SVERIGES
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INSTITUTIONEN FÖR MARKVETENSKAP

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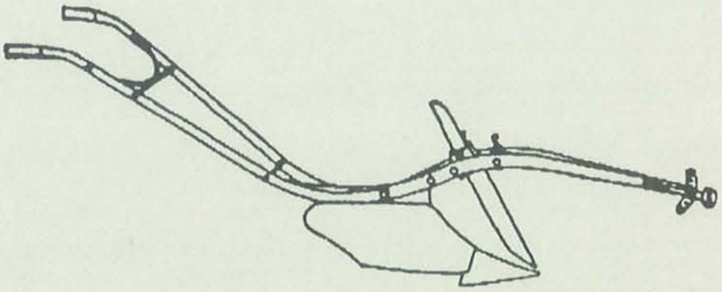
Bulletins from the Division of Soil Management



Nr 5 1993

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EFFECTS OF SOIL COMPACTION ON PHYSICAL, CHEMICAL AND BIOLOGICAL SOIL PROPERTIES AND CROP PRODUCTION

ISSN 0348-0976
ISRN SLU-JB-M--5--SE

Sveriges lantbruksuniversitet
Institutionen för markvetenskap
Avdelningen för jordbearbetning

Meddelanden från jordbearbetnings-
avdelningen. Nr 5, 1993
ISSN 0348-0976
ISRN SLU-JB-M--5--SE

EFFECTS OF SOIL COMPACTION ON PHYSICAL, CHEMICAL AND BIOLOGICAL SOIL PROPERTIES AND CROP PRODUCTION

by

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To be presented as a seminar at the Department of Soil Sciences at the Swedish University of Agricultural Sciences in December 1993

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EFFECTS OF SOIL COMPACTION ON PHYSICAL, CHEMICAL AND BIOLOGICAL SOIL PROPERTIES AND CROP PRODUCTION

INTRODUCTION

The mechanisation of crop production is increasing in most parts of the world. In many countries this trend is viewed with concern because of the compaction which results when wheels pass over the soils as a growing medium for crops. To a greater or lesser extent, compaction influences nearly all physical, chemical and biological soil properties and processes as well as crop development and yield. These soil properties must be maintained at an optimum level if maximum crop yields are to be maintained. Crop growth and yield will decline if the compactness lies either above or below an optimum value which will vary with different soils, crops and weather conditions (Fig.1). Under–compaction is associated with problems arising in the early growth of crops in dry weather, but farmers are generally aware of the methods to overcome this problem. In contrast, over–compaction problems tend to be experianced especially during wet weather and may occur on most soil types if vehicle traffic has been exessive. In recent years, there has been concern that over-compaction of soils is becoming more widespread as a result of the increasing intensity and weight of agricultural and, in certain circumstances, it is thought to be restricting the profitability of crop production with accomponying enhanced risks of soil erosion (Fig.2). The incidence of such problems is likely to be influenced by the type and use of field vehicles, soil type, weather conditions and the type of crop. It is therefor important to establish the role of these factors and the methods which are available to overcome these problems.

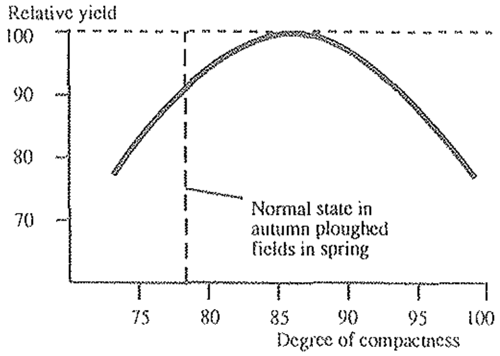


Fig. 1 General relationship between degree of compactness and yield. (After Håkansson, 1989).

People concerned with soil managment have long been aware that tillage ans traffic are closely related. Even when horses were primarely used for ploughing in Europe, it was observed that the passage of hooves in the furrow bottom was harmful to the soil, while the advent of mechanical traction was accompanied by forecasts of the impending ruin of soil structure as a result of the excessive weigth of the early machines (Soane & van Ouverkerk, 1980/81). Adoption of the internal combustion engine in place of steam power and of high quality steel in place of wrought iron led to the evolution of comparatively light tractors, but, the steady increase in tractor power and weight over the last thirty years or so has brought into prominence again the problems of deterioation of soil structure by field traffic and the negative effects to be expected in soil workability, crop development and yield (Soane & van Ouwerkerk, 1980/81).

In developed countries traffic from wheeled vehicles now extends to many operations other than tillage, for instance spraying, slurry spreading and, in particular, harvesting which often involves very heavy vehicles for both separating and transporting the crop (Fig.3).

In the developing countries mechanisation is also increasing and, although the vehicles used may still be comparatively light, the low structural stability of many tropical soils combined with the high erosivity of rainfall together increases the chances of serious soil degradation by field traffic (Pers. observation).

Fig. 2 Compaction under tractor tyres can lead to increased risks of erosion on cereal seedbeds.

(After Soane, 1987)

Fig. 3 Evidence of soil damage arising from cereal harvesting operations during periods of high soil moisture

(After Soane, 1987)

THE FUNCTION OF THE SOIL AND THE ROOT

The value of the soil with regard to crop production depends on its ability to provide the roots with water, oxygen and nutrients. The solid material consists of mineral particles and organic substance which together creates the soil sceleton (Tamm & Wiklander, 1963). The pore system is a complicated network of channels and cavities, which below the ground water table are completely filled with water. If the ground water table is lowered, the pore system will gradually be drained of water and air will enter the system (Tamm & Wiklander, 1963). The distribution of air and water in the soil is determined by the pore size distribution, the position of the ground water table and the supply and consumption of water in the soil.

The geometry of the pore system is primarely depending on the soil type and dominating soil fraction. Fig.4 gives an attempt to decribe the sizes of the soil particles and root hairs. It is mainly the clay-and the organic matter which influence the soil structure and soil water capacity, but even if an increasing clay content means an increasing water holding capacity, the amount of available water is not consistently increased which is due to the fact that small clay particles are able to hold water so strongly that it remains unavailable to the roots (Tamm & Wiklander, 1963). Anyhow, the clay fraction has the abilty to give rise to aggregates and to maintain structure features created in the soil, which gives possibilities of quick movements of water and air in the pore system (Tamm & Wiklander, 1963).

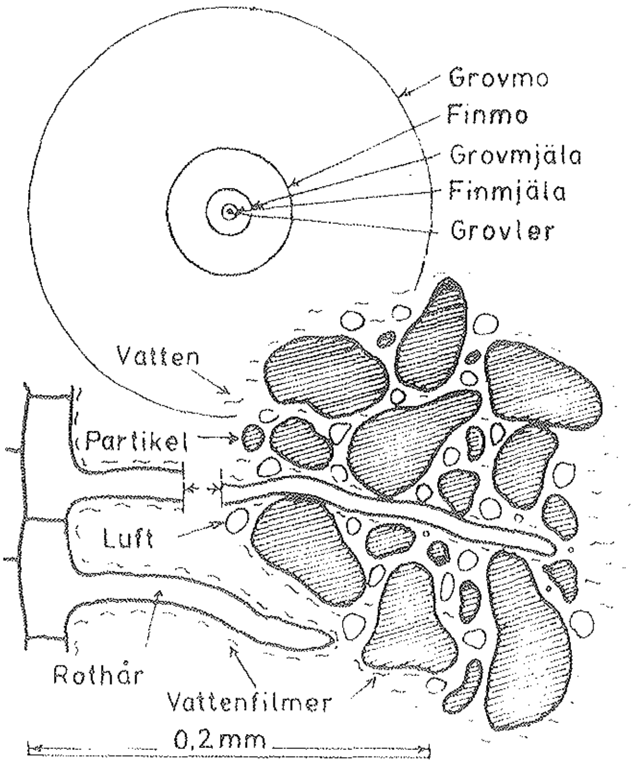


Fig. 4 Schematisk bild av rothår, markpartiklar och porer vid ca 300 gångers förstoring. Rothårets verkliga längd ca 4,2 mm och tjocklek ca 0,01 mm (efter S. Andersson).

The possibility for the root system to develope is partly depending on its genetical disposition but also the root environment to a great extent modifies its growth and appearance (Bengtsson, 1984). High mechanical resistance, high groundwater table and other unfavourable conditions can give rise to a limited root system with accomponying reduced plant growth. Anyhow, several field observations suggest that some species have a greater ability than the average to overcome mechanical resistance in the soil. Plants which apparently display this characteristic, often perennial grasses, may thus improve soil conditions for crops which are planted subsequently (Russel, 1971). The explanation for this could be that species which can continue growing for extended periods, during which their roots extend only slowly, may be more successfull in penetrating a heavily compacted soil than plants with a shorter growing season (Russell, 1971).

Water and nutrient uptake mainly occurs through the root tips and the number of these, which can exceed 200 000 on a mature plant, can be seen as a measure of the ability of a plant to absorb water and nutrients (Bengtsson, 1985). Fig.5 points out the structure and growth mechanism of roots and root hairs. The existence of root hairs causes a pronounced increase of the absorbing area. A root with a diameter of 0.5 mm is able to cover an absorption area of 5 cm^2 per cm root length (Eriksson et al., 1974).

