore, in addition to its effects on crop growth and yield and on energy requirement for tillage, it influences the magnitude of various ecological and environmental effects of crop production. These effects are very variable, but they seem to be mainly negative and often substantial. Unfortunately, none of them have been sufficiently studied to make it possible to quantify them in specific locations or larger regions. Therefore, only some examples of reported or possible ecological and environmental consequences of soil compaction can be shown in this chapter. Since the choice of soil management methods and machinery largely determines the extent of soil compaction, this choice is likely to also largely influence the environmental impact of crop production. Therefore, extended studies of the effects of soil compaction in this respect should be strongly encouraged.

6.2. Water economy, surface runoff and soil erosion

One of the most obvious effects of soil compaction is a drastic decrease in saturated and near-saturated hydraulic conductivity (Table 3). This may greatly limit water infiltration during rain or snow-melt (Fig. 19). Therefore, surface runoff may increase substantially and, as a consequence, the amount of water that infiltrates and can be utilized by the crop may be correspondingly reduced. This has the most serious consequences in semi-arid regions with few and heavy rains, but it may be of importance also in humid regions with less less intensive rains, especially in soils with low infiltration rate or on sloping land.

Compaction may also influence the

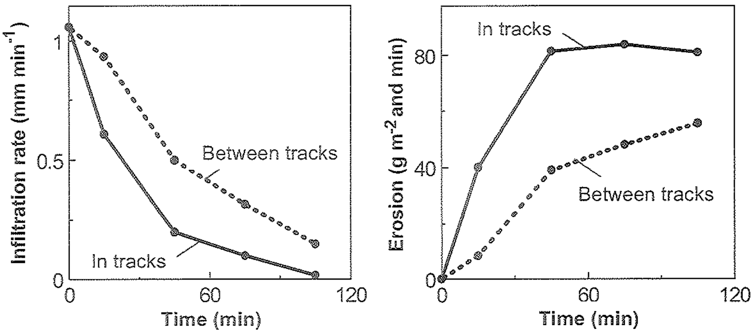


Fig. 36. Water infiltration and soil erosion measured in and between wheel tracks applied by a tractor in a loam soil in Minnesota, U.S.A. Water was applied for two hours by a rain simulator at a rate of 63 mm per hour. (After Young & Voorhees, 1982.)

water economy of the crop in other ways. It often reduces the rooting depth and root density and reduces uptake of water from deeper soil layers during dry periods (Fig. 35). This not only reduces crop yields, but also the amount of water required to resaturate the soil. Therefore, it leads to more drainage and/or surface runoff, and possibly to extended periods with supersaturated soils.

Increased surface runoff means increased risk of soil erosion. Therefore, compaction may considerably intensify this grave soil degradation process - the most serious threat to sustainable food production in large parts of the world. Increased surface runoff and water erosion also enhances the transport of phosphorus and various other substances to aquatic systems.

Increased erosion in compacted soil has been demonstrated in several investigations, but further studies are required to make it possible to quantify the effects under various conditions. Such studies would be of great value, particularly in parts of the world with severe erosion problems. Fig. 36 shows an example from the U.S.A. In this study, water infiltration was much smaller and soil erosion during simulated intensive rainfall much greater in wheel tracks of a tractor than between the wheel tracks. Rousseva & Lozanova (2000) studied the erosion in a silty clay loam soil in Bulgaria that had been either ploughed to 30 cm or tilled to 10-15 cm depth for several years. In ploughed plots, soil bulk density in the 10-30 cm layer was much lower than in shallow tilled plots, 50% more rain was required before erosion started, and a simulated rainfall of 150 mm caused only about 1/3 as great erosion. Basher & Ross (2001) reported low infiltration rates in wheel tracks on a clay loam soil in New Zealand. Loosening of the wheel tracks drastically increased the infiltration rate and reduced erosion by 95%.

An example of spectacular effects of compaction on soil erosion in practice originates from an experimental field on sloping land in Ethiopia (Dr. Janne Eriksson, pers. comm., 1970). Shallow seedbed preparation by tractor-drawn implements had produced a loose, fine-structured seedbed to a depth of a few cm, whereas the basal layer was compacted by the tractor wheels. Intensive rain after sowing washed away the whole seedbed including seed and fertilizer from most of the field area, whereas erosion was small in surrounding farm fields tilled by ox-drawn implements.

Nevertheless, soil compaction is not negative from a soil erosion point of view under all circumstances. Replacement of standard tyres of tractors by wide low-pressure tyres, which confers an advantage in many respects, is not necessarily so from a soil erosion point of view. Wider tyres lead to an increase in the track area, and depending on track pattern, traffic intensity and local soil and rainfall conditions, this sometimes leads to increased overall runoff and erosion (Bazzoffi et al., 1998). Furthermore, a compacted soil may sometimes be less erodible than a non-compacted one, both with respect to water and wind erosion. As discussed by Voorhees et al. (1979) a reason is that compaction often results in a greater percentage of coarse aggregates at the soil surface and a greater strength of these aggregates, and this may help to reduce both water and wind erosion. On the other hand, when machinery traffic is applied on a soil with coarse and dry aggregates on the surface, the wheels may crush the aggregates, thus making the structure finer and the soil more erodible.

6.3. Efficiency in the use of various commodities in crop production

A rapidly established and uniform crop that quickly develops a large leaf area and a sufficiently deep and dense root system is a prerequisite for efficient exploitation of solar energy and water. This is also required for an efficient utilization of various commodities used in crop production, such as fertilizers, herbicides and tractor fuel. A crop can only develop in this way when both aggregate structure and state of compactness of the soil are adequate with respect to the requirements at the site. Therefore, it is essential to strive for as good soil conditions as possible in these respects. Only then can the need for commodities per unit product and the release of pollutants to the environment be minimized, both per unit product and per unit area of arable land.

A soil compaction effect of great importance is that it increases both the need to loosen the soil by tillage and the draught requirement of the tillage operations. As discussed in Chapter 8.4, this increases both the fuel consumption and the release of CO_2 and other exhaust gases to the atmosphere.

6.4. Leaching of plant nutrients

Many investigations have shown that intensive compaction impairs root growth and function. Therefore, the uptake of plant nutrients is reduced (e.g. Lipiec & Stępniewski, 1993; Grath, 1996; Arvidsson, 1997a; Alakukku, 2000; Nevens & Reheul, 2003). This not only reduces crop yields at unaltered fertilization rate or increases the need for fertilizer, it also leads to a larger quantity of nutrients being left in the soil at the end of the growing season and thereby exposed to leaching. In addition, less water is often taken up by the crop (Fig. 35), and therefore the quantity of drainage water and/or surface water may be increased. For this reason too, more nutrients, particularly nitrogen, may be washed out to aquatic systems.

In a long-term lysimeter experiment in Germany (Table 9), the total amount of drainage water during a ten-year period was about 25% greater in a compacted soil than in a soil with optimal (relatively low) density, and the total leaching of nitrogen was 50% greater (469 vs. 311 kg ha^{-1}). Similarly, Torbert & Reeves (1995) found higher concentrations of NO_3-N in the soil solution at 90 cm depth in field plots with normal machinery traffic than in plots without such traffic, indicating a likely increase in subsequent nitrogen leaching. In some situations, preferential flow of water can be enhanced by compaction of the upper soil layers (Kulli et al., 2003), and this may increase the risk of nutrient leaching. However, as mentioned earlier (Fig. 29), the uptake of plant nutrients can also be impaired in a too loose soil, particularly under dry conditions. Furthermore, Nevens & Reheul (2003) showed that compaction reduced the rate of nitrogen mineralization in the growing season after massive appli-

Table 9. Water and nitrogen balance in the soil during a ten-year period in a lysimeter experiment in a sandy soil in Germany with different compaction treatments (After Petelkau et al., 1988)

State of compactness	Water balance (mm)				Nitrogen balance (kg ha^{-1})			Total dry matter yield (Mg ha^{-1})
	Precipitation	Water content	Drainage	Evapotranspiration	Fertilization	Uptake by the crops	Leaching	
Optimal	5427	+155	1390	3882	1690	1452	311	88
Compacted	5427	+135	1734	3558	1690	1254	469	75

cation of farmyard manure. Consequently, soil compaction may influence the leaching of plant nutrients differently depending on its effects on a large number of processes, including uptake and movement of water and nutrients, mineralization and denitrification (Section 6.5.3).

Fig. 37 shows three possible ways to improve the utilization of fertilizers applied to crops, when high-pressure tyres on tractors and machines used for seedbed preparation and sowing are replaced by low-pressure tyres. At the same time, other commodities are also more efficiently utilized. The figure applies to spring-sown crops in a humid region with a short growing season like that in Scandinavia, but similar effects may also be obtained under other conditions. All possibilities indicated have the potential to increase crop growth and uptake of plant nutrients and consequently to reduce the amount of nutrients remaining in the soil at harvest. If sowing time is unaltered, soil structure is improved and root development and nutrient uptake is favoured. Alternatively, sowing can be carried out earlier (in wetter soil) without increasing the risk of excessive compaction. This makes it possible to grow crops with a longer growing season and greater uptake of nutrients, to establish more autumn-sown crops or autumn cover crops (catch crops), or to practise double-cropping. In any of these cases, smaller quantities of plant nutrients are left in the soil in the autumn and exposed to leaching in the subsequent winter.

6.5. Biological activity in soils

It may be claimed that compaction affects the conditions for life for nearly all soil organisms to a smaller or greater extent. Hence, nearly all biological processes in soils, as well as the composition and diversity in soil flora and fauna, may be influenced. Individual effects are still poorly known, but they are presumably very varying and complex. When reviewing studies of biological effects of soil compaction, Whalley et al. (1995) concluded that "the scenario was so complex that we were only able to give a few examples". In spite of many studies during recent years, the situation is still the same.

6.5.1. Soil fauna

Earthworms are the group of soil animals most intensively studied with respect to the response to soil compaction. Reviews by Brussard & van Faassen (1994) and Whalley et al. (1995) show that this response is often very negative. An example from a long-term compaction trial on a heavy clay soil (Table 10) shows a much lower number of earthworms in plots with normal tractor traffic than in untrafficked plots. Machinery traffic can probably affect the earthworms in various ways. The

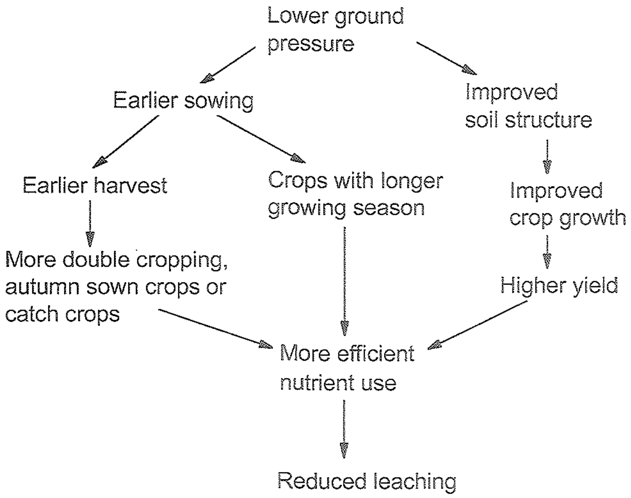


Fig. 37. Various ways to improve the utilization of plant nutrients and to reduce nutrient leaching by using low-pressure tyres instead of high-pressure tyres on tractors and other machines during seedbed preparation and sowing in spring in a region where the growing season is short and soils are fully water saturated after winter.

wheels induce stresses and shear actions that may injure individuals dwelling near the soil surface, partly destroy the burrow system and possibly even entrap some individuals. To restore a destroyed burrow system takes time and energy and may be impossible in intensively compacted soils (Kemper et al., 1988). When forming new burrows in compacted soil the earthworms may have to eat their way through the soil rather than pushing the soil aside (Joschko et al., 1989). Compaction also increases the risk of anaerobic conditions in the soil adverse to the earthworms.

Other fauna groups are also affected by compaction. Röhrig et al. (1998) studied the effects of vehicular traffic in spring on *Enchytraeidae* in soils with conventional and conservation tillage. They found a reduced abundance after traffic in both tillage systems, and one year afterwards no regeneration of the populations was found. Larsen et al. (2004) studied the abundance of some *Collembola* species in a sandy loam soil with various bulk densities under laboratory conditions. Within the bulk density range typical for the experimental soil under field conditions, they found that increased density reduced the abundance. They concluded that for this group of animals, which are not able to make their own burrows, the effect of soil compaction is most likely due to a decrease in habitable pore space.
Compaction effects on *nematodes* may be great (Brussard & van Faassen, 1994), since only pores >30 μm are accessible to them, and these pores are largely affected by compaction. However, in a study by Griffiths et al. (1991) (cited by Whalley et al. 1995), where increased soil bulk density caused a decrease in root elongation rate of barley, nematode activity remained constant in the bulk soil and increased in the rhizosphere. Increased mucilage secretion was thought to be the reason.

6.5.2. Micro-organisms

Micro-organisms in soils may be largely affected by compaction. Consequently, many important biological processes, such

Table 10. Number and weight of earthworms in a field trial on a heavy clay soil in Sweden, where all field operations during a 20-year period had been made with implements drawn either by tractors with single wheels, by tractors with dual wheels or by cable and winch (Box 18), the latter leaving the plots virtually untrafficked. (After Boström, 1986)

	Single wheels	Dual wheels	Cable and winch	Significance[a]
Number of worms per m^2	16	33	92	**
Biomass of worms, g per m^2	6	10	23	*

[a] * = $p < 0.05$; ** = $p < 0.1$.

as decomposition of organic matter, mineralization of plant nutrients and release of carbon dioxide (CO_2) may also be affected. However, the effects are very variable.

An effect of compaction of importance for micro-organisms is the influence on the pore size distribution in the soil. Postma & van Veen (1990) divided the pores into size classes from a soil microbial point of view. They classified pores <0.8 μm as inaccessible to micro-organisms and pores >0.8 μm as accessible. Pores between 0.8 and 3 μm were classified as protective to the micro-organisms, since these pores are too small for most of the predators. Pores over a certain size were classified as non-habitable by the micro-organisms, because they are air-filled and unsuitable for growth. Therefore, since the pore size distribution differs between soils of different texture and structure and since the drainage and climatic conditions differ between sites, it is likely that compaction influences the micro-organisms and their activities differently at different locations.

Displacement and shearing actions generated in soils by wheel passes are possibly also of importance for the microbial activity. This probably brings some micro-organisms into contact with new substrates. Fragments of organic matter in soils are often thought to be covered with clay particles that make them inaccessible to micro-organisms. A shearing action may remove the protective cover from some of the fragments, and even though the opposite may also occur, this may lead to a temporary increase in microbial activity in the soil immediately after application of traffic similar to that occurring after tillage. If so, it also means a short-term increase in decomposition of organic matter and mineralization of plant nutrients.

A more long-lasting effect is the reduction in air permeability and gas diffusivity in soils occasioned by compaction (Stępniewski et al., 1994; Section 4.3.1). This often leads to oxygen deficiency during wet periods, especially in the central parts of large aggregates. This occurs particularly when oxygen consumption is high, i.e. when the temperature is high and the soil has a great content of fresh organic matter. Oxygen deficiency in a soil may lead to unfavourable chemical and biological processes. At severe deficiency, various substances that are detrimental to plant roots or soil animals may be produced, such as hydrogen sulphide or high concentrations of aluminium ions. Root diseases may also increase (Grath, 1996) and nitrogen can be lost by denitrification (Section 6.5.3).

Influences of soil compaction on biological activity in a soil also mean influences on carbon sequestration. If a possible temporary increase in microbial activity immediately after compaction is disregarded, most aerobic microbial processes in a soil are likely to rapidly decrease, particularly under wet conditions. For instance, Jensen et al. (1996) showed that CO_2 fluxes from the soil surface decreased by more than 50% after traffic application in both a pasture and a cropped field with silty clay loam in New Zealand. However, the microbial biomass was not affected.

Decomposition of soil organic matter also means mineralization of plant nutrients. The well-known effect that tillage increases the mineralization rate (e.g. Stenberg et al., 1999) must at least partly be an effect of the looser conditions that are generated. Therefore, compaction may be assumed to cause a reverse effect. Such an effect was shown for instance by Haunz et al. (1992), Breland & Hansen (1996) and Nevens & Reheul (2003) and may be a contributing reason for reduced uptake of plant nutrients by crops in compacted soil. An investigation by Tubeileh et al. (2003) showed greater carbon exudation from the roots of maize in compacted soil than in loose, and this was accompanied by a larger microbial biomass in the soil.

The quantitative effects of compaction on release of CO_2 in soils and on mineralization of plant nutrients are poorly known, but short-tem effects possibly differ from long-term. The effects may depend on local soil and climatic conditions and on time, intensity and frequency of compaction and loosening treatments. It is likely that compaction most often tends to reduce the CO_2 release and increase the content of soil organic matter in the long-term. If so, this is an effect analogous to the well-known effect that the content of organic matter in soils tends to be higher the cooler and wetter the climate. On the other hand, the most important fact may be that excessive compaction reduces plant growth, thereby reducing the input of crop residues into the soil.