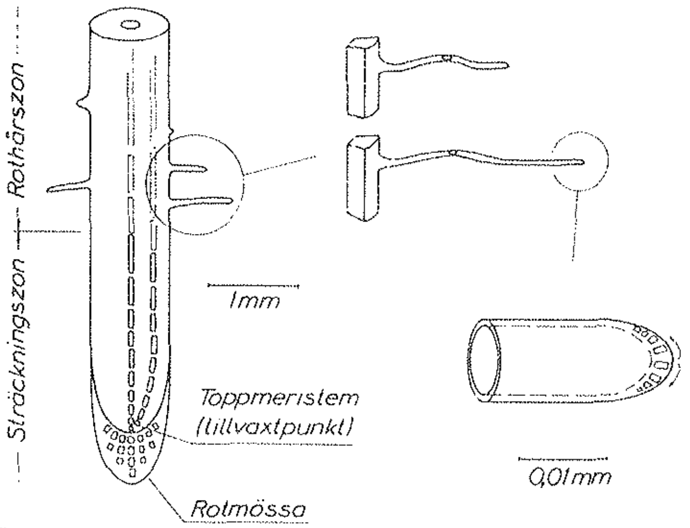


Fig. 5 Rotspetsen och rothårens byggnad och tillväxtmekanism.

(After Eriksson et al., 1974)

MECHANICAL IMPEDANCE OF ROOT GROWTH

The primary effect of soil compaction is to reduce pore volume, and to cause a redistribution amongst pore size groupings and these changes will affect many soil physical properties and processes to a greater or lesser extent, including air capacity and gaseous exchange, water retention and hydraulic conductivity, soil strength and mechanical impedance to root growth, and compaction will also indirectly affect many chemical and biological processes (Håkansson et al., 1988).

As long as there exists larger cracks, channels and coarse pores in the soil the roots are able to grow unimpededly provided water, nutrients and oxygen are available. When the pore diameter continues approaching the diameter of the roots, the pore system is increasingly affecting root growth. Most plant roots are thicker than approx. 0.1 mm in diameter while the root hairs normally are about 0.01 mm in diameter (Åberg et al., 1972). When root and pore diameters approach each other, future downward penetration of roots will now tend to be restricted. An intermediate bulk density between 1.3 and 1.8 kg dm^{-3} is normally, due to soil type, considered being the limit restricting root growth (Bengtsson, 1985).

Fig.6 describes how the penetration resistance increases in a soil previously exposed to various external pressures. The values constitute mean values of four measurements, which are carried out at matric water tensions of 0.05 and 6.0 m water column. It appears from this investigation that the penetration resistance considerabely increases at the higher tension and it can also be seen that an additional compaction pressure is very obvious. Also, notice the characteristic increase in the top soil and plough pan. All values at 6.0 m water column exceed what is to be considered as a moderate root resistance. The same is true for compaction pressures greater than 200 kPa at 0.05 m water column (Eriksson, et al., 1974).

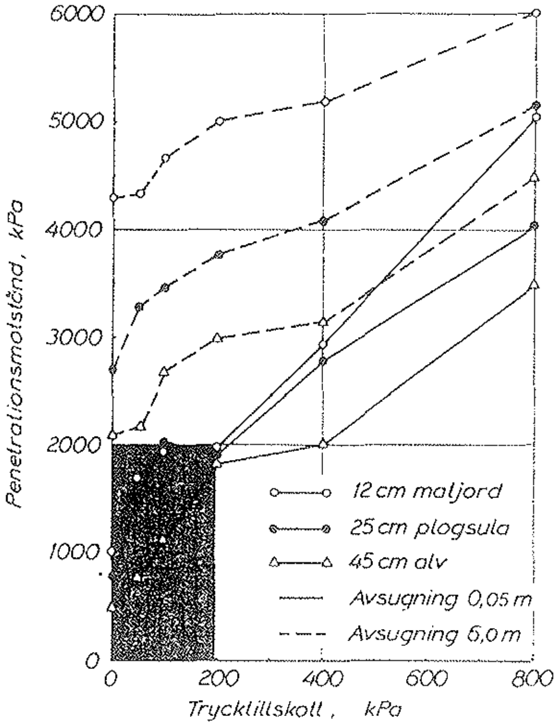


Fig. 6

Samband mellan trycktillskott och penetrationsmotstånd vid dränering motsvarande 0,05 och 6,0 mvp. Matjord, plogsula och alv i lerprofil, Ultuna. Inom det skuggade området måttligt rotmotstånd.

(After Eriksson et al., 1974)

When a soil is subject to stress, the soil sceleton is exposed to forces with different directions and dimensions, which partly are transmitted through the contact between soil particles and partly through the pore water and pore gas. The compaction of the soil reduces the volume occupied by pores, especially those of relatively large diameter (Fig.7). This can cause greater mechanical resistance or impedance to root extension. Also the continuity of macro pores is affected and these changes in pore structure may restrict subseqent root growth (Grable, 1971).

The most obvious change in soil properties caused by compaction, is the reduction in the volume of large pores (> 0.03 mm) (Riley, 1983). Such pores are of importance for gaseous exchange (both diffusion and mass flow) and saturated hydraulic conductivity (Håkansson et al., 1988). They also represent the space most easily occupied by plant roots and higher soil organisms. Populations of soil arthropods and earthworms have been shown to be seriously affected by soil compaction and the reasons may be direct effects of the stresses, soil displacements or a changed soil environment (Boström, 1986).

Fig.7 points out how the pore size distribution is changed with increasing pressure upon a clay soil. In the initial state the percentage of pores larger than 0.03 mm is approx. 10 %. These pores are drained at 1.0 m column of water and creates a network of subterranean channels and cavities where the roots can develop. At the same time they give rise to high water and air permeability. If the soil is exposed to a compaction pressure of 200 kPa the volume of coarse pores are reduced considerabely and at 800 kPa they are completely collapsed. At pressures more than 200 kPa, even pores less than 0.03 mm are reduced.

This pattern of reaction is also applicable on other soil types. A stress of 200 kPa can from this point of view often be considered as a limit (Eriksson et al., 1974).

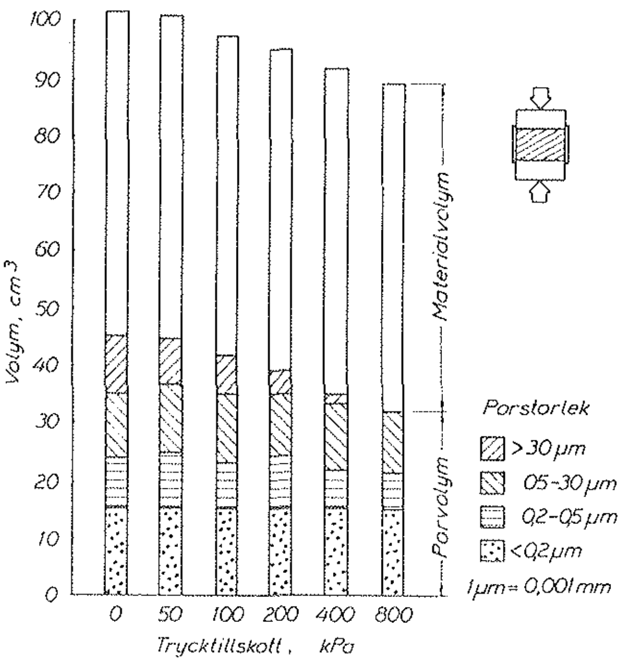


Fig. 7
Förändring i porvolym och porstorleksfördelning vid stigande trycktillskott. Grävsta, Uppsala län, horisont 40,0 - 42,5 cm, välaggregerad lerjord, lerhalt 40 %.

(After Eriksson et al., 1974)

In a water saturated soil, the applied pressure is initially entirely taken up by the soil water, but due to the overpressure which arises, the water is driven out from the pores and the external applied pressure is transmitted to the soil sceleton (Bengtsson, 1985). Successively the pressure in the water is decreased and the effective pressure in the contact surfaces increases correspondingly. The soil sceleton will partly be collapsed when its internal forces no longer are able to resist the increasing stress, which finally leads to a reduction of the soil- and pore volume (Bengtsson, 1985). In coarse-textured soils the internal forces are dominated by friction between the particles, while in fine-textured soils cohesion dominate (Tamm & Wiklander, 1963). In a water saturated soil, the water acts as a lubricant between soil particles and when applying an excessive pressure the pore system is effectively broken down, but on the contrary when the soil is dry, friction and cohesion forces between soil particles increase and the soil sceleton is better able to resist applied pressures (Eriksson, 1982).

PENETRATION BY ROOTS INTO A GROWTH MEDIUM

The root tip forms an effective organ in order to penetrate the pore system because of its ability to take advantage of small variations in the soil, and it is also able to push its way forward where it meets least resistance. The friction against the root tip is normally of a moderate magnitude because it has the possibility to sëcret slime (Åberg et al., 1972). The penetration of the root can also cause changed mechanical properties in the soil, as cracks caused by shrinkage are developed due to the water uptake of the root.

When growing roots reach pores in a rigid medium which are smaller than their diamter, continuing extension is possible only if they are able either to exert sufficient pressure to expand pores or to decrease in diameter. The work of Wiersum (1957) provides clear evidence that roots could not penetrate rigid pores the diameter of which was less than that of the extending zone of the root. He found that roots are not only unable to decrease in diameter, instead they normally increase by an external pressure. He also noticed that the size of the stele was little affected but the cross-sectional area of the cortical cells became greater. Fig.8 describes the appearance of root systems and cross-sections of roots of spring barley grown in an uncompacted (A) and compacted (B) silty loam soil (Lipiec et al.,1991). The experimental compaction treatment consisted of 8 passes of a heavy tractor (weight 4.8 t, a rear axle load of 31.8 kN and an inflation pressure of 160 kPa). Roots grown in the severely compacted soil were characterized by a greater diameter, a higher degree of flattening, an irregular surface with distorted epidermal cells which had been penetrated by soil particles and radially enlarged cortex cells. It was suggested that the wider cortex cells, with their greater absorptive surface, will aid in overcoming nutrient stress. The above findings imply that the main factor limiting root growth in the compacted soil in that case was soil strength.