6.5.3. Emission of greenhouse gases, denitrification

Compaction may greatly influence the amount of greenhouse gases other than CO_2 emitted from or taken up in a soil. Gases of particular importance in this respect are nitrous oxide (N_2O) and methane (CH_4). Agricultural soils are regarded as important sources of N_2O to the atmosphere and sinks of CH_4 (Mosier et al., 1991). When reviewing studies of the effects of soil compaction on these gases, Soane & van Ouwerkerk (1995) found many examples of increased N_2O emission to the atmosphere. The production of N_2O in soils may be the result of both nitrification and denitrification. The former is dominant in well aerated soil, the latter under anaerobic conditions. Denitrification means a transformation of nitrate either to N_2O or to N_2. In a compacted and wet soil, this process can be rapid and substantial.

In Norway, Bakken et al. (1987) found that denitrification during a 75-day period increased from 3-5 kg N ha^{-1} in uncompacted wheat plots to 15-20 kg N ha^{-1} in plots that had been compacted by tractor traffic in spring. In another Norwegian investigation, as much as 50 kg N ha^{-1} (40% of the fertilizer N applied in spring) were lost by denitrification in a compacted sandy soil with a ley crop of grass in a wet growing season. In investigations by Hansen & Bakken (1993) and Hansen et al. (1993), it was shown that compaction by machinery traffic considerably increased the release of N_2O to the atmosphere. At the same time, it reduced the uptake of CH_4 in the soil by 50%. In Germany, Ruser et al. (1998) found much greater N_2O emission from the soil in interrows with tractor traffic than in untrafficked interrows in a potato field at the same time as there was a change from uptake to release of CH_4. Haunz et al. (1992) found a loss of 34 kg N ha^{-1} by denitrification during a 16 day period in a compacted and wet soil. In Scotland, Ball et al. (1999a, b) found larger N_2O emissions from a sandy loam after heavy compaction than after no or light compaction, particularly in case of a rainy period shortly after nitrogen fertilization. Lipiec & Stępniewski (1995) reviewed the effects of compaction on plant nutrients in soils. They reported several examples of increased denitrification rate as a result of both increased bulk density and increased aggre-

Table 11. Number of *Rhizobium*-nodules per plant on roots of peas in the 0-15 cm layer in a compaction trial on a sandy soil in Sweden (From Grath & Arvidsson, 1997)

	Treatment[a]					
	A	B	C	D	E	LSD[b]
Dry bulk density Mg m^{-3} (4-23 cm depth)	1.17	1.22	1.29	1.34	1.41	0.024
Degree of compactness (4-23 cm depth)	79	83	87	91	96	1.6
Number of nodules on primary roots	7.6	6.5	5.1	4.2	2.9	2.4
Number of nodules on secondary roots	28	22	27	26	22	n.s.

[a] A = no traffic; B = 1 pass, 4.2 Mg tractor, tyre inflation pressure 37 kPa; C = 1 pass, 6.5 Mg tractor, 90 kPa; D = 2 passes, 6.5 Mg tractor, 160 kPa; E = 9 passes, 6.5 Mg tractor, 160 kPa.
[b] LSD = least significant difference ($p<0.05$); n.s. = no significance.

gate size in the soil. The latter is an important secondary effect of soil compaction (Section 5.3) that often increases the fraction of the soil volume with anaerobic conditions (Renault & Stengel, 1994). When summarizing Russian compaction studies, Bondarev et al. (1990) report both considerably increased denitrification and reduced nitrification in densified soil.

6.5.4. *Fixation of nitrogen by leguminous crops*

Several studies have clearly shown that the state of compactness of soils can influence the formation of *Rhizobium*-nodules on the roots of leguminous plants. Therefore, it can be assumed that com paction also influences the fixation of nitrogen. In a field trial in Minnesota, U.S.A., Voorhees et al. (1976) found a negative impact on both number and mass of *Rhizobium*-nodules on roots of soya bean after application of tractor traffic in the inter-rows on both sides of the crop rows. In pot experiments with various bulk densities, Faiz et al. (1977) found that the number of nodules on soya bean roots decreased drastically with increasing soil bulk density under wet conditions, but had an optimum at a relatively high bulk density under drier conditions. Table 11 shows an example of reduced nodulation on pea roots in a field trial where various traffic treatments were applied at spring sowing in a field ploughed in the previous autumn. Dry bulk density and degree of compactness (Box 11) were determined in the layer between harrowing depth and ploughing depth. The number of nodules on the primary roots (which were formed while the soil was still relatively wet) differed significantly between treatments. Similar differences in nodulation on pea roots between more or less compacted areas in a group of farm fields were found by Grath & Håkansson (1992).

Chapter 7

Methods to minimize compaction or its negative effects

Summary

Many measures can be taken to minimize soil compaction or to mitigate its effects, but the feasibility and profitability of the individual measures vary widely between regions and individual farms.

The most crucial measure is usually to avoid machinery traffic under wet conditions whenever possible. This is facilitated by a cropping system in which traffic is concentrated to the season when soils are driest. Other important measures include good drainage of the soil, matching sizes of implements and tractors, four-wheel-drive rather than two-wheel-drive tractors and low-pressure tyres or dual wheels with low tyre inflation pressure. The distances driven can often be substantially shortened by combining operations and by careful planning of harvesting, spreading and transport operations. The use of a restricted system of permanent routes for the heaviest vehicles can minimize detrimental traffic in the rest of the field area. Use of separate vehicles for transport on roads and in fields facilitates the use of more suitable field vehicles. To avoid subsoil compaction, wheel loads should be limited and all tractors should run on-land rather than in the furrow when ploughing. Mouldboard ploughing or other deep primary tillage loosens the topsoil and may be necessary in excessively compacted soil. Subsoiling is a more doubtful measure.

In the long run, the current systems for field operations should be replaced by non-compacting systems. Some strict form of controlled traffic is a possibility that is already attracting some interest in parts of the world. A historical non-compacting system was the steam ploughing developed in the Nineteenth Century. Heavy steam engines pulled the implements, particularly the ploughs, by cable and winch. However, any new non-compacting systems must combine soil-friendliness with flexibility and high work rate.

7.1. Measures must be adapted to the conditions on individual farms

Many authors have discussed possibilities and measures to reduce soil compaction or to alleviate its harmful effects (e.g. Eriksson et al., 1974; Soane, 1985; Håkansson et al., 1988; Bondarev et al., 1990; Medvedev et al., 1993, Tijink et al., 1993: Larson et al., 1994; Keller & Arvidsson, 2004b). Depending on differences in climate, soils and cropping systems, the most important or economically most motivated measures differ greatly between regions and individual farms.

Some of the measures that can be taken are simple and require very small investments, but rather attention and preparation. Such measures include for instance, frequently adjusting the tyre inflation pressure to the loading and driving situation, choosing suitable days for field operations in terms of soil moisture conditions and planning harvesting, spreading and transport operations carefully in order to minimize the distances driven. On many farms, such simple measures would eliminate a large part of the compaction damage, often one third or more.

Another part of the compaction damage can be profitably eliminated by investments in machines or running gear with less compaction potential. Chapter 8.1 presents a model aimed at allowing predictions of the 'compaction costs' on a farm level to make it possible to include these in the economic calculations, for instance when planning investment in new machines. Compaction costs can then be included in the calculations, in addition to the machine, labour and timeliness costs. This applies in particular to machines with a long annual use, such as machines operated by contractors or in cooperative use. Farmers are likely to be willing to pay higher rates for machines that cause less damage to their soils.

In the present chapter, a great number of measures that can contribute to reducing the compaction costs are discussed. On an individual farm or on an individual occasion, one or more of these can be applied. Some of the methods are only briefly mentioned here, since they are discussed in other chapters. Methods that are not discussed elsewhere are treated in greater detail. Examples of economic calculations are given in Chapter 8.

The most important measure of all is to minimize the machinery traffic when soils are wet. However, this is not always easy and may require both foresight and flexibility and a machinery system of large capacity. The general planning of the production system is also crucial for the ability to minimize damage by compaction, and it largely influences the need for more specific counter-measures.

7.2. General crop production measures

7.2.1. Good drainage

In soils with imperfect natural drainage, artificial drainage speeds up the drying, improves trafficability and counteracts excessive compaction. This facilitates earlier sowing in spring or after heavy rain, thus improving the possibility of growing crops with a long growing season or of practising double-cropping (cf. the use of low-pressure tyres, Fig. 37). It can also reduce the risk of oxygen deficiency in soils during the growing season and improve over-wintering of autumn-sown crops and ley. However, artificial drainage is expensive, and before it is undertaken it is necessary to also consider many other factors in addition to the risk of soil compaction, so it is not further discussed here.

7.2.2. Choice of crops

The development of a favourable soil structure is promoted by crops that are rapidly and uniformly established, have a deep root system and produce large quantities of crop residues. Furthermore, the crop canopy should cover the soil surface during as large a part of the year as possible. It then uses a large quantity of water, and this helps to keep the soil as dry and resistant to compaction as possible. It also protects the soil surface from the impact of raindrops and from erosion.

Among the common agricultural crops, perennial forage crops such as ley with grass or legumes have the best potential to fulfil these requirements, and consequently to minimize soil compaction and to alleviate its effects. On the other hand, with some of the current harvesting systems the total annual traffic intensity in a ley is high, particularly where many cuts are taken each year and heavy transport vehicles are used (Table 1). Furthermore, in such a crop, the traffic also damages the plants themselves. In addition, rigorous quality requirements may make it impossible to pay attention to soil moisture conditions when harvesting, and this may lead to harvest under wet conditions.

In annual crops such as cereals, the likely incidence of compaction depends not only on traffic intensity and on weight and running gear of the machines used, but also on the time of the year when individual field operations must be carried out. In Scandinavia, for example, soils are usually drier at the time of seedbed preparation for autumn-sown crops than for spring-sown. Therefore, the former crops are more favourable from a soil compaction point of view. Accordingly, when ploughing, farmers usually obtain a better soil structure after autumn-sown cereal crops than after spring-sown.

In root crops and potatoes, the traffic intensity is greater than in cereals (Table 1). This particularly applies to harvesting, which is often carried out in late autumn in wet soil. Therefore, when these crops are grown using current techniques, soils may be seriously compacted.

7.2.3. Application of fertilizer, manure, crop residues and other amendments

Soil structure is improved by all measures that increase the organic matter content of the soil up to a relatively high level, such as incorporation of manure and crop residues. The same usually applies to the application of various soil amendments, such as lime, particularly calcium oxide. However, manure, lime, etc. are often spread using very heavy vehicles, and to avoid unacceptable soil compaction, great attention must be paid to times and methods of spreading.

Soil structure is also favoured by rational use of mineral fertilizers, since this enhances crop growth, root development and water uptake. It also increases the quantities of crop residues produced, and accordingly it increases the organic matter content of the soil in the long run (e.g. Carlgren & Mattsson, 2001).

7.2.4. Pioneer plants

Some plants have roots with special ability to penetrate compacted soils and to act as 'pioneer plants' that open pathways for roots of subsequent crops with weaker roots (e.g. Löfkvist, 2005). However, the efficiency of various pioneer plants in this respect and the possibilities to profitably utilize them in practice are still poorly known. No plants seem to be able to actually loosen a compacted subsoil layer, only generate a system of new root channels through the layer. However, even this may be important, particularly in situations where it can help roots of subsequent crops to reach uncompacted and looser layers underneath.

7.3. Machinery

7.3.1. Machinery capacity

High machinery capacity makes it possible to carry out field operations when conditions are suitable and to avoid traffic on wet soil. Unfortunately, increased capacity usually means heavier machines, but when the use of such machines enables traffic under drier conditions, they do not necessarily cause more soil compaction. A light machine used under wet conditions may cause more harm than a heavy machine used under drier conditions. However, increase of machine capacity requires massive investments.

7.3.2. Efficient use of tractor capacity

Unnecessary traffic can be avoided if the size of implements is well adapted to the size of the tractors used. Therefore, when a new tractor is bought, the implements should often be replaced at the same time. Furthermore, it is usually an advantage to combine operations as much as possible. Examples of combined operations that often (but not always) result in a reduction in total traffic intensity include combined fertilizing and sowing and the attachment of a furrow press to the mouldboard plough.

7.3.3. Four-wheel-drive tractors; weight transfer from implements

Four-wheel-drive (4WD) makes it possible to utilize the whole tractor weight to produce draught force. 4WD tractors can produce considerably more draught force than 2WD tractors of the same weight.

Therefore, the working width of the implements can be correspondingly larger, and the traffic intensity in Mgkm ha^{-1} correspondingly smaller. Transfer of weight from implements or trailers to tractors may reduce the weight of the tractor itself. Thereby, the traffic intensity is reduced in operations where the tractor is not used to produce draught force.

7.3.4. Wide low-pressure tyres, dual wheels and adjustment of tyre inflation pressure

Replacement of traditional tyres by wider tyres or dual wheels (sometimes even triple wheels) to increase the ground contact area is a simple and widely used way to reduce the ground pressure and to limit the risk of excessive soil compaction. Nowadays, there are many tyres available on the market designed for much lower inflation pressure than those built fifteen or twenty years ago. Some of the new tyres have a very soft carcase, and therefore they can only induce a ground pressure slightly higher than the inflation pressure. This has made it possible to reduce stresses and compaction in the plough layer and upper part of the subsoil. Alternatively, field operations can be carried out under wetter conditions with no increase in compaction (Fig. 37; Box 17). In some cases is a reduction in power requirement for tillage as important an outcome of low-pressure tyres as increased crop yield or improved timeliness of operations (Dickson & Ritchie, 1996a, b).

Wider, low-pressure tyres or dual wheels lead to compaction of a larger percentage of the field area. Therefore, in a ploughed field where a random type of traffic has been used, the mean degree of compactness of the plough layer in the whole field after seedbed preparation and sowing does usually not differ very much from that after the use of standard tyres. However, the state of compactness is usually much more uniform, and this is a great advantage, since both uncompacted and excessively compacted areas are substantially reduced (Section 8.3.1).

The full effect of wider tyres or dual wheels is only obtained if the tyre inflation pressure is also reduced as much as possible. For most vehicles used in agricultural field operations, the traffic situation varies considerably. This means that the lowest recommendable tyre inflation pressure also varies considerably. To limit soil compaction, it is important to always reduce the inflation pressure whenever possible, even though the ground pressure is not reduced quite as much as the inflation pressure. The inflation pressure should be frequently adjusted with regard to the traffic situation. According to the manufacturers recommendations, factors such as reduced wheel load or draught force, reduced speed or softer soil all make it possible to reduce the inflation pressure. On transport and spreading vehicles that alternately move on roads and in the field, equipment to quickly change the inflation pressure while moving can be a great help. Such equipment is available, but it is unfortunately expensive and not yet frequently used.

7.3.5. Tracked vehicles

In some situations, the use of tracked tractors and other vehicles may help to reduce the compaction problems (Erbach, 1994). Tracked tractors can produce higher draught forces than wheeled tractors of the same weight and pull implements with larger working width. This results in fewer Mgkm ha^{-1}. In most cases, the track width and the area affected are smaller, the ground pressure lower and compaction in the track area less. However, the latter is not always the case because of very uneven ground pressure distribution (Section 2.3). Unfortunately, the use of tracked vehicles is limited both by the costs and by several practical problems, even though modern rubber-belt tracks cause much smaller problems than older steel tracks (Erbach, 1994).

Box 17
Early sowing in various soils

By the use of tyres with very low ground pressure, soil compaction can be substantially reduced. This may also increase the possibility of carrying out field operations under wet conditions in order to better utilize a short growing season or to facilitate the establishment of autumn-sown crops etc. (Fig. 37). A system for spring sowing up to three weeks before traditional sowing time has been introduced in some parts of Sweden by the use of such tyres. This usually requires that sowing is carried out without harrowing in spring. If the soil is sufficiently wet, a traditional seedbed is not required for protection against evaporation. Such a system has attracted the greatest interest in areas with sandy soils or with heavy clay.

In *sandy soils*, spring ploughing can replace traditional autumn ploughing and may considerably reduce mineralization and leaching of nitrogen in autumn and winter. It can often be carried out a couple of weeks before traditional seedbed preparation is possible in autumn-ploughed fields. If ploughing is done with a furrow press attached, it can be immediately followed by combined sowing and fertilizing without harrowing. By filling up the whole working width by wide wheels with low ground pressure on the tractor and drill and by a special packer unit in the gap between the tractor wheels (Fig. 3), the whole plough layer can be rather uniformly recompacted. Farmers denote this 'full-width recompaction'. In trials on sandy soils this has resulted in a yield increase of more than 20% as compared to the traditional system with autumn ploughing (Fig. A).