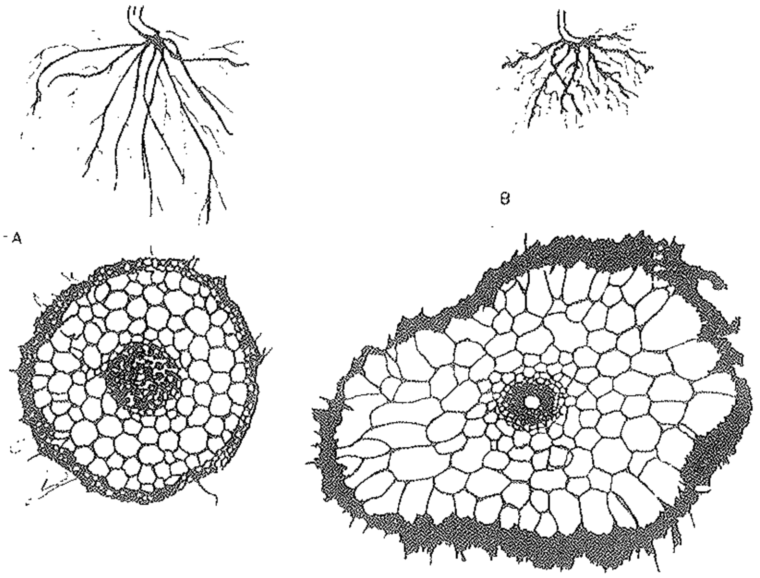


Fig. 8 Root system and cross-section of roots grown in loose (A) and compacted (B) (Treatment e) silty loam soil (× 150).

(After Lipiec et al., 1991)

The maximum pressure roots can exert was first reported by Pfeffer (1893). He anchored the fully extended zone of growing roots in blocks of plaster of Paris and encased their apices in separate blocks of the same material. The forces exerted by the roots when rigidly restrained were thus tranmitted through the latter blocks and measured with a proving ring. He found that roots could exert longitudinal pressures of about 10 bar (1000 kPa) and radial pressures of slightly more than half this magnitude. Tailor and Ratliff (1969a) showed that roots of a number of species could exert maximum longitudinal pressures of between 9 and 13 bar (900–1300 kPa), which well supported the original work of Pfeffer. Anyhow, from the viewpoint of growth and yields of crops, interest centres not so much on the maximum pressure which roots are capable of exerting but on the minimum pressures at which their elongation is appreciably reduced. These are the pressures which, in unfavourable circumstances, can prevent roots to provide the plant with adequate water and nutrients. Several investigations are undertaken to illustrate this, i.e. works by Goss (1977). The techniques used had the common feature that root growth media was subjected to known external pressures which were transmitted through membranes, all other conditions beeing maintained uniform and favourable. Fig.9 shows the combined results of numerous experiments on the elongation of the seminal root axes of barley plants during six days. An applied pressure of 20 kPa reduced root extension to about half that of the controls, and 50 kPa to about 20 %. Further increase in pressure up to 100 kPa caused only a slightly greater reduction. However, the relation between the external pressure exerted by the membrane and the penetration resistance to root elongation or to a penetrometer was not shown.

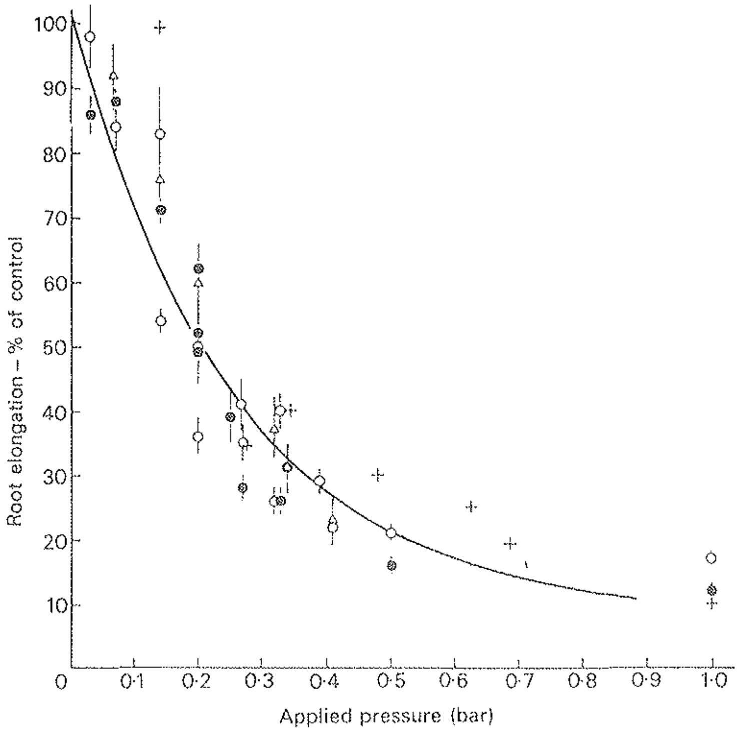


Fig. 9 *Effects of applied pressure on the extension of seminal roots of barley* (Hordeum vulgare) *grown for six days in beds of glass ballotini of different pore diameters to which ample nutrients were provided in aerated solution. Pore sizes: open circles 150 μm, closed circles 70 μm, triangles 15 μm; the curve was fitted by the equation shown above (after Russell and Goss, 1974). The results of Abdalla* et al. *(1969) are indicated by crosses.*

The water content of the soil also affects its resistance against penetrating roots. Decreasing soil water potential causes soil strength to increase with the result that extending roots experience greater mechanical impedence which is illustrated in Fig.10. This is not, however, the only way by which changes in soil water content can influence the response of roots in a compacted soil. Barley (1962), showed in laboratory observations that the effects of external pressure on root extension is enhanced when the supply of oxygen is limited to 3–5 % in the gas phase. Thus, if increasing water content reduces the air–filled pore space in a compacted soil so that the partial pressure of oxygen in the soil air is reduced, the restriction of root extension caused by mechanical impedence may be greater.

The amount of water and nutrients a crop is able to take up depends on physical, chemical and biological conditions in the soil. These factors affect both the ability of the soil to store and transport water, and the possibility for the root to utilize the soil water and nutrients. The interaction between root growth, mechanical treatment, oxygen and water supply is illustrated in Fig.11. An increased bulk density leads to reduced root growth. At poor drainage, oxygen deficiency occurs, which becomes more pronounced at increased bulk density. At high tensions, the root growth is reduced due to water deficiency in combination with mechanical resistance.

In most cases it is not merely soil mechanical resistance which restricts root growth, but more often it is a question of a combination of mechanical resistance and the fact that a compacted soil has a low oxygen rate which impedes the root growth and resticts its possibilities to overcome the mechanical resistance. Experiments indicate that ethylene is formed in the root tips during low oxygen conditions and it is considered to act as a growth reductant (Wilkins et al., 1976). Finally, it should be observed that the interactions between oxygen deficiency and mechanical resistance on growth restrictions are not clearly investigated.

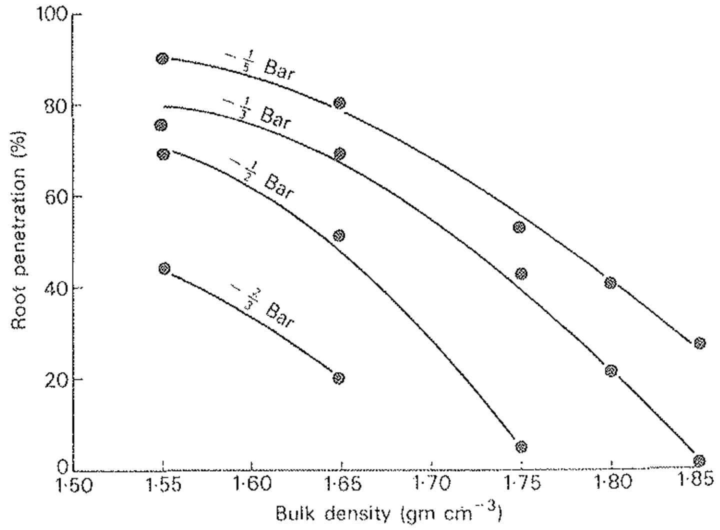


Fig. 10 *Effect of bulk density and water potential on the penetration of the seeding roots of cotton* (Gossypium hirsutum) *through layers of a fine sandy loam soil (redrawn from Taylor and Gardner, 1963). (Original source © 1963, Williams and Wilkins, Baltimore.)*

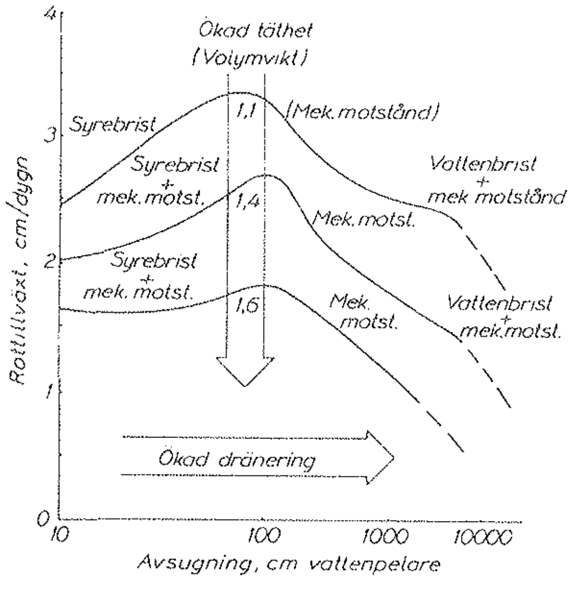


Fig. 11 Rottillväxt vid olika packningsgrad under varierande avsugning. Jordart: lerig sand. Enligt data av Eavis 1972.