In *clay soils*, ploughing in spring is inpracticable. Therefore, primary tillage must be carried out in the autumn and be followed when required by levelling of the soil surface. Combi-sowing of seed and fertilizer in one operation can be performed in early spring as soon as a very shallow surface layer has dried up, but before the soil is trafficable and workable by traditional machines. This usually requires that the tractor has soft tyres with an inflation pressure <50 kPa. In trials on heavy clay soils (Fig. B), this resulted in increased yields, provided the soil was wet enough to make a traditional seedbed unnecessary. In clay loam and silt loam soils with a less stable structure, this system is not recommended.

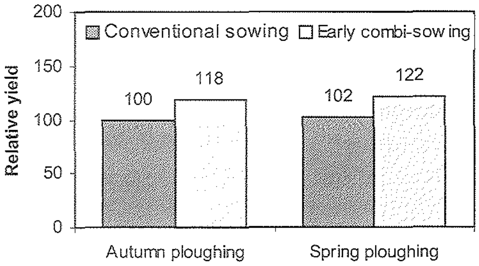


Fig. A (top). Mean grain yield of spring-sown cereals in 14 Swedish trials on sandy soils, where early spring ploughing with a furrow press on the plough was immediately followed by combi-sowing of seed and fertilizer with a tractor/seed drill unit equipped for full-width recompaction as the only operation. Conventional sowing included autumn ploughing, usually two harrowings in the spring and separate sowing.

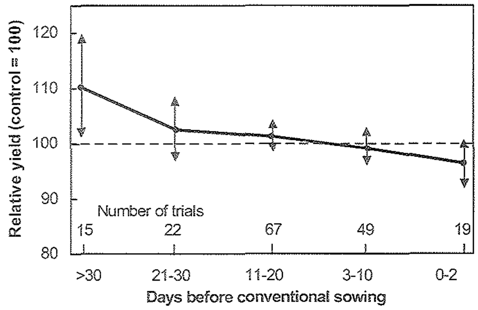


Fig. B (bottom). Mean grain yield of spring-sown cereals in Swedish trials on clay soils, where early combi-sowing with extreme low-pressure tyres on the tractor was the only spring operation. The fields were ploughed in the autumn and levelled as required. In control plots, sowing was carried out at the traditional time and was preceded by two to three harrowings. The number of sites where the early sowing was carried out within the indicated time interval is shown at the bottom. (Bars indicate ± 1 standard deviation.) (After Arvidsson, 1997b.)

7.3.6. Limitation of the wheel or axle load

A high wheel load may lead to compaction of deep subsoil layers, where the effects are very persistent or even permanent and very difficult to alleviate. To avoid permanent damage to soils, layers at depths greater than 35-40 cm should not be exposed to stresses greater than their bearing capacity (strength). Vehicles that induce stresses exceeding the strength of these layers should be used only in a very restricted system of permanent field roads or wheel tracks. In the remaining field area, load limits should be established. However, the stresses should of course be as low as possible even in the layer immediately below ploughing depth.

The need for load limits and ways to specify them are discussed in Chapter 9.2. For example, under Swedish conditions, load limits of 6 Mg for single axles and 10 Mg for tandem axle units were recommended many years ago, when only tyres with relatively high ground pressure were available (Håkansson & Danfors, 1981). When wide low-pressure tyres are used, it may be more appropriate to specify limits in terms of load per wheel (cf. Chapter 2) and to choose the limits with regard to the ground pressure. In the former Soviet Union, a standard was introduced that specified limits both of the ground pressure and the estimated vertical normal stress at a depth of 50 cm (Table 18). Van den Akker and Schønning (2004) proposed limits based on predicted stresses, calculated as functions of depth, wheel load, wheel arrangement and ground pressure, and adapted to local soil and climatic conditions. In practice, when assessing the value of low-pressure tyres as compared to high-pressure tyres for high loads, it must be considered that the positive effects of lower stresses in the soil are to a greater or lesser extent offset by larger (wider) track areas.

Up to now it has generally been thought that even very heavy vehicles can be used without risk of subsoil compaction when soils are dry. However, in comprehensive measurements by Trautner (2003), heavy vehicles caused the greatest vertical displacement in deep subsoil layers, when soils were driest (Chapter 3.3). Therefore, it is still an open question whether, or on which soils, traffic under dry conditions is a safe way to avoid compaction of deep subsoil layers. It has always been known that a pure sand, contrary to more fine-textured soils, loses its strength when it dries out.

7.3.7. Driving the tractor 'on-land' at ploughing

Up to now, the highest stresses in the subsoil on many farms have been induced by the furrow wheels of tractors during mouldboard ploughing, even where relatively light tractors have been used (Tijink & van der Linden, 2000). At least for large ploughs, a viable technique is available by which the tractors can be driven 'on-land'. Use of such techniques in all mouldboard ploughing should be strongly encouraged, and the heavier the tractor, the greater the urgency. A step in that direction is to use some type of knife or similar tool on the rear plough body to cut some soil from the edge of the furrow and move it to the furrow bottom. Then the tractor wheels can run on that soil and not directly on to the bottom of the furrow. This also facilitates the use of wide, low-pressure tyres that are partly supported by the sloping sides of the furrow.

7.3.8. Separate vehicles on roads and in arable fields

Transport vehicles are often used both on roads and in arable fields, in spite of quite different demands on the wheel equipment. Road vehicles run at high speed, and stability and traffic safety usually make it necessary to use a high tyre inflation pressure. Field vehicles, on the other hand, should be equipped with soft tyres with low inflation pressure, and this is facilitated by a low driving speed. Therefore, whenever possible, different vehicles should be used in the field and on the road. However, this may only be economically feasible for machinery systems with a long annual use, and it requires an efficient system for load-transfer.

7.3.9. Sprayer boom system for spreading slurry

During recent years, various boom systems for spreading slurry have been developed. A light sprayer aggregate is supplied through a long, flexible tube from the border of the field or from a transport vehicle running in permanent traffic lanes. The sprayer aggregate may be pulled by a light tractor or moved by winding in the feeder tube. With such a system, the traffic intensity can be much less than with a traditional tanker system.

7.4. Soil tillage

7.4.1. Ploughing

Mouldboard ploughing or other deep primary tillage loosens the soil and helps to alleviate compaction effects in the loosened layer (Section 5.3). Cultivation to a shallower depth works in a similar way, just in a shallower layer. However, at the same time, ploughing itself generates a high amount of tractor traffic (Table 1). This affects a large part of the plough layer, and tractor wheels in the open furrow are often the greatest source of subsoil compaction.

Immediately after ploughing, the degree of compactness of the loosened layer is usually similar, regardless of whether or not the soil was compacted before ploughing. In both cases, the degree of compactness is lower than the optimal (Section 5.2), and crop growth is almost equally improved by moderate recompaction. However, in a soil that was compacted before ploughing, the furrow slices are generally more massive and coherent or have coarser and harder clods than in an uncompacted soil. Such residual effects of compaction increase with the clay content of the soil, are to some extent cumulative (Section 5.3) and affect crop growth negatively. However, annual ploughing prevents these effects from becoming permanent. In soils subjected to both annual machinery traffic and annual ploughing, the structure of the plough layer usually approaches a dynamic equilibrium state within a few years. In soils which are not annually loosened, the compaction effects are much more persistent.

7.4.2. Reduced tillage

When a change is made to reduced tillage, the total annual traffic intensity usually decreases to some extent, and this may reduce the long-term compaction effects correspondingly. However, at least in sandy soils, compaction effects may accumulate in the topsoil to an extent that makes periodic loosening necessary. This has been observed for instance in sandy soils in Sweden, where compaction seems to be the most serious obstacle to reduced tillage (Box 15). In such soils it is of particular importance to minimize the compactive stresses. In clay soils, on the other hand, the continuity and stability of the macropore system gradually improve in soil layers that are no longer disturbed, and this compensates at least to some extent for the increased density (Section 5.4; Box 15). In annually loosened soil layers, the compaction problems usually increase with increasing clay content, because the residual effects after tillage increase (Section 5.3). On the other hand, in layers which are not regularly loosened, the reverse seems to occur, since the natural loosening processes are much less active in coarse-textured soils than in fine-textured.

7.4.3. Subsoil loosening

When a subsoil has been compacted by machinery traffic to a certain extent, the effects can at least partly be reduced by deep loosening (subsoiling, or in some cases deep ploughing), provided this is carried out when the soil is sufficiently dry.

However, deep loosening cannot usually completely alleviate the effects of machinery-induced subsoil compaction (Box 7), and its effects are sometimes even negative. In many cases, a loosened subsoil becomes recompacted within a few years, and once a field has been subsoiled, this operation must often be repeated periodically. It is also an expensive operation. For instance, Munkholm et al. (2005b) concluded that, under their conditions, subsoil loosening is only recommendable in case of very severe subsoil compaction. Accordingly, the strategy should usually be to minimize subsoil compaction rather than to try to cure it after it has occurred (Håkansson & Petelkau, 1994). However, the effects of subsoil loosening may be prolonged if it is carried out immediately before or after the establishment of a perennial crop like lucern (Löfkvist, 2005) and heavy traffic in this crop can be avoided.

7.5. Operational systems and routines

7.5.1. Time of traffic

The time of traffic is very important for the incidence of compaction, particularly since soil water content varies greatly with time. With the possible exception of compaction in deep subsoil layers (Chapters 2.2 and 3.3), the damage caused by traffic generally increases with soil wetness. Therefore, strategic planning that makes it possible to minimize traffic under wet seasons is crucial (Sections 7.2.2 and 7.3.1). Daily work should be planned in such a way that field operations can be carried out on full capacity on days with the most favourable conditions. However, for many operations, such as seedbed preparation, sowing and harvest, the time cannot usually be altered very much in order to limit the risk of soil compaction, since this may lead to still more negative timeliness effects. Instead, it is important both to invest in a machinery system with reasonably low compaction potential and to limit the susceptibility of the soils, e.g. by artificial drainage.

7.5.2. Good planning of traffic pattern

In field operations that include heavy transport, such as ley harvest and manure spreading, good planning of the traffic pattern is essential. Measurements made during slurry spreading on some Swedish farms revealed that the total distance driven in the field was sometimes as great as five times the distance in which manure was actually spread (I. Håkansson, unpublished data). In most cases, more thorough planning could have substantially shortened the distance driven and reduced both soil compaction and spreading costs. One hour of planning using a field map in the office could often have reduced the time spent in the field by several hours.

In operations that include collection or spreading of material in the field, it is a great advantage to make the distance driven during loading or unloading coincide with the field length. Very long fields should be subdivided into sections of suitable length (Barkusky, 1990). Many and well-positioned entrances to the fields contribute to minimizing the distances driven by vehicles within the fields and may be of great economic value. In most transport and spreading operations, the 'non-productive' driving should usually be concentrated to a limited number of tracks.

7.5.3. Permanent traffic lanes for heavy field transport

In many cases, it is an advantage to concentrate heavy transport and other heavy traffic to a restricted network of permanent traffic lanes rather than to use a random traffic pattern. It is possible to improve the trafficability of such lanes by artificial drainage or by some form of soil structure stabilization. As far as plough layer compaction is concerned, the advantages may arise immediately, but to actually minimize compaction damage in the subsoil, the position of such traffic lanes must remain constant for decades and not be relocated after some years.

7.5.4. Traffic only between rows

In row crops with large row spacing, it is possible to concentrate machinery traffic to between rows. If the row positions are set immediately after primary tillage, it may be possible to avoid subsequent traffic in the row zones completely, or to just apply traffic required for optimal compaction. It is reasonable to assume that a super-optimal density is usually less detrimental to the crops in the inter-row zones than in the row zones. Restricting traffic to the inter-row zones is of course particularly important for field operations carried out after crop establishment, such as ridging, mechanical weed control, fertilizing or spraying, since the traffic may then also directly damage the plants. It is often more important to minimize such damage than to limit soil compaction. Under sufficiently dry conditions this can be achieved by using narrow wheels adjusted to run exactly in the centre of the inter-rows, and in the same inter-rows at each operation. Where crops with the same row spacing are grown year after year, the same row and track positions can sometimes be used for several years (Fig. 4). Efforts to completely avoid traffic in the row zones are crucial, particularly in perennial row crops such as sugar cane (Braunack, 1995).

7.5.5. Controlled traffic

Controlled traffic is a term commonly used for a system in which all wheel traffic throughout the growing season is concentrated to a restricted system of permanent, parallel tracks. Various controlled-traffic systems have been introduced or tested in several countries (e.g. Taylor, 1994; Chamen et al., 1994). In a fully developed system of this kind, the same tracks are used for all field operations for many years. The track spacing can vary from a few metres up to more than ten metres. Automatic steering of the machines, for instance by GPS-support, facilitate a controlled traffic system.

The system can be based on traditional machines with a module system for the working widths. However, if relatively small machines are used the track spacing may be rather small and the tracks may cover a relatively large percentage of the field area. With heavier machines the track spacing can be larger and the percentage of the field area covered by tracks can be smaller. By using special machines such as gantries (Fig. 39), a large track spacing and a small track area are possible. In a controlled-traffic system, it may not be necessary to use low-pressure tyres, because even with such tyres the track areas will be severely compacted and poorly utilized by the roots of the crops. However, a prerequisite for this is that the position of the tracks are never moved. Otherwise, new areas will be exposed to very persistent subsoil compaction.

In the untrafficked zones between the tracks, subsoil loosening will be more persistent than in soil with normal traffic. Furthermore, there may no longer be any need to loosen the topsoil, and this increases the possibility of using reduced tillage or direct drilling. If tillage is still needed for other purposes, this requires very little energy (Section 8.4), but some recompaction may be required. In the compacted tracks, trafficability of the soil is usually improved, and this reduces the rolling resistance. Timeliness of field operations can sometimes be considerably improved. Even though there may be very low crop yield in the untilled, permanent tracks, or perhaps no crop at all, there are sometimes yield increases on a field basis, provided the track area is small (Taylor, 1994). However, if deep primary tillage is still carried out, there may be yield losses unless the loosened layer is re-compacted (e.g. Lamers et al., 1986).

A similar system of short duration frequently used in crops with small row spacing is the tramlining method of closing some seed coulters during sowing in order to mark track positions for subsequent spraying and fertilizing operations. However, the main purpose of this is often just to improve the precision of these operations.

7.5.6. GPS-supported steering

GPS-support for steering of the machines has recently become a realistic option, and development of GPS-supported steering systems is going on in many places. This will lead to better precision in the steering of the machines and to less overlap, and consequently to reduced traffic intensity.

7.6. Future possibilities

Some of the soil compaction problems occurring today cannot be eliminated unless completely new machinery systems for field operations are introduced. It is crucial that manufacturers of farm machinery, including manufacturers of tyres and tracks, contribute to the efforts to minimize compaction problems by developing equipment that is less aggressive to the soil. Unless very strict controlled traffic systems can be introduced everywhere, avoidance of intolerable compaction of deep subsoil layers requires that the present trend of continuously increasing wheel loads of farm machinery be broken. This applies in particular to frequently used machines with small working width. For nearly all arable soils, there are limits of tolerable stresses in the subsoil that should not be exceeded. In the long run, it may be necessary to introduce completely new principles for the machinery systems. However, any new system must have a high operational capacity, since this is a prerequisite for cost efficiency and timeliness of operations. Even though it is important to minimize soil compaction, it is usually still more important to carry out the field operations close to the optimal time.

A historical system that left most of the field area uncompacted was the cable-and-winch system used with the steam ploughs developed in the 1800s (Fig. 38; Timberg, 1913). It may not be completely impossible to introduce a similar system again by utilizing modern techniques for automatic steering and operational control. A possibility might be a permanent system of traffic lanes with a spacing of 100 m or more and a cable-and-winch system in between. Reduced compaction would then eliminate the need for soil loosening and would substantially reduce the energy consumption for such tillage operations that are still required for other purposes. Such a system would also have the potential to improve seedbed quality, timeliness of field operations and crop establishment and yield, to increase water infiltration (Fig. 19), to reduce surface runoff, erosion and nutrient leaching and to increase the persistence of subsoil loosening and possibly also the diversity in soil micro-flora and fauna.

The extensive use of such a system may be a Utopian dream. However, in two long-term field trials in Sweden in 1964-1984 on heavy clay soils very susceptible to compaction (Box 18), the use of cable-drawn implements led to substantially increased crop yields and much more efficient use of fertilizer and other commodities. For 19 location-years with spring-sown cereals in these trials, the grain yield was on average 26% higher in plots with cable-drawn implements than in plots with the same amount of fertilizer etc., where the implements were pulled by tractors with single wheels. Still only a minor part of the positive timeliness effects that could potentially be achieved by such a system (cf. Fig. 37) was utilized.

This demonstrates that serious efforts should be encouraged to develop techniques for field operations that do not cause undesirable soil compaction. Indeed, several efforts in that direction have already been made. Controlled traffic (Section 7.5.5) have been introduced in some areas during recent years, for instance in parts of the USA and Australia. These have often been based on traditional tractors and machines with a module system for the work-

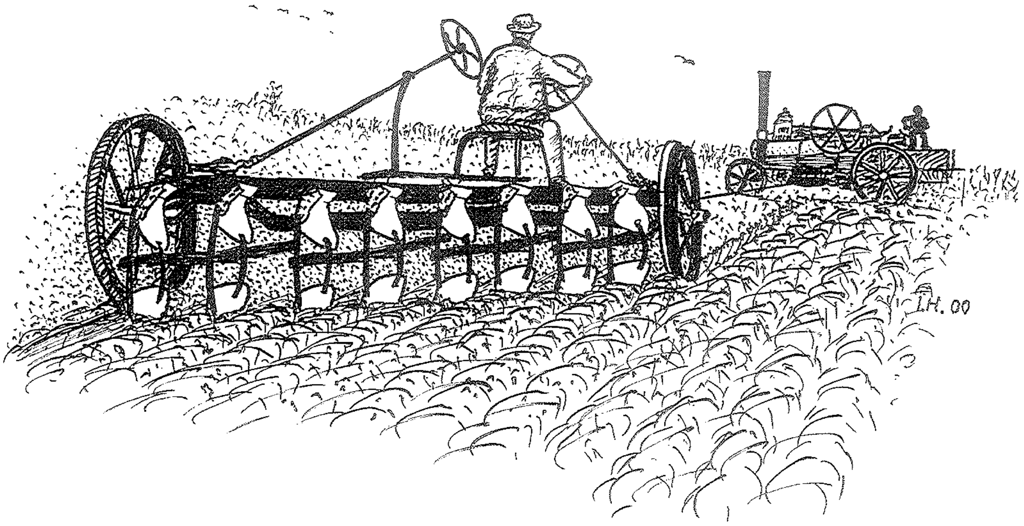


Fig. 38. In the late Nineteenth and early Twentieth Century, a cable-and-winch system was used on some large farms, mainly to pull ploughs. Heavy steam engines were used as sources of power, either with engines at both ends of the field or an engine at one end and an anchor wagon at the other.

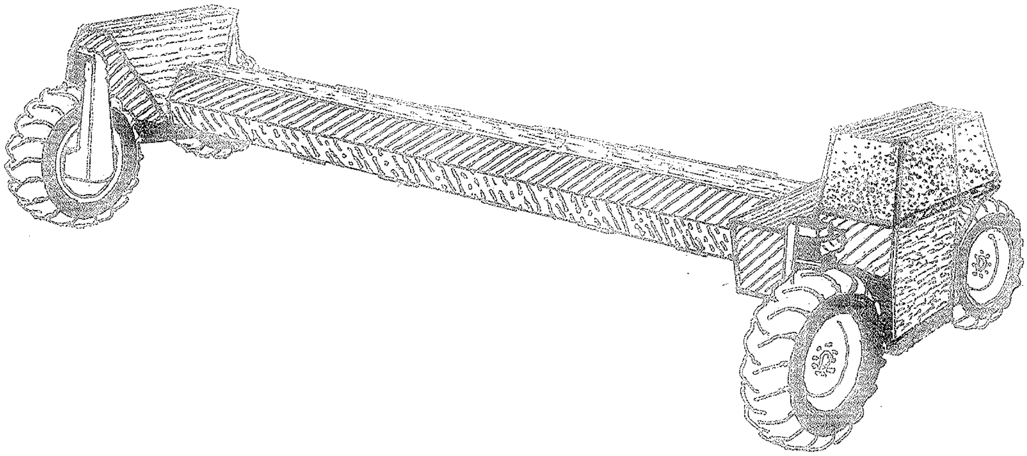
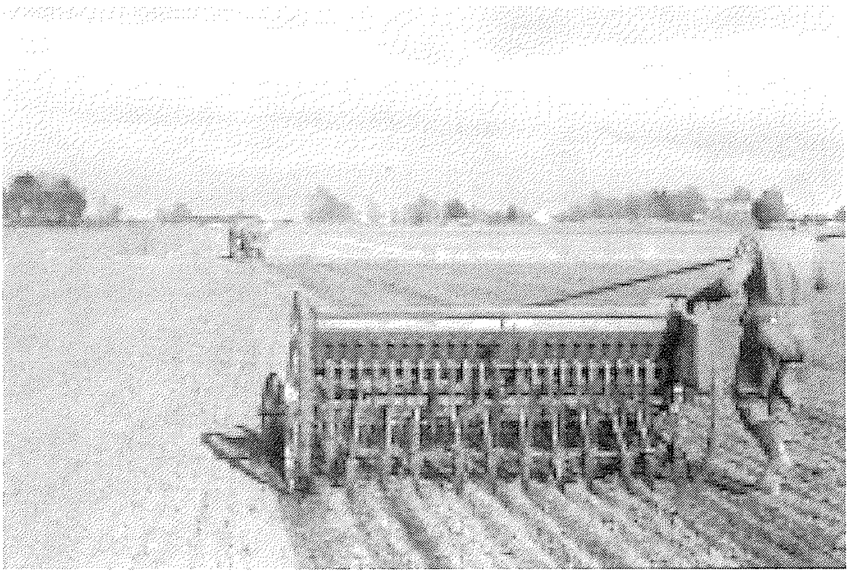


Fig. 39. Outline of a so-called gantry, by which it is possible to apply a controlled-traffic system to protect the main part of the field area from soil compaction. The wheels follow a restricted system of permanent tracks. Various implements can be attached under the frame and operate in the area between the tracks. For driving on roads, the wheels are turned through 90°.

Box 18

Trials with cable-drawn implements



In two long-term trials in 1964-1984 on Swedish heavy clay soils, very vulnerable to compaction, a system with normal traffic intensity by 2-3.5 Mg tractors was compared with a zero-traffic system, where all implements except a very light plot-harvester were pulled over the plots by cable and winch (Håkansson et al., 1985). The table below shows the effects on grain yield of spring-sown cereals (mainly barley and oats) throughout the period 1968-1982. Use of tractors with single wheels (inflation pressure of rear tyres 100-120 kPa) resulted in low yields. With dual rear wheels (inflation pressure 50-60 kPa) on the tractors, mean yield was 6% higher due to reduced long-term effects on soil structure and to a more uniform state of compactness of the plough layer. In zero-traffic plots with the same sowing time, mean yield was 23% higher. In other zero-traffic plots, sowing was carried out some days earlier, and this increased the yield slightly more. However, the potential timeliness effects were only utilized to a small extent. If they had been fully utilized (Fig. 37; Box 17), the yield increase would probably have been much larger, particularly since crops with higher yield potential could then have been grown.

Mean relative grain yield of spring-sown cereals (tractors with single wheels = 100) in two long-term trials on heavy clay soils in Sweden, 1968-1982. A comparison was made between normal machinery systems with tractors with single wheels or with dual rear wheels and a zero-traffic system, where all implements were pulled over the plots by cable and winch

	Normal sowing time			Earlier sowing
Site	Tractors with single wheels	Tractors with dual wheels	Cable and winch	Cable and winch
Stensfält, 11 years	100 (2 920 kg ha^{-1})	107	120	127
Skultorp, 8 years	100 (2 910 kg ha^{-1})	105	126	125
Average, 19 years	100 (2 915 kg ha^{-1})	106	123	126

ing width. In some cases, so-called gantries (Fig. 39; Chamen et al., 1994) have been constructed and used to some extent in this way, for instance in England and Israel. Another example is an effort made in Finland to develop a very light tractor (Fig. 40) equipped with rubber tracks and automatically steered by a GPS system with a precision of a couple of centimetres.

Thus, modern techniques offer increased possibilities to construct machinery systems that induce a minimum of soil compaction. A realistic possibility seems to be the development of relatively small automatically steered machines like that in Fig. 40. Even though the work rate of an individual machine of this kind is low, several of them can be combined into a high-capacity system controlled by one person. The individual units can then either have the same or different functions, and they may be kept working round the clock. The same sizes of machines can be used on all farms. Instead of producing small series of very large and expensive machines for large farms, the manufacturers can produce large series of rather small and cheap machines for all farm sizes.

Fig. 40. This light Finnish experimental tractor with rubber tracks is automatically steered by a GPS system at a precision of a couple of centimetres.

Chapter 8
Economic consequences of compaction

Summary

Many models have been developed to predict machinery-induced stresses in soils and their impact on bulk density and other soil properties, but only a few models predict the effects on crop growth and yield. One of the latter is used here to show some examples of .soil compaction costs. caused by machinery traffic in arable fields. This model predicts various effects of machinery traffic on crop yield at the farm level, on the basis of information usually available on individual farms. The following four categories of effects can be predicted: 1) annual effects of re-compaction after loosening of the plough layer, 2) effects of plough-layer compaction that persist for some years in annually ploughed soil, 3) effects of subsoil compaction, and 4) effects of traffic in ley crops. The examples demonstrate that machinery-induced soil compaction in normal farm fields often causes yield reductions of 10% or more. In addition, it increases the environmental impact of crop production and costs of tillage.

One example illustrates that a change from traditional tyres with relatively high ground pressure to dual wheels or wide, low-pressure tyres on tractors and other machines during seedbed preparation and sowing in ploughed fields often leads to a few percent higher yield of the crop sown. The reason is that both uncompacted and excessively compacted areas in the fields are reduced. Another example shows that residual effects of plough layer compaction caused by normal machinery traffic in annually ploughed fields under Scandinavian conditions typically reduces the yield level by 5-10% in clay soils, but less in coarse-textured soils. One example illustrates that a heavy transport vehicle that causes compaction both in the plough layer and in the subsoil may generate soil compaction costs as large as the total machine and labour costs of the operation. A final example shows that total short-term and long-term compaction costs caused by a heavy tanker spreading slurry under unsuitable conditions may be of the same magnitude as the value of the plant nutrients in the manure that is being spread. These examples illustrate that the machinery system in a farm cannot be optimized unless soil compaction costs are considered. However, they also illustrate that economically-warranted countermeasures vary greatly between regions and individual farms.

8.1. Various models to estimate compaction effects

Traffic by heavy machines causes significant 'soil compaction costs' for farmers, particularly by reducing crop yields, but also for instance by increasing the need for tillage and the costs of individual tillage operations. Therefore, the machinery system on a farm usually cannot be optimized unless these costs are considered. This is evident from a review of estimations of such costs in various cropping systems (Eradat Oskoui et al., 1994). In addition, soil compaction may increase the ecological and environmental impact of crop production. However, the effects of compaction on crop growth and tillage costs, as well as on the environment, are very complex and varying and depend on soil and climatic conditions and on machinery and cropping systems.

Efforts made to develop models to predict soil compaction costs were reviewed by Eradat Oskoui et al. (1994). To be useful as a guide for practical measures, crop responses and other effects of compaction must be predicted quite accurately. At present it seems impossible to develop pure mechanistic models (models based on cause-effect relationships) that can predict these effects sufficiently accurately. This would require that all biologically important short-term and long-term influences caused by machinery traffic on soil properties and processes, including a large number of interactions, could be accurately predicted, as well as crop responses and other effects of these influences.

More limited mechanistic models have been developed by scientists in various parts of the world. Using such models, it is possible to predict the resulting state of compactness of soils with various mechanical properties and water contents, when traffic is applied by vehicles with various wheel loads, tyre sizes and ground pressures. Reviews of such models have been made for instance by Gupta & Raper (1994) and Defossez & Richard (2002). Many models start with a recently loosened soil with specified initial properties and predict the bulk density (or a directly related soil property) generated in various layers by specified traffic treatments. If optimal or critical densities of the soil in question are known, the results can provide valuable information even on the response of a crop subsequently grown at the site. Some models, for instance the SOCOMO model (Van den Akker, 1988), make predictions for soil profiles that include unloosened (subsoil) layers. On the basis of the mechanical properties of the profiles, the latter model predicts the maximum depth of compaction caused by specified vehicles. However, the review by Defossez & Richard (2002) shows that predictions made by existing models are usually rather inexact, particularly in soils with dissimilar layers or large clods. Furthermore, the predictions of some models are limited to the situation under the centre line of the wheel tracks and make no predictions for the rest of the soil volume affected. Such models can only form an incomplete base for predictions of crop responses on a field basis. Horn et al. (1998) discussed advantages and disadvantages of various types of models and the possibilities of modelling also the effects of mechanical stresses on various soil properties and processes.

Efforts have also been made to go one step further and predict effects of machinery traffic on soil properties of more direct biological importance than the bulk density. For instance, Perdok et al. (2002) showed that critical limits of penetration resistance and aeration can sometimes be reasonably well predicted. Soil compaction models have also been combined with crop production models as shown in a review by O´Sullivan & Simota (1995).

For periodically loosened soil layers, it is possible to predict the effects of traffic on some relative bulk density value, e.g. the degree of compactness (Box 11), instead of the bulk density itself. This seems to be easier, and to lead to more generally applicable and useful results (Håkansson & Lipiec, 2000). In the Swedish compaction model described in Section 8.2, prediction of the degree of compactness of the plough layer is the first step in part 1 of the model, where short-term effects of compaction on crop yield are predicted.

For predictions of crop responses to residual effects of compaction that persist after re-loosening of the soil, the only possibility for the time being seems to be a so-called statistical model based on crop response data from field trials. So far, no effort seems to have been made to include such effects in a mechanistic model. This is probably virtually impossible, even though these effects are sometimes the most important, particularly in clay soils (Section 5.3). However, to be relevant to a certain location, any statistical model must be based on an extensive pool of locally applicable experimental results, and this is still the case only in limited parts of the world. For American conditions, Gunjal et al. (1987), Lavoie et al. (1991) and Eradat Oskoui & Voorhees (1991) have developed such models, but these only consider some of the compaction effects. A somewhat wider approach was adopted by Eradat Oskoui et al. (1994).

Scandinavia seems to be the region in the world where the largest pool of locally applicable results concerning various types of crop responses to machinery traffic is available. This facilitated the development of the model by Arvidsson & Håkansson (1991) presented in Section 8.2. This model is mainly based on experimental results obtained in Sweden. It can predict the economic consequences of short-term and long-term effects of compaction in the plough layer and in the subsoil, as well as the effects of traffic in ley fields. The model is presented here in some detail, partly for pedagogic reasons and partly because it is used in Section 8.3 to show examples of economic consequences of machinery traffic. It seems possible to use a similar model even in other parts of the world after due adaptations to local cropping systems and experimental results.

8.2. A model to predict various effects of soil compaction on crop yield

A statistical model to predict the effects of machinery traffic on crop yield was developed by Arvidsson & Håkansson (1991). It was primarily intended for use on farm level to facilitate the choice of economically favourable machines or machinery systems. It can predict the four categories of effects presented in Chapter 5 (Sections 5.2, 5.3, 5.5 and 5.6).

The model is mainly based on mean crop responses obtained in Swedish field trials over periods of many years. In the individual trials, the responses varied considerably between years depending on variations in influential factors, particularly the weather. However, when a farmer decides upon a machine investment, he does not know the weather conditions during the time span when the machine is to be used. Therefore, his decision must be based on expected consequences, and these are best derived from mean effects during previous years.

Using this model, predictions can be made for an individual machine, for a group of machines or operations or for the entire machinery system on a farm. As a first step, each relevant individual category of effects is predicted and specified as a percentage of the yield of individual crops. After that, the sum of the individual effects in each crop can be calculated. Using the areas of the crops grown and the values of the harvested products, the total compaction costs are then computed for each machine or machinery system compared.

8.2.1. Annual effects of recompaction of the plough layer after ploughing

This part of the model predicts the type of effects on the crops described in Section 5.2, i.e. the crop response to the degree of compactness (*D*) of the layer between harrowing depth and ploughing depth. Then it is necessary to simultaneously consider all traffic applied after the latest ploughing up to the time when the new crop is established. The *D*-value is influenced by all field operations during this period, but after that it is assumed to persist unaltered throughout the growing season (cf. Fig. 11). Thus, all traffic during seedbed preparation, sowing and fertilizing must be considered, as well as any pre-emergence rolling, spraying or other operation. Possible spreading of manure or other soil amendment must also be considered, provided it is only followed by superficial tillage. Under the conditions in northern Europe, traffic after crop emergence can usually be disregarded, since by then the soils have usually become relatively dry and resistant to compaction, the machines used are relatively light, and many roots have already penetrated the plough layer.

The first step in the calculations is to estimate the percentages of the field area covered various numbers of times by wheel tracks as exemplified in Fig. 2. This is done on the basis of the width of the wheels and the working width of the implements, usually assuming a random traffic pattern. Areas with the same number of passes are further divided into sub-areas with different combinations of passes by individual wheels. The *D*-values generated in the individual sub-areas are then computed using load and ground pressure of the individual wheels and soil moisture conditions when they pass. After that, the *D*-value distribution is calculated for the inner parts of the field, for the headlands and, depending on the relative area of the headlands, for the whole field. Fig. 41 shows an example based on the same series of operations as that in Fig. 2, with the use of single wheels and dual wheels on the tractor.