EFFECTS OF ANAEROBIC SOIL CONDITIONS

The composition of soil air differs from that of the atmosphere. The CO_2 level of the atmosphere by volume is about 0.03 % whereas in the soil it is higher and in the order of 0.2–1 % in the surface levels. Soil air also contains a correspondingly lower O_2 content of about 20.3 % as compared with that of 20.99 % in the atmosphere (Mengel & Kirkby, 1987). Higher levels of CO_2 result from the respiration of living organisms in which O_2 is consumed and CO_2 released. This shows that O_2 is essential in the soil atmosphere. The respiration of plant roots depends to a high extent on the O_2 supply in the soil air. Respiration provides the energy for various metabolic processes including active ion uptake by plant roots (Mengel & Kirkby, 1987). The partial pressure of O_2, however, required for root metabolism can be considerably lower than that of the atmosphere. Thus Hopkins et al. (1950) showed that nutrient uptake of tomato plants was impaired only when the O_2 content in the soil air was lower than 10 %. An air filled porosity of at least 10 % is also now generally considered as the minimum limit for satisfactory root and plant growth.

Anerobic means the absence of free oxygen. Under natural conditions the entire soil is never anaerobic as some oxygen always enters the surface layers and if the partial pressure of oxygen decreases below atmospheric, depletion is seldom uniform throughout an appreciable volume of the soil (Russell, 1977). When anaerobiosis supervenes, it usually occurs first at localized sites.

The development of anaerobic soil conditions

Anaerobic soil conditions occur only when the rate at which oxygen enters the soil from the atmosphere is less than that at which it is utilized in the respiratory process of plant roots, bacteria, fungi or other organisms.

The air-filled porosity of the soil is the physical soil characteristic which has the greatest influence on gas exchange with the atmosphere and this is because oxygen diffuses in the gas phase some ten thousand times more rapidly than in a water solution (Russell,1977). The saturation of the soil with water - waterlogging - is thus the most common cause of anaerobiosis but waterlogging or flooding, does not necessarily have this effect. If the hydraulic conductivity of the soil is sufficiently high, and drainage is unimpeded, the movement of aerated surface water through the soil may provide sufficient oxygen, which i.e. happens in flooded water meadows especially in cool conditions when relatively little oxygen is beeing used in biological processes (Russel,1977).

There is no constant relationship between the air-filled pore space in a soil and the degree of anaerobiosis which can develop (Grable, 1966). Differences in the distribution of air filled pores and their continuity can modify the transport of oxygen, both in gas and solution phases, to different zones in the soil. Moreover, variations in the rate at which oxygen is utilized can have a large effect. Tab.1 from the work of Currie (1970) shows that the consumption of oxygen of a well drained field soil can change by a factor exceeding ten depending on the temperature. Tab.1 also shows the influence of roots; the markedly higher respiration of the cropped soil reflects the respiration both of roots and of microorganisms for which root exudates or dead roots provide substrates. Russell (1973) points out that if a soil which contains 20 % per volume of air uses oxygen at the rate of 7 g per m^2 surface area per day the total oxygen contained in the soil air would be exhausted in about two days if its surface was completely sealed from the atmosphere. Thus, if oxygen is beeing used at the highest rate indicated in Tab.1 the interruption of gas exchange for less than a day could lead to a marked depletion of oxygen.

Tab. 1

Oxygen consumption in winter and summer by soil either bare of crops or under kale (Brassica oleracea).

(After Currie, 1970)

	July	January
Soil temperature at 30 cm	17 °C	3 °C
Oxygen consumed per m^2 ground surface (g d^{-1})		
Bare soil	11·6	0·7
Under kale	23·7	2·0

Localized anaerobic zones

When the rate at which oxygen diffuses into the soil starts to fall below that at which it is consumed, considerable differences in its concentration can occur between sites only a short distance apart. If the finer pores of the soil are filled with water, but the larger ones contain air the soil can, on a simplified model, be regarded as consisting of water–filled aggregates separeted by air–filled pores (Currie, 1961). He concluded that the maximum radius (r) of a crumb, to the centre of which oxygen would just reach, could be expressed by the equation:

$$r^2 = 6DC/M$$

where D is the diffusion coefficient of oxygen in the crumb which varies depending on the size and tortuosity of the water–filled pore space, C is the concentration of oxygen in the water on the outer surface of the crumb and M is the rate of which oxygen is utilized within it. It was estimated that, depending on the rate of respiration, the concentration of oxygen could fall to zero at the centre of water–filled crumbs of approx. 0.1–1.0 cm in radius when their surfaces are bathed with water saturated with air (Greenwood, 1969, 1970).

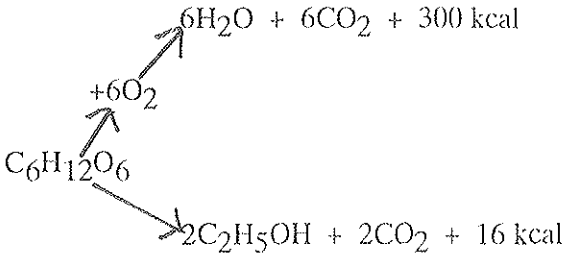
The non–uniform distribution of organic substrates is an additional cause of variation in the concentration of oxygen within the soil, the rate at which oxygen is utilized beeing greatest when abundant substrates favour the proliferation of the microflora (Russell, 1977). Fig.12 attempts to illustrate in simplified form how anaerobic zones may develop when the water content of the soil increases.

Effects of anaerobic conditions in the soil

The restriction of the supply of oxygen to roots is not the only potential cause of injury to plants when anaerobic conditions develop in soils. Numerous and complex biological, chemical and physical changes occur, which in an extensive literature is discussed by i.e. Allison (1973), Russell (1973) and Skinner (1975). Attention will here mainly be limited to aspects concerning metabolic pathways in anaerobic soils, toxic substances evolved under anaerobic conditions and losses of soluble compounds of nitrogen.

Metabolic pathways in anaerobic conditions

When free oxygen is absent many of the changes in the soil which can effect plant growth are due to the products of metabolism in obligate or facultative anaerobic microorganisms (Russel, 1977). The majority of these are heterotrophic, depending on the oxidation of organic substrates needed for their energy. Thus, a comparison of aerobic and anaerobic respiration indicates the general nature of some of the most important changes which can occur when anaerobiosis supervenes. Taking glucose as an example of a simple substrate the two types of respiratory pathways can be summarized as follows (Conn & Stumpf, 1966):



$$C_6H_{12}O_6 \xrightarrow{+6O_2} 6H_2O + 6CO_2 + 300\ \text{kcal}$$

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 + 16\ \text{kcal}$$

The most important similarities and differences between the anaerobic and aerobic processes are (Russell, 1977):

1. All respiration depends on the transfer of electrons from the substrate which is oxidized, to an acceptor which is reduced. In the aerobic process free oxygen is the electron acceptor, combining with hydrogen ions to form water.

When oxygen is absent a wide range of other reactions can occur. Combined oxygen in the substrate may be utilized as in the above example. Oxygen may also come from the reduction of other substrates, such as nitrate and sulphate. Cations of high valency, i.e. trivalent iron (Fe^{3+}) or tetravalent manganese (Mn^{4+}) may accept electrons and be reduced respectively to ferrous (Fe^{2+}) or manganous (Mn^{2+}) ions. The pathway of electron transfer depends on the redox potential which is influenced by pH and other factors (Tab.2).

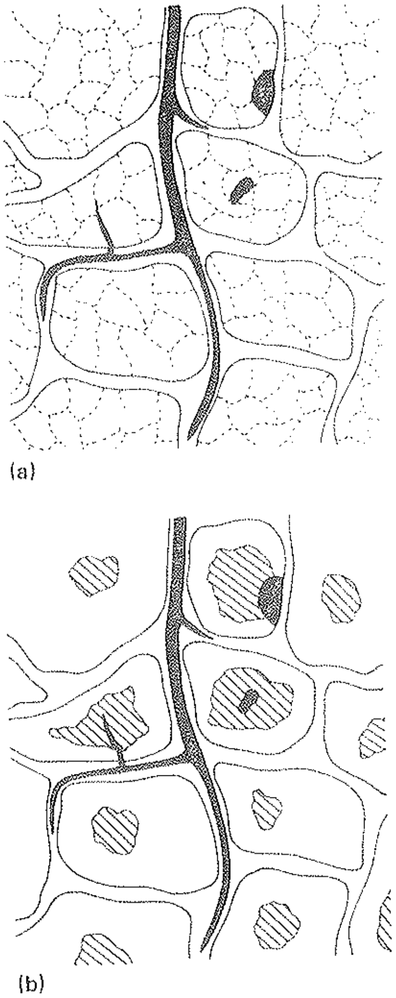


Fig. 12 *Schematic representation of onset of anaerobic soil conditions.* (a) *Soil well aerated: Pores between aggregates are air-filled and there are smaller air-filled pores (dotted) in aggregates: a growing root and two zones with abundant organic substrates are shown (shaded).* (b) *Increasing soil water has displaced air in the fine pores within aggregates: Anaerobic zones (lightly shaded) are developing within aggregates, especially where substrates are abundant. The distance from air-filled pores to which the anaerobic zones may eventually extend is discussed on page 195.*

(After Russell, 1977)

Tab. 2 *Oxidation-reduction potentials at which reactions occur in typical soil systems at 25 °C and pH 5–7.*

Product of reduction	Oxidation-reduction potential mV
H_2O (reduction of oxygen)	930 – 820
NO_2^-	530 – 420
Mn^{2+}	640 – 410
Fe^{2+}	170 – –180
H_2S	–70 – –220
C_2H_4	–120 – –240
H_2	–295 – –413

Simplified from data of Ponnemperuma tabulated by E. W. Russell (1973).

The redox potential is used to assess reducing conditions in anaerobic soils. It is regulated by the concentrations of reduced and oxidized substances according to the following equation (Mengel & Kirkby, 1987):

$$E = E_0 + R\,T/nF \ln (Ox)/(Red)$$

where

(Ox) = Concentration of oxidized substances
(Red) = Concentration of reduced substances
E_0 = Standard redox potential
R = Gas constant
T = Absolute temperature
n = Valency
F = Faraday constant
E is equal to E_0, if (Ox) and (Red) are each unity.

The redox potential in soils is generally measured using a platinum electrod against a reference electrode and is expressed in terms of voltage. From the equation for the redox potential (E) it can be seen that the potential decreases as the concentration of reduced substances increases relative to the concentration of oxidized substances. A low potential is thus indicative of a high reducing power or a surplus of electrons (e^-) to effect reduction, whereas a high redox potential indicates a lack of electrons. In the presence of O_2 rather high redox potentials prevail due to the fact that O_2 is a powerful oxidant driving the oxidation of carbon, hydrogen, nitrogen, sulphur, iron and manganese to the formation of the appropriate oxides CO_2, H_2O, NO_3^-, SO_4^{2-}, Fe_2O_3 and MnO_2.

During the period of submergence the soil undergoes reduction and the oxides mentioned above are reduced (Ponnamperuma, 1972). This reaction is often linked with the consumption of H^+ as shown in the following example:

$$Fe(OH)_3 + e^- + 3H^+ \rightleftharpoons 3H_2O + Fe^{2+}$$

It is mainly for this reason that during the period of submergence the pH of acid soil increases. If the redox potential falls drastically, leading to extreme reducing conditions, hydrogen ions can accept electrons and give rise to molecular hydrogen (Tab.2).

2. Whereas aerobic respiration can cause the complete oxidation of carbohydrates to carbon dioxide and water, anaerobic processes do not. They thus yield much less energy and a widrange of partially reduced organic compounds result. These include alcohols and numerous organic acids as well as other substances. Some of them may be decomposed giving rise to hydrocarbons and carbon dioxide, those which are volatile may escape rapidly from the soil but others may persist until they are metabolized in aerobic processes when a supply of oxygen is restored.

Toxic substances in the soil

Many substances which can be produced by anaerobic metabolism can be injurious to plants. They can reach toxic concentrations if sufficient quantities of readily metabolized organic substrates are present. Their effects can be particularly conspicuous when massive quantities of slurry produced by intensive animal production are applied to the soil (Burford, 1976), but the incorporation of plant debris can be sufficient to cause significant effects, particularly when the temperature is favourable for rapid anaerobic decomposition.

The microbiological products found in anaerobic soils have been extensively reviewed, i.e. by Russell, (1973). Comments here are limited to noting some of the major groups of substances which have been considered in relation to the response of plants.

Organic acids. Numerous organic acids arise in anaerobic soils (Stevenson, 1967) and of these the volatile fatty acids are often the most abundant, especially acetic acid, but formic, propionic, butyric and valeric acids also occur and the quantity of these acids evolved per 100 g of waterlogged soils sometimes exceed 2×10^{-3} M when ample substrates are present. In addition aromatic acids can be present, i.e., p-hydroxybenzoic, p-coumaric and vanillic acids (Wang et al., 1967). Many other acids have been detected but by comparison with the volatile fatty and aromatic acids they appear to be of minor importance as phytotoxins. Despite the production of organic acids the pH of the soil does not change in a consistent manner when anaerobic conditions develop. Many factors affect soil pH and may stabilize it close to neutrality (Russell, 1973).

Hydrocarbons

Hydrocarbons are organic carbon compounds containing only carbon and hydrogen and are highly insoluble in water. Some hydrocarbons are aliphatic compounds, a class of carbon compounds in which the carbon atoms are joined in open chains, while another important group of hydrocarbons contains the aromatic ring and can be viewed as derivates of benzene (Brock & Madigan, 1991).

The occurrence of methane (CH_4) in anaerobic soils has long been recognized and more recently ethylene and a number of the higher hydrocarbons have been identified (Smith & Restall, (1971). The production of ethylene in anaerobic soils has attracted attention because it is also an endogenous growth regulator in plants and it can induce biological effects in very low concentrations (Smith & Dowdell, 1974). A supply of oxygen in the soil, less than 0.1 %, is normally necessary for ethylene to be produced and when ample substrates are added to the soil abundant ethylene may be released (Lynch, 1974a).

Brock & Madigan (1991) conlude that "certain unsuturated aliphatic as well as aromatic hydrocarbons can be degraded anaerobically by mixed cultures of microorganisms, like denitrifying, phototrophic and sulphate reducing bacteria. These bacteria have been shown to degrade benzoate and other substituted phenolic compounds yielding CH_4 and CO_2 as final products. The anaerobic catabolism of aromatic compounds proceeds by reductive rather than oxidative ring cleavage (Fig.13). Anaerobic catabolism involves ring reduction followed by ring cleavage to yield a straight chain fatty acid or dicarboxylic group. Benzoate derivates are common natural products and are readily degraded anaerobically".

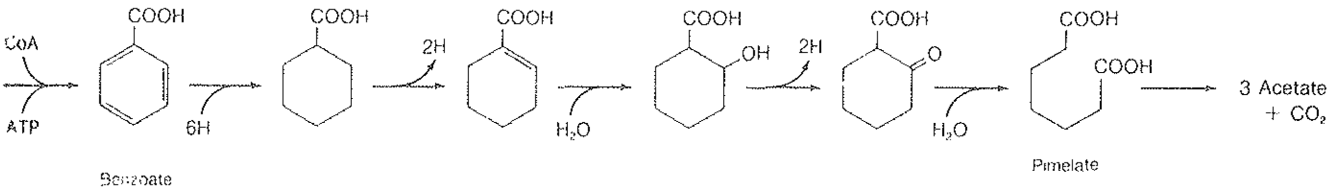


Fig. 13 Anaerobic degradation of benzoate by reductive-ring cleavage. All intermediates of the pathway are bound to coenzyme A.

(After Brock & Madigan, 1991)

Carbon dioxide

Brock & Madigan (1991) report that "carbonate (CO_3^{2-}) is one of the most common inorganic anions in nature and is, of course, a major product of the energy metabolism of organotrophs. Several groups of bacteria are able to use CO_2 as an electron acceptor in anaerobic respiration. The most important CO_2- reducing bacteria are the methanogens, a major group of archaebacteria. Some of these organisms utilize H_2 as electron donor (energy source); the overall reaction is:

$$4H_2 + H^+ + HCO_3^- \quad CH_4 + 3H_2O$$

Another group of CO_2- reducing bacteria are the homoacetogens, which produce acetat rather than CH_4 from CO_2 and H_2. The overall reaction of homoacetogenesis is:

$$4H_2 + H^+ + 2HCO_3^- \quad CH_3 - COO^- + 4H_2O$$

Examples of homoacetogenic bacteria are Clostridium aceticum and Acetobacterium woodii".

When gas exchange is restricted and anaerobic metabolism proceeds in the soil the concentration of carbon dioxide increases (Russell, 1977). However, its greater water solubility than oxygen, by a factor of about thirty, causes it to diffuse more readily in solution (Greenwood, 1970). Concentrations in excess of 5 % by volume and exceptionally of over twice this magnitude have been reported in the zones of soil which roots explore (Russell, 1973). High concentrations of CO_2 can be toxic to plants, the effects often being generally similar to those caused by deficient oxygen. However, evidence reviewed by Kramer (1969) suggests that in anaerobic soils carbon dioxide is a minor source of injury to plants by comparison with the deficiency of oxygen.

Tab.3 lists major examples of various microbial fermentations and some of the organisms carrying them out. Many of these products can themselves become energy sources for other fermentative organisms (Brock & Madigan, 1991). For example, succinate, lactate and ethanol, produced from the fermentation of sugars, can themselves be fermented by other organisms and the fermentation of these "fermentation products" leads ultimately to the formation of acetate, H_2 and CO_2. However, two fermentation products listed in Tab.3 can not be further fermented: CO_2 and CH_4, the most oxidized and the most reduced forms of carbon. Thus, the terminal products of anaerobic decomposition are CH_4 and CO_2. It is to these two carbon compounds, one the most reduced, the other the most oxidized, to which all anaerobic decomposition processes ultimately lead (Brock & Madigan, 1991).