On the basis of the *D*-value distribution and the crop type, the model then predicts the crop yield reduction as a percentage of the yield that would have been obtained if the *D*-value had been optimal throughout the field. Distinction is made between sub-areas with sub-optimal and super-optimal *D*-values. In accordance with the experimental results, the crop response curve is assumed to be the same for all soils but to differ slightly between crops (Fig. 27). The predictions are made separately for the inner part of the field, for the headlands and for the whole field. The example in Fig. 41 shows that in this case, dual wheels on the tractor caused less yield decrease because of reduced area of uncompacted soil as well as of less compaction in the tracks.

8.2.2. Residual effects of plough layer compaction that persist after ploughing

This part of the model predicts the type of residual effects of plough layer compaction on subsequent crops that may persist for up to five years in annually ploughed soils as described in Section 5.3. In this case, all field operations throughout the year may be of interest. The predictions are primarily made separately for each operation. The effects can then be summed up as desired, e.g. for all operations with a certain machine or in a certain crop, for a group of operations or for all operations throughout the year in an individual field or on the whole farm. This is possible, since the trials indicated that the crop response is approximately proportional to the traffic intensity within the range of annual traffic intensities of interest in normal farming.

For an individual field operation, the first step is to calculate the traffic intensity in Mgkm ha^{-1}, i.e. the weight of the machine in Mg multiplied by the distance driven in km ha^{-1}. For most operations, such as tillage, sowing, spraying and fertilizing, a 'productive' distance of driving is calculated from the working width of the machines. For such operations, an additional distance driven resulting from turning, overlap, etc. can usually be estimated sufficiently accurately by a schematic addition of 20-25% to the productive distance (Section 1.2). For some operations, such as manure spreading or harvest of forage crops, the additional distance is usually much larger and much more variable, and cannot be estimated in a schematic way. In these cases, the addition must be chosen with respect to the situation on the individual farm or field and may be as high as several hundred percent.

The next step is to compute what could be called the 'compaction potential' of the vehicle during the operation. The original Mgkm-value is multiplied by an adjustment factor that depends on the ground pressure

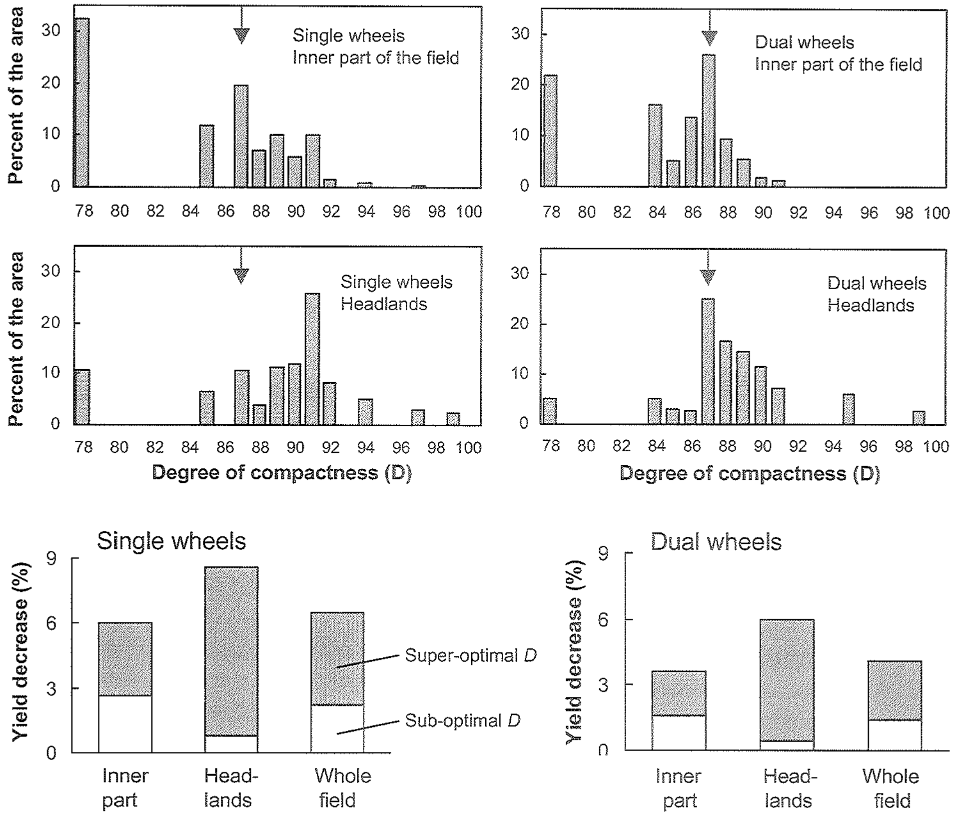


Fig. 41. Predicted annual effects of compaction of the plough layer during traditional seedbed preparation and sowing of a spring-sown cereal crop in an autumn-ploughed field in Sweden. The same series of field operations as in Fig. 2 is carried out, i.e. three harrowings, fertilizing and sowing. The four diagrams at the top show distribution of the degree-of-compactness (D) in the field caused by the whole series of operations when using single, standard tyres on the tractor and when using dual wheels. Data are shown separately for the main part of the field (the inner part) and for the headlands. The D-value in the untrafficked area is assumed to be 78. Arrows show the optimal D-value. The diagrams at the bottom show the yield decreases in the crop sown (wheat or barley). These are given as a percentage of the yield that would have been obtained if the D-value had been optimal throughout the field area, with a distinction made between decreases in areas with super-optimal (grey) and sub-optimal (white) D-values.

Widths: harrow 8 m, fertilizer spreader 12 m, seed drill 6 m, tractor rear wheels 0.65 m (single, ground pressure 100 kPa) or 0.94 m (duals, 80 kPa), tractor front wheels 0.55 m (single 130 kPa, duals 100 kPa), wheels of seed drill and fertilizer spreader 0.50 m (170 kPa). Weights: tractor 7 Mg, seed drill and fertilizer spreader 3.5 Mg (when half loaded).

of the tyres (often equal to the inflation pressure or slightly higher) and on the moisture conditions at time of traffic (Fig. 42). Soil moisture conditions are characterized on a subjective soil moisture scale (Table 12). The adjustment factor increases linearly with the soil moisture class and the logarithm of the ground pressure. Its highest value is 1.5, since this forms a kind of trafficability limit over which the machine can no longer move. The values of the adjustment factor were mainly established on

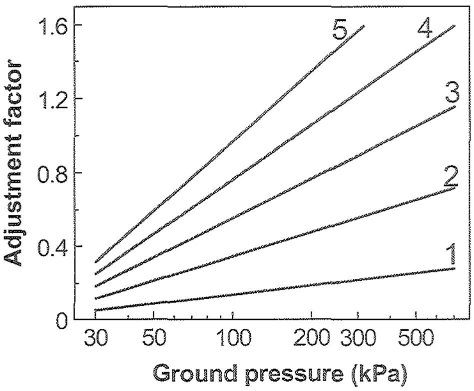


Fig. 42. Adjustment factor for ground pressure and soil moisture conditions used to calculate the 'compaction potential' of a vehicle during a field operation. The ground pressure is usually assumed to be the same as the tyre inflation pressure or slightly higher. The moisture conditions are classified on a subjective scale from 1 to 5 according to Table 12. At normal spring sowing in northern Europe, the moisture class is usually between 3 and 3.6 and this results in an adjustment factor for the tractors between 0.4 and 0.9 depending on the wheel equipment.

the basis of the experimental results presented in Fig. 30 and Table 5. By setting the adjustment factor to 1.0 for the mean conditions that occurred when traffic was applied in the trials in Fig. 30 (ground pressure 200 kPa; soil moisture class 3.7), the mean yield loss in these trials could be directly used for prediction of the crop responses.

On the basis of the compaction potential of the vehicle during the operation, expressed by the adjusted Mgkm-value, the yield loss in subsequent crops is predicted. In accordance with the experimental results (Arvidsson & Håkansson, 1994; Fig. 30), the yield loss in percent is assumed to be proportional both to the adjusted Mgkm-value and to the clay content of the soil, and is assumed to be the same for all crops. The

The yield reduction is predicted from the number of reduced and adjusted Mgkm ha^{-1} and from the crop response sum of the effects on all subsequent crops affected (up to five years) is given as a percentage of one year's yield. Finally, the loss in € ha^{-1} is calculated. As an example, Table 13 shows the effects generated by 100 adjusted Mgkm ha^{-1}, which is a value often generated annually in a farm field.

8.2.3. Effects of subsoil compaction

The effects of subsoil compaction are predicted on the basis of the crop responses presented in Section 5.5. The calculations are made in a similar way to when the residual effects of plough layer compaction are predicted (Section 8.2.2). All traffic throughout the year with axle loads high enough to cause subsoil compaction can be considered. For individual operations, the traffic intensity in Mgkm ha^{-1} is first estimated, but then the total weight of the vehicle is not used. Instead, the topsoil is considered a protective 'cushion' that removes some of the load from each axle.

In the calculations, the subsoil is divided into two layers, 25-40 cm and >40 cm. For the 25-40 cm layer, the load on each axle is first reduced by 4 Mg. Only the reduced load is used when estimating the traffic intensity, except for the furrow wheels of tractors at mouldboard ploughing, for which the whole load (= half the axle load) is used. For the >40 cm layer, the axle load is reduced by 6 Mg before the traffic intensity is estimated, since the protective cushion is then thicker. In this case, for the furrow wheels of a ploughing-tractor, the axle load is reduced by 3 Mg. Even here, an adjustment factor for ground pressure and soil moisture conditions at time of traffic is used, and this differs to some extent from that for the plough layer. This way of handling the stress attenuation by depth is of course a simplification of the real situation, but Fig. 14 indicates that it can be justified.

The yield reduction is predicted from the number of reduced and adjusted

Table 12. Subjective soil moisture scale used when determining the value of the adjustment factor according to Fig. 42

Class	Description
1	The soil is very dry and hard; too hard for mouldboard ploughing (e.g. in the summer after several weeks without rainfall in a field with a growing crop).
2	The soil is dry and firm; barely possible to plough (e.g. in the summer after a two to three week period without rainfall in a field with a growing crop).
3	The soil is well drained and further dried to some extent by evaporation; optimal moisture conditions for ploughing (e.g. after a two week period without rainfall in a bare field previously drained to field capacity).
4	The soil is incompletely drained; pronounced wheel ruts are formed except by wide wheels with very low ground pressure; considerable wheel slip at ploughing (e.g. a day or two after a large rain).
5	The soil is very wet, surface water usually occurs in spots; deep ruts are formed even by vehicles with low-pressure tyres, vehicles with normal wheel equipment get stuck; ploughing practically impossible.

Mgkm ha^{-1} and from the crop response data shown in Fig. 34. It is assumed that half of the yield reductions in the trials were caused by compaction of the 25-40 cm layer and the other half by compaction of the >40 cm layer. Furthermore, it is assumed that crop responses to compaction of the 25-40 cm layer disappear linearly during a ten year period, whereas they are permanent in the >40 cm layer. This is probably an underestimation of the persistence of the effects in the former layer, but on the other hand, the effects in the latter layer may not be completely permanent.

For the 25-40 cm layer, it is assumed in the model that each reduced and adjusted Mgkm ha^{-1} causes a total crop yield reduction during subsequent 10-year period of 0.025% of one year's yield. This implies that an application of 40 reduced and adjusted Mgkm ha^{-1} each year during a period of more than 10 years leads to an equilibrium state with a yield reduction of 1%. An annual application of 2-3

Table 13. Total value of crop yield losses (€ ha^{-1}) in subsequent years caused by plough layer compaction in annually ploughed soils with different clay contents when the traffic intensity is 100 adjusted Mgkm ha^{-1} and the mean value of the harvested product varies. Yield losses occur up to five years after compaction and are assumed to increase linearly from 0 in a soil without clay to 0.077% per adjusted Mgkm ha^{-1} at a clay content of 50%

Annual crop value (€ ha^{-1})	Clay content of the plough layer (%)				
	10	20	30	40	50
500	7.7	15.4	23.1	30.8	38.5
1000	15.4	30.8	46.2	61.6	77.0
1500	23.1	46.2	69.3	92.4	115.5

times this value may occur on farms with intensive use of heavy machines.

For the >40 cm layer, it is assumed that the yield reduction caused by traffic on one occasion is permanent and amounts to 0.0025% for each reduced and adjusted Mgkm ha^{-1}, calculated as described for this layer. Thus, each increment of 400 Mgkm ha^{-1} permanently reduces crop yields by 1%, and on farms with intensive traffic by heavy vehicles such an increment may be reached in less than ten years. It is up to the user of the model to decide which time span to consider when calculating the economic consequences of compaction in this layer.

For both layers, it is tentatively assumed that crop responses in percent are the same in all soils and crops. Experimental results are not yet sufficient to make it possible to use different values for different soils or crops. Only the mean results of all trials are reasonably well established. This, however, is not too severe a limitation for practical use, since negative responses have been established in various crops and soils, and since most farms grow more than one crop and have a quite wide range of soils.

In the short term, the crop yield reductions caused by subsoil compaction may seem small. However, since they are cumulative and very persistent they are important in the long run. Furthermore, they are obtained in addition to the effects caused by the same traffic in the plough layer.

8.2.4. Effects of machinery traffic when harvesting ley crops

This part of the model predicts the type of effects presented in Section 5.6.1. The first step is to calculate the wheel track distribution in the field in a similar way to that when predicting the annual effects of plough layer compaction (Section 8.2.1; Fig. 2). After that, yield losses at subsequent cuts are predicted on the basis of the experimental results presented in Section 5.6.1, while considering load and ground pressure of individual wheels, soil moisture conditions at time of traffic, age of the ley and number of cuts per year. Furthermore, the climatic region is considered, since in the Swedish trials the negative crop response was more persistent in regions with harsh winters than in those with mild winters. This implies that this part of the model should not be used unless locally acquired crop response data are available. The results can be shown both for the inner part of the field and for the headlands. The distribution of sub-areas with different yield reductions (Fig. 43) as well as the yield loss for the whole field can be shown.

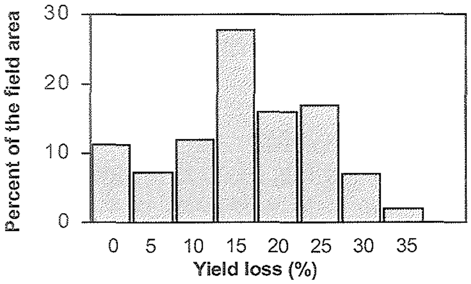


Fig. 43. Percentage of the field area with predicted crop yield losses of various magnitudes caused by machinery traffic at harvest of ley. This example shows losses at the second cut in a field where nearly 90% of the field area was covered by wheel tracks at the first cut, when the soil was wet and a considerable wheel slip occurred.

8.3. Example of economic calculations

This section shows some examples of economic consequences of machinery traffic in various situations as predicted by the model presented in Section 8.2. The examples are chosen to illustrate the importance of various influential factors. Predictions by the model are most directly applicable to Scandinavian conditions, since it is mainly based on experimental results from this region. However, in a more qualitative way

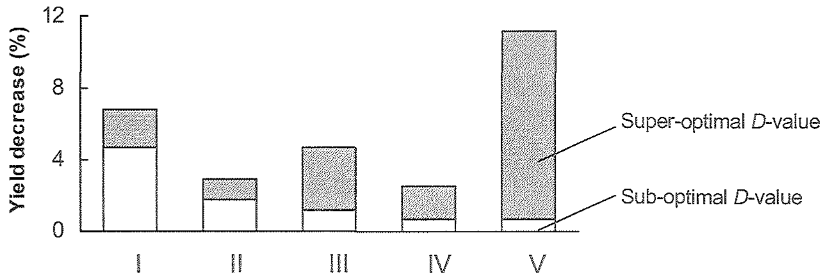


Fig. 44. Estimated effects in a spring-sown wheat or barley crop caused by soil compaction during seedbed preparation and sowing by five machinery systems described in the text. Each column shows total yield losses as a percentage of the yield that would have been obtained if the degree of compactness (*D*) had been uniform and optimal (i.e. 87, cf. Section 5.2) throughout the field area. Losses in areas with sub-optimal and super-optimal *D*-values are indicated by different colours.

the results are applicable to other regions with a temperate climate or even to regions with quite different conditions. In Chapter 9 the present situation concerning soil compaction in various agricultural regions is discussed in more general terms. Examples of economic calculations have also been presented by Gunjal et al. (1987), Lavoie et al. (1991), Eradat Oskoui & Voorhees (1991) and Eradat Oskoui et al. (1994).