Tab. 3 **Examples of various microbial fermentations and some of the organisms carrying them out**

Type	Overall reaction	Organisms
Alcohol fermentation	Hexoses → Ethanol + CO_2	Yeast *Zymomonas*
Homolactic fermentation	Hexose → lactic acid	*Streptococcus* Some *Lactobacillus*
Heterolactic fermentation	Hexose → Lactic acid Ethanol CO_2	*Leuconostoc* Some *Lactobacillus*
Propionic acid	Lactate → Propionate Acetate CO_2	*Propionibacterium* *Clostridium propionicum*
Mixed acid	Hexoses → Ethanol 2,3-Butanediol Succinate Lactate Acetate Formate $H_2 + CO_2$	Enteric bacteria *Escherichia* *Salmonella* *Shigella* *Klebsiella*
Butyric acid	Hexoses → Butyrate Acetate $H_2 + CO_2$	*Clostridium butyricum*
Butanol	Hexoses → Butanol Acetate Acetone Ethanol $H_2 + CO_2$	*C. butyricum*
Caproate	Ethanol + Acetate + CO_2 → Caproate + Butyrate + H_2	*C. kluyveri*
Homoacetic	$H_2 + CO_2$ → Acetate	*C. aceticum* *Acetobacterium*
Methanogenic	Acetate → $CH_4 + CO_2$	*Methanothrix* *Methanosarcina*
Succinate	Succinate → Propionate + CO_2	*Propionigenium*
Oxalate	Oxalate + H^+ → Formate + CO_2	*Oxalobacter*

(After Brock & Madigan, 1991)

Sulphur compounds. Several inorganic sulphur compounds are important electron acceptors in anaerobic respiration. A summary of the oxidation states of the key sulphur compounds is given in Tab.4. Sulphate (SO_4^{2-}) is used by the sulphate-reducing bacteria and the end product of sulphate reduction is H_2S, an important natural product which participates in many biochemical processes (Brock & Madigan, 1991). Organic sulphides such as methyl and butyl sulphides are also formed, which like H_2S are both characterized by an unpleasant odour (Mengel & Kirkby, 1987).

Certain sulphate-reducing bacteria are capable of a unique form of energy metabolism, disproportionation, the term refering to the splitting of a compound into two new compounds, one of which is more oxidized and one of which is more reduced than the original substrate (Brock & Madigan, 1991).

Tab. 4 Sulfur compounds and sulfate reduction electron donors

Compound	Oxidation state
A. Oxidation states of key sulfur compounds	
Organic S (R–SH)	−2
Sulfide (H_2S)	−2
Elemental sulfur (S^0)	0
Thiosulfate ($S_2O_3^{2-}$)	+2 (average per S)
Tetrathionate ($S_4O_6^{2-}$)	+2 (average per S)
Sulfur dioxide (SO_2)	+4
Sulfite (SO_3^{2-})	+4
Sulfur trioxide (SO_3)	+6
Sulfate (SO_4^{2-})	+6
B. Some electron donors used for sulfate reduction	
H_2	Propionate
Lactate	Acetate
Pyruvate	Butyrate
Ethanol	Fatty acids
Fumarate	Benzoate
Malate	Indole
Choline	

(After Brock & Madigan, 1991)

Desulphovibrio sulphodismutans can for example disproportionate thiosulphate and sulphite as follows:

$$S_2O_3^{2-} + H_2O \rightarrow SO_4^{2-} + H_2S$$

Note that one sulphur atom of $S_2O_3^-$ becomes more oxidized (forming SO_4^{2-}) and the other more reduced (forming H_2S). Disproportionation of sulphite occurs according to:

$$4SO_3^{2-} + 2H^+ \rightarrow 3SO_4^{2-} + H_2S$$

Under waterlogged conditions, inorganic S occurs in reduced forms such as FeS, FeS_2 (pyrites) and H_2S and of these H_2S is the most important end product of anaerobic S degradation (Mengel & Kirkby, 1991). Photosynthetic green and purple bacteria can oxidize H_2S to S by utulizing the H of the H_2S for photosynthetic electron transport. When this process is restricted H_2S may accumulate to toxic levels and thus impair plant growth (Mengel & Kirkby,1991). However, if ferrous iron (Fe^{2+}) is present a highly insoluble sulphide is formed according to the reaction:

$$H_2S + Fe^{2+} \rightarrow FeS + H_2$$

Sulphides are therefore unlikely to be toxic when soil contains appreciable quantities of soluble iron (Vamos, 1964).

Sulphate reduction under anaerobic conditions is mainly brought about by bacteria of the genus Desulfovibrio (Ponnamperuma, 1972) and these bacteria utilize the oxygen of the SO_4^{2-} as a terminal electron acceptor.

The process of S conversion in soil is shown in Fig.14. Under reducing conditions H_2S is produced. Some H_2S can be released into the atmosphere and is thus lost from the soil system. Aerobic soil conditions shift the process in favour of SO_4^{2-} formation.

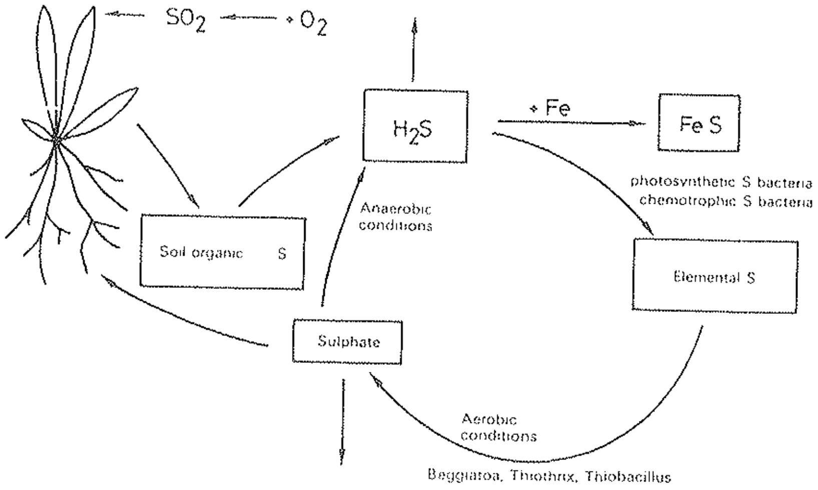


Fig. 14 Sulphur cycle in nature.

(After Mengel & Kirkby, 1987)

Iron and manganese

Iron and manganese are related metal ions which are reduced by various bacteria under anaerobic conditions. It is known definitely that these metals serve as functional electron acceptors for energy generation, but the reduction processes are so widespread that they are of interest even if usable energy is not obtained (Brock & Madigan, 1991).

When soils are waterlogged, ferric ions (Fe^{3+}) are reduced to ferrous ions (Fe^{2+}). This process is carried out by many organisms which also reduce nitrate and at least in some cases the same enzyme, nitrate reductase, functions in the reduction of both nitrate and Fe^{3+} (Brock & Madigan, 1991). Reduction is brought about by anaerobic bacteria which use Fe oxides as e^- acceptors in respiration (Munch & Ottow, 1983). A close contact between the bacteria and the Fe oxides is required for this process. Amorphous Fe is preferred but goethite, haemtite and lepidocrocite can be reduced by the action of microbes. This process (Ponnamperuma, 1972) of Fe reduction is of particular importance in paddy soils where rather high Fe^{2+} concentrations can result. This can often produce toxic effects in rice plants, known as "bronzing." In soils subjected to anaerobic conditions the ratio of activities of Fe^{3+}/Fe^{2+} can be an important parameter in relation to crop growth. This ratio can be assessed by measurement of the redox potential according to the equation (Mengel & Kirkby, 1987):

$$E = 0.77 + 0.059 \log Fe^{3+}/Fe^{2+}$$

Under anaerobic conditions reducing processes are favoured. Hydrous Fe oxides give rise to Fe^{2+} (Ponnamperuma, 1972) according to the equation:

$$Fe(OH)_3 + e^- + 3H^+ \rightleftharpoons Fe^{2+} + 3H_2O$$

From this eqution it is evident that the reduction of Fe^{3+} to Fe^{2+} is associated with the consumption of H^+ and thus with an increase in pH. The reverse is the case as soil aeration is increased, a fall in pH being accompanied by the oxidation of Fe^{2+} to Fe^{3+}.

Differences in redox potential can often be observed in the same profile. In the deeper soil layers which are less well aerated, the fraction of Fe^{2+} of the total soluble Fe is frequently higher than in the upper horizons. The observations of Wiklander & Hallgren (1949), showed that at a depth of 2 m, over 90% of the soluble Fe was present as Fe^{2+}. The redox potential thus generally falls from the upper to the lower horizons.

The metal manganese has a number of oxidation states, of which Mn^{4+} and Mn^{2+} are the most stable. Mn^{4+} forms highly insoluble compounds whereas Mn^{2+} is more soluble and the reduction of Mn^{4+} to Mn^{2+} is carried out by a variety of bacteria (Brock & Madigan, 1991).

The most important Mn soil fractions are Mn^{2+} and the Mn oxides in which Mn is present in trivalent or tetravalent form. The relationships between the Mn^{2+} and the Mn oxides are presented in Fig.15. This Mn cycle in the soil (Dion & Mann, 1946) shows that the equilibrium between the various Mn forms is governed by oxidation– reduction processes. The most important fraction in plant nutrition is Mn^{2+}.

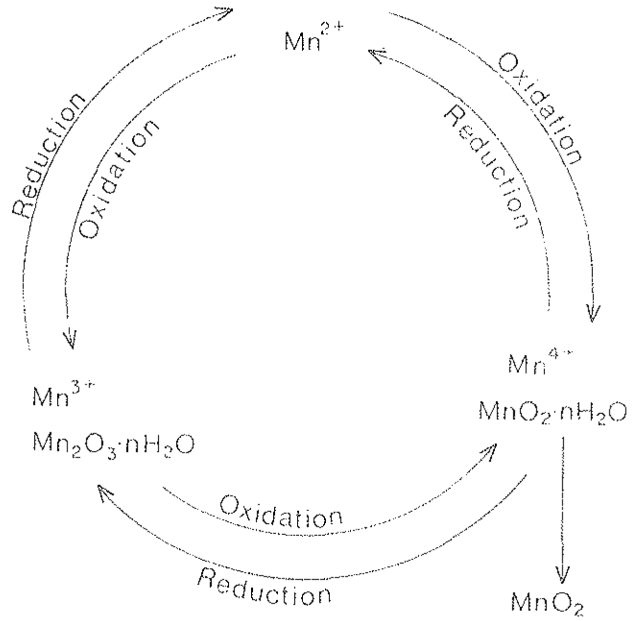


Fig. 15 Mn oxidation-reduction cycle in the soil (after Dion and Mann [1946]).