8.3.1. Effects of recompaction of the plough layer after loosening

Fig. 44 shows an example of effects predicted by the component of the model presented in Section 8.2.1. It shows the effects in a spring-sown wheat or barley crop caused by compaction during seedbed preparation and sowing with different machinery systems in an autumn-ploughed field. Machines typical for a relatively small Swedish farm are used. In all cases, a drill for combined sowing and fertilizer placement is used. Traditional seedbed preparation with separate harrowings is compared with an once-over system, where the above-mentioned drill is combined with a powered harrow. Sowing is carried out a couple of days after the field has dried up enough to be workable with traditional implements (soil moisture class 3.4; Table 12). The tractors used have either single wheels or dual wheels. In system V, farmyard manure is also spread, but this is done some days earlier, when the soil moisture class is 3.7. The following systems are compared:

I Once-over system with a powered harrow and a drill for combined sowing of seed and placement of fertilizer; the tractor has relatively narrow single wheels;
II As in I, but with one initial, separate harrowing; the tractors have dual rear wheels;
III Three separate harrowings, combined sowing of seed and placement of fertilizer; the tractors have wheel equipment as in I;
IV As in III, but the tractors have wheel equipment as in II;
V As in III, but with manure spreading before harrowing.

The weight of the tractor used for pulling the harrow/drill combination in systems I and II is 6.1 Mg, for separate harrowings in systems II-V it is 5.0 Mg and for combined sowing of seed and placement of fertilizer in systems III-V it is 4.0 Mg. The manure spreader in system V weighs 7 Mg when carrying half the maximum load, and it is pulled by a 5.0 Mg tractor. Ground pressure of the rear tyres of the tractors in I, III and V is 100 kPa, in II and IV it is 75 kPa and of the manure spreader 200 kPa. The working width is 5.5 m for separate harrowing, 3 m for combi-sowing and 5 m for manure spreading.

The yield loss is largest in system V, less in systems I and III, and least in systems II and IV (Fig. 44). In system V, a large proportion of the field area is intensively compacted at manure spreading. Particularly in system I (tractor with single wheels), a substantial loss is inflicted because a large part of the field area is uncompacted, whereas the soil in some of the wheel tracks is too dense. In systems II and IV (tractor with dual wheels), the loss is small, since most of the field area is compacted, but only to a *D*-value near the optimal.

8.3.2. Effects of compaction in the plough layer that persist after ploughing

Table 14 shows residual effects in subsequent crops caused by normal annual machinery traffic in two crops, spring-sown cereals and sugar beet, as predicted by the component of the model described in Section 8.2.2. Data in the table were originally obtained for machines typical for Scandinavian farms in the late 1990s. At that time, tractors used for most operations weighed about 8 Mg and cereal and sugar beet harvesters about 10 and 8 Mg, respectively, when loaded to half their capacity. The efficient working width was about 9 m for harrows, 2 m for mouldboard ploughs, 6 m for cereal harvesters, 1.5 m for sugar beet harvesters (tractor-drawn, 3 rows) and 24 m for sprayers. However, re-calculations for new and heavier machines showed that, for most operations, this scarcely altered the results at all, since the working widths had increased nearly proportionally to the weights of the machines. The table shows estimated Mgkm-values as well as percentage yield losses in subsequent crops on soils with clay contents of 10% and 40%.

There is a large difference between cereals and sugar beet in total number of Mgkm ha^{-1}, and most of this difference is generated at harvest. In sugar beet, harvest alone usually generates at least as large Mgkm-values as all traffic throughout the year in a cereal crop. If harvesting is carried out when the soil is wet, the adjusted Mgkm-values become very large, and in clay soils this leads to substantial yield losses in subsequent crops.

The importance of wheel equipment and moisture conditions when harvesting sugar beet is highlighted in Table 15. This table shows predicted residual effects of plough layer compaction caused by a harvester generating a traffic intensity of 170 Mgkm ha^{-1} before adjustment for ground pressure and soil moisture conditions. In addition, the harvester probably causes compaction in the subsoil, to an extent that depends on load and ground pressure on individual wheels, but this is not considered here. The values in the table clearly show the importance, particularly on clay soils, of choosing wheel equipment and time of harvest carefully. They also indicate one of the reasons why there was a tendency to move sugar beet production in Sweden from clay soils to coarse-textured soils when harvesting was mechanized.

8.3.3. Effects of subsoil compaction

The following example illustrates the effects predicted by the part of the model presented in Section 8.2.3. It shows yield losses caused by compaction both in the plough layer and in the subsoil as a result of a transport operation in the autumn. A trailer with a single axle and weighing 4 Mg when empty and 14 Mg when fully loaded, is pulled by a 7 Mg tractor (Table 16). When the trailer is empty, the whole tractor-trailer unit weighs 11 Mg and axle loads are (from front to rear) 2 Mg, 6 Mg and 3 Mg. With fully loaded trailer, the total weight is 21 Mg and the axle loads are 2 Mg, 8 Mg and 11 Mg. Mean ground pres-

Table 14. Estimated annual number of Mgkm ha^{-1} and total yield loss in subsequent crops (% of one year's yield) caused by residual effects of compaction of the plough layer that persist after ploughing. Estimations are made for the number of annual field operations traditionally used for spring-sown cereals and sugar beet in Scandinavia. It is assumed that machines of normal type and size are used and that they are equipped with tyres commonly available on the market. The resulting yield loss is given for soils with clay contents of 10% and 40%

	Spring-sown cereals				Sugar beet			
	Mgkm ha^{-1}		Yield loss (%)[b]		Mgkm ha^{-1}		Yield loss (%)[b]	
Operation	A[a]	B[a]	10% clay	40% clay	A[a]	B[a]	10% clay	40% clay
2-3 harrowings	27	11-25	0.3	1.1	35	14-32	0.4	1.5
Sowing	12	5-11	0.1	0.5	12	5-11	0.1	0.5
Fertilizing	7	3-7	0.1	0.3	7	3-7	0.1	0.3
Spraying	4	1-4	0.1	0.2	25	7-23	0.2	0.9
Mech. weeding	-		-	-	16	5-14	0.2	0.6
Harvest	35	9-42	0.4	1.5	175	105-210	2.5	9.9
Stubble cultivation	18	9-14	0.2	0.7	-		-	-
Ploughing	37	18-44	0.5	1.9	37	18-44	0.5	1.9
Total	140	60-140	0.9-2.2	3.7-8.6	307	160-330	2.5-5.1	9.9-20.3

[a] The Mgkm values are given A) for normal machines before adjustment and B) after adjustment for soil moisture and ground pressure (cf. Fig. 42). The lowest values in B are obtained when low-pressure tyres are used under the driest conditions that normally occur during the operation and the highest values when standard tyres are used under the wettest conditions.

[b] For each individual operation the yield loss is given for an adjusted Mgkm-value in the middle of the range in column B.

Table 15. Predicted crop yield loss in subsequent crops caused by sugar-beet harvest by a harvester generating a traffic intensity of 170 Mgkm ha^{-1} (unadjusted value). Clay content of the soil is 10% or 40%, the soil is either drier than normal for Swedish conditions (below field capacity, class 3.0; Table 12) or wet (class 4.0), ground pressure of all tyres is 150 or 250 kPa and the mean annual value of subsequent crops is 500 or 1500 € ha^{-1}

Clay content (%)	Soil moisture class	Yield loss, % of one year's yield		Yield loss, € ha^{-1}, at a crop value of			
				500 € ha^{-1}		1500 € ha^{-1}	
		150 kPa	250 kPa	150 kPa	250 kPa	150 kPa	250 kPa
10	3.0	1.8	2.2	9	11	27	33
10	4.0	2.5	3.0	12	15	37	45
40	3.0	7.1	8.7	36	48	107	130
40	4.0	9.8	12.0	49	60	148	181

sure is 100 kPa for the tractor wheels and 200 kPa for the trailer wheels. The traffic is applied after harvest (1000 m ha^{-1}) and is followed by ploughing. Clay content of the plough layer is 20% and soil moisture class (Table 12) is 3.0 (relatively dry) or 4.4 (nearly the wettest possible for this vehicle).

When the trailer is empty, compaction effects in the subsoil are small. The rear axle of the tractor is the only axle with a load over 4 Mg, which is considered in the model to be a limit below which no subsoil compaction occurs. No axle load exceeds 6 Mg, which is the lower limit for compaction in the >40 cm layer. Yield losses are mainly caused by plough layer compaction.

When the trailer is fully loaded, the subsoil compaction effects are larger. Now the >40 cm layer is also affected, and this is assumed to cause permanent yield reductions. The effects may seem small even now, but since they are very persistent, the total effects over many years are considerable. However, in the calculations here (Table 16) only the effects during the first fifteen-year period are considered.

To facilitate a comparison between compaction costs and machine and labour costs when using this vehicle Table 16 shows the driving distance required to cause a yield loss of 1 €. This is based on the predicted total yield loss during the whole subsequent fifteen-year period. The mean annual value of the harvested products is assumed to be 800 € ha^{-1}. Traffic by the fully loaded trailer under wet conditions is predicted to generate a loss of 1 € when driving a distance of only 90 m. When driving in the field for one hour, the distance driven is likely to be about 6 km. If half this distance is driven with the trailer fully loaded and the other half with the trailer empty, the estimated compaction costs would be 43 €, caused almost equally by subsoil and plough layer compaction. With higher crop values or when considering a longer period than fifteen years, the losses would be greater than those shown in the table. Furthermore, a relatively small increase in the axle loads would cause con-

Table 16. Number of reduced and adjusted Mgkm ha^{-1} and yield loss in subsequent crops caused by compaction in three soil layers due to traffic at harvest time by a tractor (7 Mg) and trailer (4 Mg when empty, 14 Mg when fully loaded). The distance driven is 1000 m ha^{-1} (one track every 10 m). Clay content of the plough layer is 20% and soil moisture class at driving is 3.0 or 4.4 (Table 12). The driving distance leading to a yield loss of 1 € during subsequent fifteen years is also shown for a mean annual value of the harvested product of 800 € ha^{-1}

Moisture class	Layer	Mgkm ha^{-1}		Yield loss (%)[a]		Driving distance (m)	
		Empty	Loaded	Empty	Loaded	Empty	Loaded
3.0	0-25 cm	7.1	14.7	0.22	0.45		
	25-40 cm	1.0	6.0	0.03	0.15		
	>40 cm	0.0	3.6	0.0	0.13		
	Totally	8.1	24.3	0.25	0.73	500	170
4.4	0-25 cm	10.7	22.1	0.33	0.68		
	25-40 cm	2.3	14.3	0.06	0.36		
	>40 cm	0.0	8.9	0.0	0.33		
	Totally	13.0	45.3	0.39	1.37	320	90

[a] Yield loss as a percentage of one year´s yield during periods of 5, 10 and 15 years, respectively, caused by compaction of the 0-25, 25-40 and >40 cm layers (cf. Chapter 5).

siderably greater losses due to subsoil compaction. Lower clay content in the soil would cause smaller effects of plough layer compaction and higher clay content would cause greater effects, but the predicted effects of subsoil compaction would be unaltered.

8.3.4. Combined effects

Table 17 shows an example of traffic that causes both plough layer and subsoil compaction and affects the crops both in the short-term and in the long-term. It comprises a comparison between spreading of slurry manure by a non-aggressive and a very aggressive procedure on soils with various clay contents. The spreading is made some days before sowing of a spring-sown crop and the manure is incorporated only by shallow harrowing. It is assumed that mouldboard ploughing is carried out each autumn.

In both cases, an 8 m^3 spreader is used. This weighs 4 Mg when empty and is pulled by a 6 Mg tractor. In the first case (the non-aggressive procedure), the spreader has a tandem axle unit. When the spreader is empty, the loads on the front and rear axles of the tractor and on the tandem axle unit of the spreader are 2 Mg, 5 Mg and 3 Mg, respectively, and when the spreader is fully loaded, these loads are 2 Mg, 7 Mg and 9 Mg. Both tractor and spreader tyres have a ground pressure of 80 kPa. Spreading width is 12 m and spreading is carried out when the soil has dried up well and soil moisture class is 3.5 (cf. Table 12). The traffic system is well planned and the distance driven is 1.8 times the spreading distance.

In the second case (the very aggressive procedure), the spreader has a single axle that carries the same load as the tandem

Table 17. Predicted crop yield losses and increased tillage costs caused by soil compaction in the plough layer and in the subsoil when spreading slurry before spring sowing in fields with clay contents of 10%, 30% and 50%. The spreading is carried out either in a non-aggressive way or in a very aggressive way

	Non-aggressive spreading			Very aggressive spr.		
Type of effects	10%	30%	50%	10%	30%	50%
1. Effects in the plough layer in the same year (%)[a]	2.8	2.8	2.8	8.9	8.9	8.9
2. Residual effects in the plough layer (%)[b]	0.2	0.6	1.0	1.5	4.6	7.7
3. Effects in the 25-40 cm layer (%)[c]	0.1	0.1	0.1	0.9	0.9	0.9
4. Effects in the >40 cm layer (%)[d]	-	-	-	0.3	0.3	0.3
Total yield loss (%, sum of 1-4)	3.1	3.5	3.9	11.6	14.7	17.8
Total yield loss (€ha^{-1})						
at an annual crop value of 500 € ha^{-1}	15	17	19	58	73	89
at an annual crop value of 1000 € ha^{-1}	31	35	39	116	147	178
Increased tillage costs (€ ha^{-1})[e]	2	4	6	5	9	13
Total loss (yield loss + increased tillage costs, € ha^{-1})						
at an annual crop value of 500 € ha^{-1}	17	21	25	63	82	102
at an annual crop value of 1000 € ha^{-1}	33	39	45	121	156	191

[a] This effect may vary considerably depending on the methods of seedbed preparation and sowing.
[b] Total loss during a five-year period (% of one year´s yield).
[c] Total loss during a ten-year period (% of one year´s yield).
[d] Total loss during a fifteen-year period (% of one year´s yield).
[e] Only roughly estimated, possibly too conservatively (cf. Section 8.4).

axle unit in the previous case. The loads on the tractor axles are unaltered. The ground pressure of the tractor is 140 kPa and of the spreader 200 kPa. Spreading width is 6 m and spreading is carried out while the soil is still wet and the soil moisture class is 4.1. The traffic system is poorly planned and the distance driven is 4.0 times the spreading distance.

In the coarse-textured soil, the effects in the same year as the spreading dominate. However, the higher the clay content, the greater are the residual effects, and in the clay soil, these can be as great as the effects in the year when spreading is carried out. The compaction effects in the subsoil mainly depend on whether the spreader has a single axle or a tandem axle unit. With the very aggressive procedure (high ground pressure, single axle, small spreading width, large distance driven, wet conditions), the compaction costs may be higher than the spreading costs or the value of the plant nutrients in the manure. With the non-aggressive procedure, the compaction costs are much lower. The cheapest and most influential countermeasure is to plan the traffic pattern carefully to obtain the shortest possible driving distance, particularly when the spreader is fully loaded. Proof that the yield losses presented in Table 17 are realistic is provided by some Swedish experiments with various times of spreading of farmyard manure to spring-sown small grains (Etana, 2004). A spreader similar to that in the example was used and a relatively high amount of manure was applied, but no mineral fertilizer. When spreading was carried out in a clay soil under wet conditions some days before sowing, the crop yield in the year of spreading was even lower than in unmanured and untrafficked control plots, and in addition, residual effects could be expected in subsequent years.

8.4. Draught requirement in compacted soil

Compaction of the plough layer increases the draught forces required for tillage operations, and thereby both fuel consumption and costs. Sometimes the number of tillage operations must also be increased. In a German investigation (Petelkau, 1986), the draught force required to loosen a sandy soil was more than twice as great in wheel tracks repeatedly trafficked by wheels with ground pressures of 300 and 500 kPa than in untrafficked soil. In a long-term field trial on clay loam soil in Scotland (Dickson & Ritchie, 1996a), machinery systems with conventional tyres and low-pressure tyres increased the mean power requirement for primary cultivation by 59% and 39%, respectively, and for secondary cultivation by 52% and 39% compared to a zero traffic system. In these trials, tyre inflation pressures for conventional and low-pressure tyres were: 100-120 kPa and 30-40 kPa, respectively, for tractors, 160 kPa and 120 kPa for combine harvesters and 250 kPa and 150 kPa for trailers. This indicates that in spite of a larger wheel track area, reduced compaction in the tracks when using wide, low-pressure tyres may reduce the power requirement on a field basis by more than 10% compared to the use of conventional tyres. In the Netherlands, Lamers et al. (1986) found the specific ploughing resistance to be 25% lower in untrafficked soil than in soil with normal field traffic by tractors and other machines. In investigations in the former Soviet Union (Nikiforov et al., 1993), the fuel consumption for subsequent field operations decreased by 7-60% after changing from high-pressure tyres to low-pressure tyres on the machines.

In a Swedish investigation (Fig. 45), the draught force required in the autumn to pull a winged cultivator coulter at a depth of 18 cm was measured in plots where tractor traffic had been applied in spring. After one pass track by track by a tractor with single wheels while the soil was wet, the draught force was about three times greater than in untrafficked control plots. One pass track by track by the same tractor with dual wheels, or when the soil was drier, caused a much smaller increase in draught force. However, when using dual wheels, the tracks were twice as wide as when using single wheels, and this made the traffic intensity as measured in Mgkm ha^{-1} only half as great.

These examples show that increased costs of tillage operations may be an economically important consequence of soil compaction. This is particularly the case if the number of tillage operations has to be increased. However, more systematic investigations of these effects are required to make it possible to quantify them under various conditions. In cases where soil compaction prevents a change from traditional mouldboard ploughing to a reduced tillage system with lower tillage costs and reduced erosion, this may even be its most detrimental consequence. In addition, increased fuel consumption for tillage operations in compacted soil leads to greater release of exhaust gases to the atmosphere in the form of CO_2 and NO_X, and consequently to increased environmental impact.

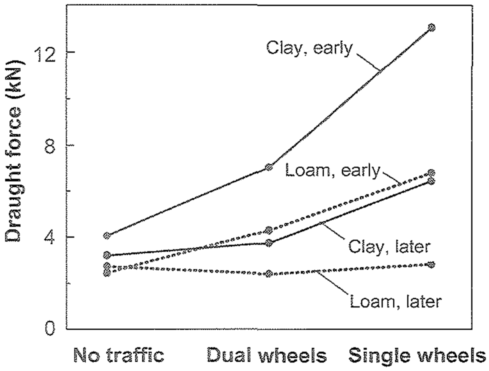


Fig. 45. Draught force required in the autumn to pull a winged cultivator coulter at a depth of 18 cm in soils with and without tractor traffic in spring. The tractor had either single or dual rear wheels and one pass track by track had been applied either very early, while the soil was still wet, or a couple of weeks later, when the soil was drier. Measurements were made on a loam soil and a heavy clay soil. (After Edling & Fergedal, 1972).

Chapter 9
Current situation and need for load limits

Summary

Ever since agricultural field operations became mechanized, agricultural soils have repeatedly been subjected to machinery-induced compaction. However, when a traditional tillage system is used, annual loosening in combination with various natural processes seem to preclude permanent compaction damage in the plough layer. In this layer, there is rather a dynamic equilibrium nowadays between annual compacting and loosening processes. Effects of increased machinery size have usually been counterbalanced by lower ground pressure and by shorter driving distances due to reduced number of field operations and increased working width of the machines. However, the incidence and effects of plough layer compaction vary greatly and depend on soils, crops, machinery systems and climate. For most farms in Northern Europe, residual effects of previous years´ traffic together with a sub-optimal or super-optimal degree of compactness of the plough layer is currently estimated to cause crop yield losses of 5-10%. Similar effects are likely to occur in many other parts of the world as well. In addition, plough layer compaction increases the environmental impact of crop production. Therefore, for both economic and environmental reasons, compaction effects in this layer call for continuous attention, particularly since the situation can be improved.

As far as subsoil compaction is concerned, the situation is quite different. Because of its persistence and cumulative character, subsoil compaction is a serious threat to long-term soil productivity. Both the depth and intensity of subsoil compaction increase because of increasing wheel loads of machinery. For instance, on the basis of penetrometer measurements in 1993-95 in a sugar beet and potato production district in Sweden, it was estimated that compaction effects accumulated in the subsoil during 50 years of mechanized agriculture caused a persistent mean crop yield reduction of 6% in the whole district. After the time of these measurements this percentage has probably increased. To avoid intolerable permanent reduction of soil productivity, it is necessary to establish limits for mechanical stresses in the subsoil. Earlier, when only high-pressure tyres were available for high loads, pure wheel-load or axle-load limits were recommended. Today, it may be more appropriate to choose combined ground-pressure and wheel-load limits adapted to the strength of individual soils. Since subsoil compaction is a long-term issue, such limits should be the concern of society as a whole. An alternative to such limits might be a strict controlled-traffic system with completely permanent wheel tracks covering only a very small percentage of the field area.

9.1. Current situation

9.1.1. Plough layer compaction

In most industrialized countries, mechanization of agricultural field operations started in the 19th century and was completed in the middle of the 20th century. Accordingly, on most farms in Europe and North America, field operations have been fully mechanized for 50 years or more. Since the wheels of the machines affect larger portions of the field area than the hooves of draught animals did in previous systems, mechanization led to increased soil compaction (Håkansson, 1965). However, with the exception of some heavy steam engines used in the early stages, most machines used initially were rather small, and when they ran on the soil surface they mainly compacted the plough layer. Subsoil compaction was mostly caused by tractor wheels running in the open furrow during mouldboard ploughing.

Since that time, the size and weight of tractors and other machines have gradually increased. For some field operations, particularly harvest and transport operations, this has led to increased traffic intensity as measured by the number of Mgkm ha^{-1}. For other operations, such as tillage and sowing, the increased tractor weight in itself has only increased the number of Mgkm ha^{-1} marginally (Table 1), since the working width is usually almost proportional to the tractor weight. In large regions, however, the mechanization initiated an extended period with gradually increasing ploughing depth and tillage intensity, and this must have led to increased traffic intensity. More recently, this trend has been replaced by an opposing trend, since many farmers now at least temporarily use some kind of reduced tillage with shallower working depth or fewer operations. More efficient implements or combined operations have also tended to reduce the traffic intensity.

The incidence of soil compaction has also been influenced in other ways. In the model for prediction of crop responses to compaction presented in Section 8.2, the incidence of compaction is estimated on the basis of the Mgkm-values, but these are first adjusted for ground pressure of the machines and soil moisture conditions at time of traffic. For individual seedbed preparation and sowing operations, the adjusted Mgkm-values are now often lower than previously due to the introduction of low-pressure tyres. For harvest and transport operations, on the other hand, these values are often higher, since increased weight of the machines has not been fully compensated for by larger working width or lower ground pressure. However, where use of heavier machines has meant increased machinery capacity, this may have increased the possibility to avoid traffic on wet soil. On the other hand, fields have become larger and more heterogeneous, and it may have been more difficult to avoid traffic when parts of the fields are wet.

Since no statistics or systematic regional studies of trends in the extent of machinery-induced soil compaction in practical farming are available, only a rough estimation can be made. It is likely that on farms or in regions where up-to-date possibilities to minimize compaction are utilized (low-pressure tyres, combined operations, careful planning, etc.), the damage to the topsoil has not increased at all or only slightly for many years. In some farms, the damage has probably even decreased. However, on farms or in regions where compaction issues have attracted less attention, topsoil compaction may have increased considerably.

For Scandinavian conditions, a rough estimation of the crop yield losses can be made on the basis of many predictions of compaction effects on individual farms similar to those shown in Section 8.3. These predictions indicate that yield losses caused by a combination of residual effects of previous traffic and short-term effects caused by sub-optimal or super-optimal density of the plough layer on typical farms in the region amount to 5 to 10% of yield. The losses are probably seldom smaller than 5%, but with unfavourable combinations of soils, climate, crops and machinery systems they can be much larger than 10%.

It is likely that crop yield losses of similar magnitude occur in most parts of the world with mechanized agriculture. Where relatively deep annual primary tillage is carried out, the major problem in dry regions is probably losses caused by sub-optimal density of the plough layer, whereas in wet regions, losses caused by super-optimal density are more important. Residual effects of compaction probably increase with the clay content of the soil in all parts of the world, and in most areas with clay soils they are probably as important as the short-term effects. Where zero tillage or very shallow annual tillage is practised, the compaction problems are likely to be greatest in coarse-textured soils, where natural alleviating processes are relatively inactive.

9.1.2. Subsoil compaction

As far as subsoil compaction is concerned, the situation differs considerably from that for plough layer compaction. In Sections 3.3 and 5.5 it was shown that repeated passes by vehicles with high wheel loads cause cumulative compaction effects in the subsoil and that this is probably the case up to a large number of passes. It is likely that this applies even when there is a prolonged interval between individual passes. As a result, high bulk densities are usually found in the upper part of the subsoil. For example, Leinweber & Menning (1992) investigated the state of compactness of the subsoil in farm fields in Germany. They clearly found persisting compaction effects, particularly in the headlands. In the Ukraine, the bulk density of the subsoil in arable fields was compared with that in adjacent natural grassland areas in 1967 and 1982 (Håkansson & Medvedev, 1995). The bulk density was higher in the arable fields than in grassland and the differences had increased from 1967 to 1982 (Fig. 46).

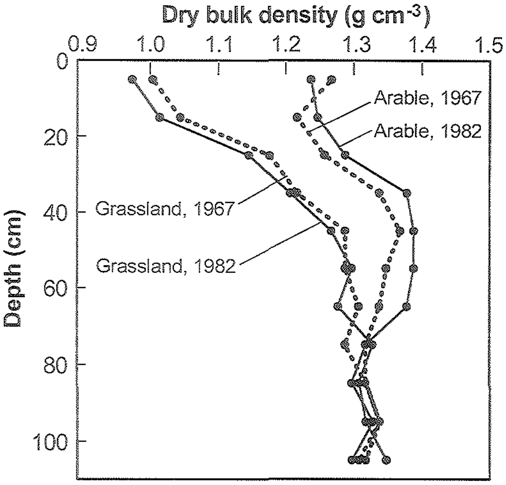


Fig. 46. Dry bulk density in soil profiles from natural grassland areas and adjacent arable fields in the Ukraine in 1967 and 1982. (After Håkansson & Medvedev, 1995.)

In most farms in northern Europe, the first generation of machines introduced when the field operations were mechanized in the mid-1900s or earlier had rather low axle loads (usually <4 Mg). This applied in other parts of the world as well. When running on the soil surface, these machines probably did not affect the subsoil to a great depth. At that time, tractor wheels running in the open furrow during mouldboard ploughing, i.e. directly on the subsoil, were presumably the major cause of subsoil compaction. Since then, axle loads have gradually increased. In Europe, axle loads of 20 Mg and even more are now used on some harvesters and transport vehicles. This is much higher than the load limits adopted or recommended in some countries (Section 9.2.4). Machines with even higher axle loads are used in some other parts of the world, but mainly in regions with a drier climate.

9.1.2.1. Penetrometer measurements in the subsoil in some farm fields

In this section, as an example, a project carried out in 1991-1995 with the objective of quantifying the long-term compaction effects accumulated in the subsoil in normal farm fields is described in some detail. Penetrometer measurements were carried out in two regions in Sweden, Halland and Uppland, with different cropping systems (Håkansson et al., 1996). The aim was to investigate whether machinery traffic applied during previous field operations had caused persistent compaction effects in the subsoil to an extent that could be predicted on the basis of existing experimental results. The hypothesis was that the total amount of heavy traffic applied during 40-50 years of mechanized field operations had compacted the subsoil at depths of 40 cm and deeper to the predicted extent. It was assumed that compaction before the mechanization of field operations was limited to the 0-40 cm layer.

The measurements were made to a depth of 60 cm in normal farm fields and in immediately adjacent control plots with the same soil type where no machinery traffic had been possible for more than 30 years. In Halland, the measurements were made both in headlands and inner parts of the fields. The measurements were made when soil water content was similar (at field capacity) in the fields and in the control plots.

The Halland region has intensive sugar beet, potato and animal production, and large quantities of manure are spread by heavy vehicles. In the Uppland region, cereal production dominates. The total amount of traffic by vehicles with axle loads >5 Mg since the start of mechanization was estimated to be four times higher in Halland than in Uppland. Practically no vehicles with axle loads >10 Mg had been used. In Halland, 17 sites were investigated, 8 of them on clay or clay loam soils and 9 on coarse-textured soils. In Uppland, 8 sites were investigated, all on clay or clay loam soils.

In both regions, the penetration resistance in the subsoil was significantly higher in the fields than in the control plots (Fig. 47). In Halland, the results were very similar in heavy and light soils, and therefore only the mean results are shown. In the upper part of the subsoil, the resistance was significantly higher in the headlands than in the inner parts of the fields. In the inner parts of the Halland fields, the resistance was 53% higher than in the control plots at 32 cm depth and 13% higher at 60 cm depth. In Uppland, the corresponding values were 17% and 2%.

At 40 cm depth, the penetration resistance in the Uppland fields was 10% higher, in the inner parts of the Halland fields 40% higher and in the headlands 45% higher than in the control plots. The fourfold higher increase in Halland than in Uppland is in agreement with the estimated total amount of traffic by vehicles with axle loads >5 Mg. The relative increase also agreed well with the increase that was expected from the measurements in the field trials presented in Table 2. This indicates that the results of these field trials (Table 2 and Fig. 34) are applicable to practical farm conditions.

All measurements were made in early spring before soils had started to dry and harden, yet the mean penetration resistance in the fields in both regions was above 1.5 MPa, a value usually regarded to be partly restrictive to root growth (Section 4.3.2). Since the penetration resistance increases when a soil dries out, it is likely that the resistance usually limits the growth rate of roots in the subsoil more or less during a large part of the growing season in both regions.

In the trials referred in Section 5.5, four passes by a vehicle with an axle load of 10 Mg resulted in a persistent increase in the penetration resistance at 40 cm depth of 17% and a decrease in crop yield of 2.5%.

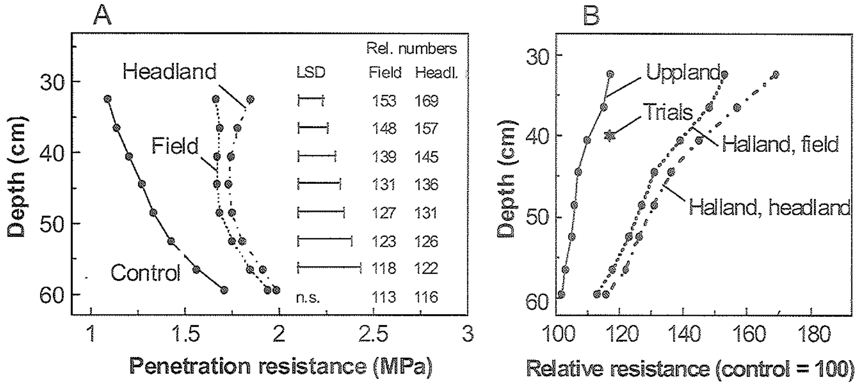


Fig. 47. Results of penetrometer measurements in the subsoil in representative farm fields in two regions in Sweden and in adjacent control plots never trafficked by heavy machines. 17 sites were investigated in Halland, a region with sugar beet, potato and animal production, and 8 sites in Uppland, a region dominated by cereal production.
A. Mean penetration resistance in control plots, in the inner parts of the fields and in the headlands in Halland. The bars to the right show least significant differences ($p<0.05$).
B. Relative values of penetration resistance in the fields (control plots = 100) in Halland and in Uppland. Mean increase in the penetration resistance at 40 cm depth in field trials with traffic by vehicles with an axle load of 10 Mg is also shown (cf. Table 2).

Both the increase in penetration resistance and the decrease in yield were approximately proportional to the number of passes (Håkansson & Reeder, 1994). These results were used by Håkansson et al. (1996) to estimate the mean yield losses due to subsoil compaction in Halland and Uppland at the time of the measurements.

In the Halland fields, the penetration resistance at 40 cm depth had increased 2.4 times more than in the trials. By assuming that the crop yield loss was also 2.4 times greater, the loss was estimated to be 6%. The corresponding value for Uppland was 1.5%. These estimations are of course somewhat uncertain (the loss may be both higher and lower), but they seem to be the best possible. Since compaction of the plough layer (together with over-loosening) probably caused an additional yield loss of between 5 and 10% (Section 9.1.1), the total yield loss in a typical Halland farm was estimated to be 12-15%. Only some of the yield loss caused by subsoil compaction was estimated to be permanent. If all further subsoil compaction could have been stopped at that time, Håkansson et al. (1996) estimated that natural processes would have gradually alleviated the effects in the uppermost subsoil layers, but not in deeper layers. They estimated that two-thirds of the yield loss of 6% in Halland would then be regained within ten to twenty years, whereas one third, or 2%, would be permanent. If traffic intensities and machinery sizes occurring at that time remained constant, it was predicted that the non-permanent part of the losses would also remain constant, whereas the permanent part would increase by 1% per 15 years. However, since heavier machines have gradually been introduced, in reality the permanent part of the loss has probably increased somewhat faster, whereas the non-permanent part is unaltered.

9.1.2.2. General assessment

The investigation described in previous section indicated that the extent of subsoil compaction induced by heavy traffic in normal farm fields can be roughly predicted on the basis of results obtained in the field experiments, and it may be assumed that the same applies to crop responses. The situation with respect to subsoil compaction in other parts of Northern and Western Europe is probably similar to that in Scandinavia. This means that crop yield losses generally increase with increasing intensity of agriculture and with increasing weight of machines used in the region. So far, subsoil compaction and resulting crop yield losses have generally been regarded as being smaller in dry regions than in wet. However, this may not be true, since findings by Trautner (2003) indicate that compaction in deep subsoil layers may even be greater under dry conditions than under wet (Section 3.3).

This means that most soils in the industrialized countries are already suffering from very persistent or even permanent reduction of their production capacity to a lesser or greater extent. With prevalent machinery sizes, the permanent reduction seems to be increasing relatively rapidly, and in some cases this applies to the non-permanent reduction as well. If the wheel loads are further increased, there is a risk of a more rapid increase, particularly of the permanent part. As indicated in Chapter 6, the environmental impact of crop production will probably also increase.