As the level of Mn^{2+} in the soil depends on oxidation - reduction reactions, all factors influencing these processes have an impact on Mn availability (Mengel & Kirkby, 1987). These factors include soil pH, organic matter content, microbial activity and soil moisture. Under waterlogged conditions as for example in paddy soils, reducing processes dominate and thus provide a high level of Mn availability which may even result in Mn toxicity (Tanaka & Yoshida, 1970). After submergence and almost parallel with the disappearance of O_2, the level of soluble Mn^{2+} rises. In acid soils high in active Mn the concentration of Mn^{2+} may easily attain toxic levels, while in calcareous or sodic soils the Mn level does not rise much after flooding and on these soils Mn deficiency can even occur in rice under submergence conditions (Randhava et al., 1978). The effect of anaerobic soil conditions and of liming on Mn availibility is reflected in the Mn content and yield of lucerne (Tab.5).

Tab. 5 Effect of liming and a 3 day period of flooding on dry matter yield and Mn contents in lucerne (Graven *et al.* [1965])

Treatment g $CaCO_3$/pot	Flooding	g, DM pot	Mn content ppm Mn in DM
0	–	3.1	426
0	+	1.2	6067
20	–	5.7	99
20	+	3.0	954

LOSSES OF SOLUBLE COMPOUNDS OF NITROGEN

Under anaerobic conditions considerable quantities of nitrate can be lost from the soil both by denitrification and by leaching in drainage water. The latter process is independent of the partial pressure of oxygen in the soil but since anaerobic soils are in practice often waterlogged, it is relevant to consider the two processes conjointly.

Leaching. Although nitrate is highly soluble and undergoes no significant interactions with the mineral phase of the soil, the extent to which it is removed by leaching can vary appreciably depending on soil structure (Russell, 1977). If water penetrates freely through large pores or cracks nitrate dissolved in water in the fine pores in the intervening solid phase may be lost relatively slowly and this can be important in conserving some agricultural soils (Cunningham et al., 1958). Thus, the amounts lost by leaching vary widely depending not only on the nitrate content of the soil and rainfall but on soil texture, losses ranging from 5 kg to nearly 50 kg ha^{-1} per year have been estimated depending on soil type in typical arable lands in England (Cooke, 1976).

Denitrification. Inorganic nitrogen compounds are some of the most common electron acceptors in anaerobic respiration. A summary of the various inorganic nitrogen species with their oxidation states is given in Tab.6. The most widespread inorganic nitrogen species in nature are ammonia and nitrate, both of which are formed in the atmosphere by inorganic chemical processes, and nitrogen gas N_2, also an atmospheric gas, which is the most stable form of nitrogen in nature (Brock & Madigan, 1991).

Tab. 6 **Oxidation states of key nitrogen compounds**

Compound	Oxidation state
Organic N ($R-NH_2$)	−3
Ammonia (NH_3)	−3
Nitrogen gas (N_2)	0
Nitrous oxide (N_2O)	+1 (average per N)
Nitrogen oxide (NO)	+2
Nitrite (NO_2^-)	+3
Nitrogen dioxide (NO_2)	+4
Nitrate (NO_3^-)	+5

(After Brock & Madigan, 1991)

Many species of bacteria found in soils are capable of reducing nitrates and nitrites to nitrogenous gases (NO, N_2O, N_2) which are then released into the atmosphere. This dissimilatory reduction is known as denitrification and may be represented according to the following reduction sequence (Mengel & Kirkby, 1987):

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

The denitrifying bacteria that bring about these reactions are essentially obligately aerobic except for the ability to utilaze NO_3^- in the absence of oxygen (Focht, 1978). Nitrate acts in lieu of oxygen as a terminal acceptor of electrons produced during anaerobic respiration.

Brock & Madigan (1991) state that "one of the most common alternative electron acceptors is nitrate, NO_3^-, which is converted into more reduced forms of nitrogen, N_2O, NO, N_2. Because these products of nitrate reduction are all gaseous, they can be lost from the environment, and because of this the process is called denitrification.

Assimilative nitrate reduction, in which nitrate is reduced to the oxidation level of ammonia for use as nitrogen source for growth and dissimilative nitrate reduction, in which nitrate is used as an alternative electron acceptor in energy generation are contrasted in Fig.16. Under most conditions, the end products of dissimilatory nitrate reduction is N_2 or N_2O. The process is the main means by which gaseous N_2 is formed biologically, and since N_2 is much less readily available to organisms than nitrate as a source of nitrogen, denitrification is a detrimental process.

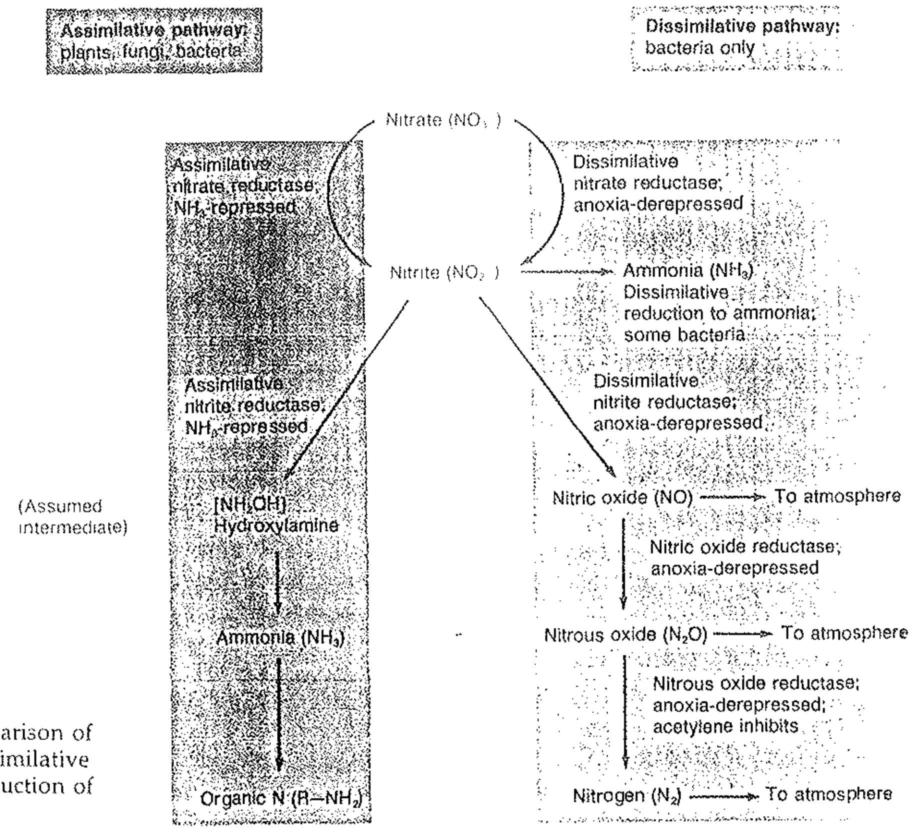


Fig. 16 Comparison of assimilative and dissimilative processes for the reduction of nitrate.

(After Brock & Madigan, 1991)

The enzyme involved in the first step of nitrate reduction, nitrate reductase, is a molybdenium containing enzyme. Because O_2 inhibits the synthesis of dissimilative nitrate reductase, the process of denitrification is strictly an anaerobic process, whereas assimilative nitrate reduction can occur quite well under aerobic conditions. Assimilative nitrate reduction occurs in all plants and most fungi, as well as in many bacteria, whereas dissimilative nitrate reduction is restricted to bacteria.

In all cases, the first product of nitrate reduction is nitrite, NO_2^-, and another enzyme, nitrite reductase, is responsible for the next step. In the dissimilative process, two routes are possible, one to ammonia and the other to N_2. The route to ammonia is carried out by a fairly large number of bacteria, but is of less practical significance. There are also some bacteria which do not reduce nitrate but do reduce nitrite to ammonia. This may be a detoxification mechanism, since nitrite can be toxic under mildy acidic conditions. The pathway to nitrogen gas proceeds via two intermediate gaseous forms of nitrogen, nitric oxide (NO) and nitrous oxide (N_2O). Several organisms are known which produce only N_2O during the denitrification process, while other organisms produce N_2 as the gaseous product".

A large number of bacteria, mainly facultative anaerobes, are capable of denitrification. Jordan et al. (1967) found 22 isolates from a single soil which could reduce nitrate to nitrite but some had little, if any, ability to mediate the subsequent reduction of nitrite. On the contrary, Focht (1978) describes the denitrifying bacteria as beeing obligately aerobic except for the ability to utilize NO_3^- in the absence of oxygen. When the supply of substrates is favourable, denitrification can occur very rapidly. In laboratory conditions the virtually complete denitrification of 300 ppm nitrate has been observed at 30^0 C; an approximate two-fold reduction in the rate of the process occurred with a 10^0 C drop in temperature (Cooper & Smith, 1963). The amounts of N which can be lost from the soil system by denitrification can vary enormously. According to Allison (1966) these losses of gaseous N can range from about 5 to 50% of the total N applied. Russell (1987) reports corresponding quantities from negligible to approx. 20–45 %. Even in aerated arable soils some N loss due to denitrification may occur because O_2 is not uniformly distributed throughout the soil and some parts of the profile may be anaerobic (Woldendorp, 1968).