Low-pressure tyres or dual wheels decrease the stresses induced in the subsoil, particularly in its upper part. This has sometimes been thought to offer a possibility to completely eliminate compaction problems in the subsoil. However, low-pressure tyres may be less efficient in this respect than they first appear. The reason is that they generate wider wheel tracks. Therefore, even though the compaction is less intensive under the central parts of the tracks, a larger soil volume is usually affected. Consequently, over a period of some years, the number of passes over each point in a field increases, and this may reduce the positive effect of lower ground pressure.

When subsoil compaction has reached a certain level, it is possible to reduce its effects in many soils by deep loosening. However, subsoil loosening can only set an upper limit to the negative effects, but a complete alleviation seems impossible (Box 7). Furthermore, deep loosening is expensive and often troublesome. Its effects are usually of short duration and sometimes even negative. Therefore, any further increase in machinery-induced subsoil compaction should be counteracted as much as possible. This means that mechanical stresses in the subsoil must be limited to a level that does not cause unacceptable compaction.

9.2. Need for load limits

This section comprises a discussion of the need to limit machinery-induced stresses in soils and efforts made in various countries with this objective. Håkansson & Medvedev (1995) specified the objectives of stress limits as follows: (1) to improve efficiency and resource economy of crop production in the short-term, (2) to maintain soil quality (productivity) in the long-term and (3) to reduce the negative impact of crop production on the environment.

Making crop production efficient and resource conservative is usually a primary economic interest of farmers. Therefore, the achievement of objective (1) can be left to them without interference from society, but the farmers need methods and machines that facilitate this goal. On the other hand, the achievement of objectives (2) and (3) may be seen as the responsibility of society as a whole.

9.2.1. Efficiency and resource economy of crop production in the short-term

Efficiency and resource economy of crop production in the short-term is mainly influenced by compaction of the plough layer. This not only affects crop growth, it also increases the need for fertilizer and other commodities, such as fuel for tillage operations. Trials in Scandinavia referred to in section 5.3 indicate that the effects of compaction of an annually loosened plough layer are usually alleviated within five years. Although plough layer compaction is probably more persistent in regions without annual freezing than in freeze/thaw areas, it seems not to be permanent anywhere, provided the soil is loosened regularly. However, compaction may pose an obstacle to the use of reduced tillage. Nevertheless, even in a reduced tillage system, permanent effects in the previous plough layer can be avoided at a reasonable cost by occasional loosening. Consequently, according to the principle formulated above, compaction problems in this layer should be left to the individual farmers in their role as farm managers.

In Chapter 7 it was shown that farmers may consider numerous methods to minimize compaction or its negative effects, and each farmer should apply all methods that are profitable. However, plough layer compaction may also increase soil erosion and several other environmental effects of crop production. Furthermore, it cannot be excluded that it has some long-term, negative effects that have not yet been observed. Therefore, even society must pay some attention to the problem of plough layer compaction (Section 9.2.3).

9.2.2. *Quality of soils in the long-term*

With regard to the long-term quality (productivity) of soils, subsoil compaction is the major concern. In this respect, plough layer compaction has only limited or more indirect effects, e.g. by increasing surface runoff and erosion. In regions where erosion problems are relatively small but where heavy machines are used for field operations, machinery-induced subsoil compaction seems to be the greatest physical threat to long-term soil productivity. Therefore, it is essential to establish limits for mechanical stresses in the subsoil. Since the effects of subsoil compaction may persist over generations of farmers, this is chiefly the responsibility of society.

In principle, stress limits should be chosen with regard to the tolerance levels of individual soils. However, this raises large problems, since it would require an extensive and time-consuming mapping of tolerance limits of soils in various regions under various moisture conditions, whereas the rapid increase in machinery size makes it essential to act quickly. Therefore, it may be necessary to establish tentative limits on a regional basis. Another argument for regional rather than local limits is that the range of soils on an individual farm is often very wide, sometimes nearly as wide as in a large region. The only alternative seems to be to introduce a strict controlled-traffic system for all heavy traffic with completely permanent wheel tracks covering only a very small percentage of the field area. Such tracks have to remain in the same position for unlimited time and must not be moved after some years.

9.2.3. *Impact on the environment*

Soil compaction influences the environmental impact of crop production in various ways and to various extents depending on production systems and natural conditions at the individual sites (Chapter 6). Therefore, it is impossible for society to establish general stress restrictions with the objective of limiting the environmental impact of crop production. Instead, possible restrictions should be directed towards the environmen tal effects themselves, e.g. by establishing limits for leaching of plant nutrients, release of greenhouse gases or soil erosion, and it must be left to farmers to act in such a way that these limits are respected. The environmental impact of soil compaction is probably significant, but

Table 18. Soviet standard for limitation of mechanical stresses in agricultural soils. Limits are specified both for the ground pressure of wheels or tracks and for the vertical, normal stress at a depth of 50 cm, and they vary depending on the soil moisture conditions expected to occur when the machines are to be used. (After Rusanov, 1994)

Soil water content (% of field capacity)	Ground pressure (kPa)		Vertical, normal stress at 50 cm depth (kPa)	
	Spring	Summer	Spring	Summer
>90	80	100	25	30
70-90	100	120	25	30
60-70	120	140	30	35
50-60	150	180	35	45
<50	180	210	35	50

unfortunately our knowledge of individual effects is still poor. Therefore, extended research is required, and this should be the responsibility of society.

9.2.4. What has been done so far?

In the former Soviet Union, efforts were made in the 1980s to establish stress limits for various soils in order to avoid unacceptable soil compaction. These were based on a research programme with measurements and field trials in various parts of the Soviet Union and other eastern European countries. They resulted in a Soviet standard for maximum mechanical stresses that was intended to act as a guideline for the production of new farm machines (Rusanov, 1994). This standard (Table 18) specifies upper limits for the ground pressure under wheels or tracks and for the predicted vertical normal stress at a depth of 50 cm. These limits were set at 80-210 kPa and 25-50 kPa, respectively, depending on soil type, moisture conditions and season. To conform with this standard in situations when the lowest stress limit at 50 cm depth (25 kPa) is applicable, the axle load must be as low as 2.5 Mg, unless the machine is equipped with extreme low-pressure tyres (Grečenko, 1989; Nikiforov et al., 1993).

Medvedev & Cybulko (1995) proposed limits for the Ukraine partly based on other criteria than those used when establishing the Soviet standard. One of the objectives was to completely avoid compaction at depths >30 cm. They proposed various ground pressure limits depending on soil moisture conditions. For the wettest conditions, the limit proposed was as low as 30 kPa, and it was assumed that in such cases no wheel or axle load limits were required.

On the basis of studies in the former DDR, Petelkau (1986, 1992) recommended a limitation of the load per wheel to 1.5-2 Mg to avoid unacceptable subsoil compaction. He also recommended a limitation of the ground pressure to 50-200 kPa depending on soil type and moisture conditions to avoid excessive compaction of the plough layer.

On the basis of measurements of soil displacement under the wheels of heavy vehicles in Sweden, Håkansson & Danfors (1981) recommended a limitation of the load to 6 Mg on a single axle and 10 Mg on a tandem axle unit. Loads higher than those had been shown to cause compaction at depths >40 cm, where the effects may be permanent. The investigation of the situation in the farm fields presented in Section 9.1.2.1 indicated that these limits were not unnecessarily low for vehicles with traditional wheel equipment.

Van den Akker & Schønning (2004) regarded stress limits as necessary to protect soil quality in the long-term. They proposed limits based on predicted stresses at various depths, calculated as functions of wheel load, wheel arrangement and ground pressure. They argued that the limits should be set with regard to the strength of local soils under local climatic conditions, in order to avoid more rigorous restrictions then necessary. However, knowledge is unfortunately limited both on the strength of individual soils under various moisture conditions and on the consequences of subsoil compaction at individual sites. Furthermore, whereas most scientists previously assumed that pre-compression stress is a useful stress limit for subsoils, recent studies (Trautner, 2003; Arvidsson & Keller, 2004; Keller et al., 2004) indicate that this is not the case.

Since many machines currently in use induce high stresses and compaction to great depths, load limits must be established quickly. In some countries, efforts are actually being made to introduce such limits, and this would be facilitated by internationally adopted guidelines. The limits should preferably be based on predicted stresses at various depths as proposed by Van den Akker & Schønning (2004) and as used in the Soviet standard. The establishment of local load limits would require local studies that may be too time-consuming. Therefore, it seems generally necessary to adopt tentative limits for larger regions. As soon as local data are available, the limits can be adapted to the local conditions.

For practical use, a limit originally formulated in terms of stresses at various depths needs to be interpreted in terms of maximum loads for wheels with various ground pressures, or the reverse. It seems impossible to completely disregard the wheel load, since this would often lead to unrealistically low ground-pressure limits. Earlier, when only relatively narrow tyres with high ground pressure (≥150 kPa) were available for high loads, it seemed relevant to specify the limits as pure load limits (cf. Chapter 2), and this was often done in terms of axle load rather than wheel load. However, when using wide tyres with low inflation pressure, wheel load limits combined with ground pressure limits are more appropriate.

Since limitations of loads per wheel or axle largely influence the design of heavy vehicles, the choice of limits may have a great economic impact. In the long run, it would be desirable to develop completely new machinery systems for field operations that combine low mechanical stresses in the soils with high work rate and low costs.

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Index

Adjusted Mgkm-values 14, 120-123

Adjustment factor for Mgkm-values (for ground pressure and soil moisture) 14, 115-117

Aeration of soils 53-54, 69-71

Aggregate structure (see soil structure)

Air-filled porosity, critical values 53-54, 69-70

Air permeability 53-54

Amendments, application 99

Anaerobic processes (see oxygen supply)

Automatically steered tractor 105, 106, 109

Axle load, effects on stress propagation and depth of compaction 21-23, 39-43, 52, 81-83

Axle load, limits 102, 133-135

Axle load, reduced values 14, 116

Biological activity in soils 58, 92-96

Bulk density, definition 32

Bulk density, optimal values 60-61

Cable-and-winch system 106-108

Capillary conductivity (see hydraulic conductivity)

Carbon dioxide, content in soil air 53

Carbon dioxide, release from soil (see greenhouse gases)

Changes in depth of soil layers (see depth of soil layers, changes)

Choice of crops 98

Classification of soils 30

Clay content (see texture of soils)

Collembola 93

Compaction, definition 28, 29

Compactness, definition 28, 29

Compression index 29, 39

Concentration factor 21-22

Consolidation 29

Controlled traffic 105

Crop response to compaction
  annual effects in the plough layer 60-72, 113-115, 119-120, 122-124
  effects in growing crops, particularly in ley 85-88, 118
  effects in unploughed soil 77-79
  in the subsoil 81-85, 116-118, 122-124
  residual effects in the plough layer 72-77, 114-116, 120-124

Current situation 128-132

Deep tillage (see subsoil loosening)

Degree of compactness
  definition and determination 62
  effects of traffic and tillage 36-39
  model predictions 112-115, 119-120
  optimal value, effects of
  cultivar 68-69
  manganese fertilization 68
  nitrogen fertilization 66-68
  soil moisture 65-69
  type of crop 65-69

Denitrification 76, 95-96

Depth of soil layers, changes,
  in the plough layer 33-35, 50, 77
  in the subsoil 39-43

Diffusion coefficient 53

Direct damage to plants, traffic induced 85-88

Displacement in the subsoil 39-43

Drainage 51-52, 98

Draught force 124-125

Dual wheels 9-11, 23, 36, 38, 52, 79, 100, 108, 119-120

Early sowing (in wet soil) 92-93, 100-101, 108

Earthworms 92-93

Enchytraeide 93

Erosion 89-91

Four-wheel drive 99-100

Frame sampling (to determine bulk density) 62

Freezing of soils 44

Frost damage to plants, compaction effects 58

Furrow wheels when ploughing 43, 102, 116

Future machinery systems 105-109

Gantries 106-107

Gas exchange in soils 53-54, 94-96

GPS-supported steering 105

Greenhouse gases 95-96

Ground pressure
  definition 18
  distribution in the contact area 17-20
  effects on crop yield 74-75, 100-101, 108, 114-115, 119-120
  effects on draught force 124-125
  effects on state of compactness 37-38
  effects on stress propagation 19-23
  limits 134-135
  under tracks 23-25
  under wheels 17-20

Hydraulic conductivity
  saturated 51-52, 89-90
  unsaturated 58, 70-71

Infiltration 51-52, 89-90

Inter-row traffic 104-105

Leaching of plant nutrients 91-93

Ley, effects of traffic 85-88, 118

Light-weight machinery 106, 109

Load limits 102, 132-135

Long-term effects of compaction on soil productivity (see soil productivity)

Loosening of soil
  definition 28
  effects on crops 58, 70-71
  effects on soil properties 50

Low-pressure tyres 100 (see also dual wheels)

Machinery capacity 99, 106

Macropores: volume, continuity and stability 41-42, 49-54, 78-79, 103

Manure 99 (manure spreading see slurry)

Materiality 32, 50

Maximum depth of compaction 40-41

Mgkm-values, definition 13

Methane (see greenhouse gases)

Micro-organisms 94-96

Mineralization of plant nutrients 58, 72, 92, 94-96

Models to predict effects of
  compaction on crop yield 113-118
  machinery traffic on soils 111-112

Nematodes 77, 93

Nitrogen (see also plant nutrients)
  fixation 96
  nitrous oxide (see greenhouse gases)

Normal stress, definition 18

Number of passes 10-12, 28, 31, 36-39, 83

On-land ploughing 102

Oxygen supply in soils 53-54, 69-70, 76, 94-95

Particle density 32

Penetration resistance
  critical values 54-56, 69-71
  effects of the state of compactness 69-71
  in the subsoil 40, 83, 130-131

Penetrometer 57

Permanent compaction in the subsoil 46-47, 81-85, 129-133

Permanent wheel tracks (see controlled traffic)

Persistence of compaction 43-47

Phosphorus (see plant nutrients)

Pioneer plants 47, 99

Planning of traffic patterns 104

Plant nutrients
  leaching 91-92
  uptake by crops 71, 76, 81-83, 91-92

Ploughing, loosening effects 33-35, 103

Ploughing time 64, 101

Plough layer, definition 13

Pore size distribution, effects of compaction 49-51

Pore volume, effects of compaction 32, 49-51

Porosity, definition 32

Potassium (see plant nutrients)

Precompression stress 18, 31, 40, 42, 134-135
Pressure, definition 18
Principal stresses 18
Proctor test 61-62
Reduced Mgkm-values 116-117, 122-123
Reduced tillage 77-80, 103
Reference compaction treatment 36, 61-63
Relative bulk density 36, 61-62
Residual effects of plough layer compaction 72-77, 114-116, 120-121, 123-124
Rhizobium-nodulation 96
Root diseases 71, 94
Root growth and rooting depth 52-56, 83, 91, 99
Root-soil contact 54-56, 58, 69-71
Rut formation 7, 117
Scandinavian conditions (climate, soils, cropping systems) 64
Scientific names of crops 67
Seedbed, definition 13
Seedbed quality 56-58, 76
Shear strength 18, 40
Shear stress 18, 20-21, 31
Shear vane tester 57
Shrinkage/swelling 62, 78-79
Single grain structure 32
Slip 18, 31, 33, 38, 86-88
Slurry, spreading 103, 122-124
Soil displacement (see depth of soil layers, changes)
Soil fauna 92-93
Soil horizon terminology 13
Soil productivity in the long-term 79-85, 116-118, 122-124, 129-135
Soil structure 31, 32, 43-45, 56-58, 76, 78-79
Solid material in soils 32, 50
Soviet standard of stresses 134
Specific volume 32, 50
Standardized compaction treatment (see reference compaction treatment)
Stress, definition 18
Stress propagation in soil 20-23
Subsoil, definition 13
Subsoil loosening 48, 103-104
Sugar beet harvest, examples of damage by compaction 42-43, 52, 120-121
Swelling/shrinkage of soils (see shrinkage/swelling)
Tandem axle units 23, 122-124
Texture of soils, effects on
  compactibility 29, 39
  crop response to compaction 60-61, 65-66, 73, 75-76, 78-79, 103, 116, 120-124
  persistence of compaction 45-46, 72-75, 114-118
Thermal properties 58
Time of traffic 104
Topsoil, definition 13
Tracked vehicles 23-25, 42, 100, 106, 109
Trafficability of soil 58
Traffic intensity 7-15
Traffic in established crops (ley) 85-88, 118
Traffic lanes for heavy transport 104
Tyre inflation pressure
  effects on crop yield 74
  effects on ground pressure 17-20
  frequent adjustment 100
Void ratio 32, 50
Volumetric relationships in soils, effects of compaction 50
Water infiltration 51-52, 89-91
Water retaining properties 50-51
Water requirement and use by crops 83-85, 89-90
Water runoff 89-91
Weeds, effects of compaction 71, 76-77
Weight transfer to tractors 99-100
Wheel load limits (see axle load limits)
Wheel tracks, area and distribution 8-12
Wide tyres (see low-pressure tyres)

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This book can be ordered from

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