Fig.17 shows results from a clay loam soil in southern England in which the water content was high throughout the period of observation. The extent of denitrification can not at present be inferred from such measurements because there is insufficient information on the rates at which nitrous oxide diffused away from the sites of production. However, it is evident that denitrification took place down to an appreciable depth in the soil and that the process can increase when the temperature rises in spring. It is of interest that widely varying ratios of oxygen to nitrous oxides can be found in samples of soil gases or water taken only a short distance apart (approx. 0.5 m) in the same field (Fig.18). This is attributed to the production of nitrous oxide in localized anaerobic zones between which there may be appreciable air filled spaces. Greenland (1962) deduced, using much simpler methods, that denitrification could occur simultaneously with nitrification in wet soils which contained both anaerobic and aerobic zones.

Temporal fluctuations in the denitrification activity of soil are determined mainly by the soil temperature and moisture content (Ryden, 1983), but also by plant growth (Stefanson, 1972), incorporation of plant residues, and soil tillage (Aulakh et al., 1984). The nitrate concentration may also be rate limiting, but apparently only at very low concentrations (Yoshinari et al., 1977). Systematic differences between soil types with respect to potential denitrification rates depend on the organic C content of the soils (Reddy et al., 1982), the soil texture (Sextone et al., 1985) and the drainage capacity (Groffman et al., 1984). The aggregate size and pore size distribution are probably also decisive factors since they determine the volume of anaerobic sites in the soil (Smith, 1977).

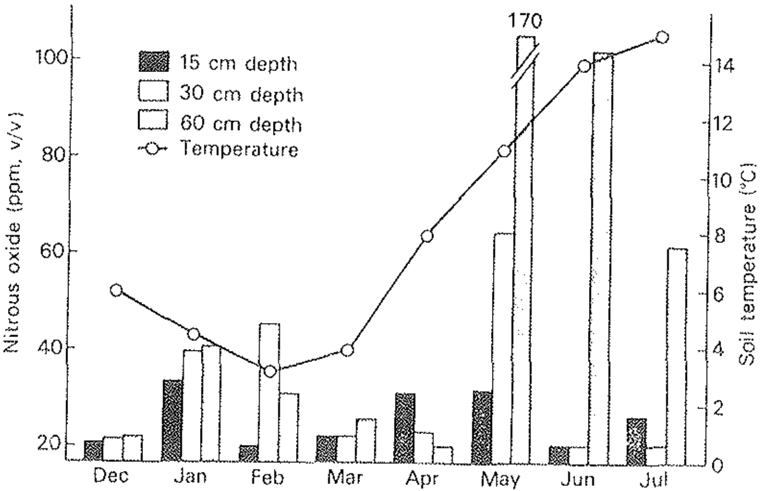


Fig. 17 *Mean concentrations of nitrous oxide in clay loam soil (Evesham series) at three depths at different times of year and the mean soil temperature at 30 cm depth (Dowdell and Smith, 1974).*

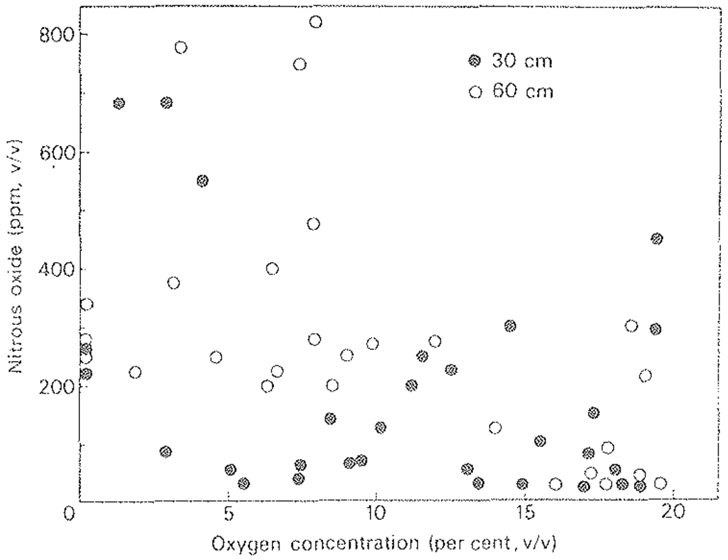


Fig. 18 *Relationship between concentrations of oxygen and nitrous oxide at two depths in a clay loam soil (Evesham Series) (Dowdell and Smith, 1974).*

Several of these parameters can be affected by agricultural practice, and a better understanding of the effect of various soil treatments on denitrification is needed in order to minimize the loss of fertilizer–N through denitrification. Tractor traffic on wet soil has been shown to increase the aggregate size and bulk density of clay soils with an accompanying reduction in the yield of small grains (Njös, 1978). It has also been demonstrated that soil compaction results in reduced redox potentials in soil (Horn, 1985). Hence, soil compaction will probably result in increased denitrification.

Thus, on well aerated sandy soils denitrification rates are generally lower than on clay soils (Tab.7). Dilz & Woldendorp (1960) found that denitrification losses are particulary high when living roots are abundant in the soil medium. It is supposed that root exudates stimulate the denitrifying bacteria and thus increase denitrification losses. This is supported by the findings of Trolldenier (1973), who observed in solution culture experiments with rice that incresed microbial activity in the rhizosphere resulted in a lowered O_2 content of the root medium and thus improved conditions for denitrification.

Tab. 7 Nitrogen losses due to denitrification from various soil types under permanent grassland (according to Dilz and Woldendorp [1960])

Soil type	N-loss in % of applied N
Sand	11–25
Clay	16–31
Peat	19–40

Denitrification losses may be greater than generally assumed. In extensive field trials with barley measuring N transformations in soil plant systems Kowalenko & Cameron (1977) have concluded that unrecovered fertilizer N could largely be accounted for by denitrification. Using N–15 labelled fertilizer it was shown that the total recovery of fertilizer N in the crop and in the soil accounted in one year to 69 % and in another year to 54 % of the original application. The remaining unrecovered 31 % and 46 % respectively represented denitrification. Denitrification rates were at a maximum in spring and early summer and coincided with the maximum rates of N uptake by the crop. Riga et al. (1980) and Kjellerup & Dam Kofoed (1983) have also found that under field conditions a greater amount of the N loss can be attributed to denitrification than to leaching provided that excessive amounts of N fertilizer were not applied.

In a field experiment in Norway (Bakken et al., 1987) with soil compaction by tractor traffic on a loam soil, the denitrification rate (using the C_2H_2 inhibition method), the soil structure and the wheat yield were investigated. Tractor traffic on wet soil (> –50 mbar matric potential) reduced the pore volume, doubled the percentage of large aggregates (>20 mm), reduced the wheat yield by about 25 % and increased the N–loss through denitrification by a factor of 3–4. Neither of these parameters were affected by tractor traffic at low soil moisture content. The weight of the tractor (1800 kg vs 4800 kg) did not significantly alter the effect of compaction on the measured parameters. There was a factor of 2–6 between the measured denitrification rate in compacted and that in uncompacted soil, and this factor showed little dependence on the average activity level on each date of measurement. Accumulated values for the measured denitrification during 75 days (May 23 – August 9) were 3–5 kg N ha^{-1} in uncompacted soil and 15–20 kg N ha^{-1} in soil which was compacted in wet condition.

Some estimates of the extent to which nitrogen is lost from soil by denitrification are summarized in Tab.8. The measurement of nitrogen gas as opposed to nitrous oxide which is produced by denitrification presents particular problems because of its presence in much larger concentrations in the atmosphere. The use of fertilizer labelled with ^{15}N reduces but does not entirely eliminate this problem as the atmosphere contains ^{15}N in low abundance (Russell, 1977). Despite this uncertainties it appears that, depending on conditions, losses due to denitrification can be as high as 45 % of the nitrogen applied to the soil. Denitrification may thus be a significant cause of losses of nitrogen in anaerobic conditions. According to Werner (1980) denitrification plays a major role in N turnover on a global scale. This is shown in Tab.9 which provides data on N circulation between the atmosphere and the soil.

Tab. 8 *Some estimates of losses of fertilizer nitrogen from soil by denitrification.*

Method	Gaseous loss* (per cent)	References
Greenhouse pot experiments – ^{15}N enriched fertilizer nitrogen	1–40	Broadbent and Clark (1965) (review)
Lysimeter experiments – loss estimated	4–42	Allison (1966) *
Enclosed chambers – direct measurement of loss to atmosphere	<1–15 per week	Stefanson (1972) Martin and Ross (1968) Craswell and Martin (1975a)
Field experiments – loss of ^{15}N enriched nitrogen	2–36	Carter, Bennett and Pearson (1967) Myers and Paul (1971) Westerman, Kurtz and Hauck (1972) Craswell and Martin (1975b)

* Unrecovered N used as the sole estimate of loss of gaseous N except in enclosed growth chambers where loss was measured by the analysis of the evolved gases.

Tab. 9 Global turnover between soil N and atmospheric N (data from WERNER [1980]), in 10^6 t/year

	Gain		Loss
Industrial production	46	Denitrification	200–300
Biological fixation	100–200	NH_3-Volatilization	165
NO_3^-/NO_2^- precipitation	60		
NH_3-precipitation	140		

Generally the escape of gaseous N from the soil medium into the atmosphere is regarded as a nutrient loss and is therefore undesirable. On the other hand considerable amounts of NO_3^- are probably denitrified when draining into deeper parts of the soil profile so that the rate of transfer of NO_3^- to the ground water is lowered (Kolenbrander, 1972). Denitrification may thus have a beneficial effect by preventing water pollution by NO_3^-.

A paddy field – an extreme example of anaerobic conditions

An excellent example of chemical and microbiological interactions that appears under extreme anaerobic conditions is a paddy field submerged with water. The soil is during rice cultivation kept under submergence to a depth of several cm. As soon as the soil is flooded, anaerobic conditions set in and a specific sequence of reaction steps can be observed which can be devided into two stages. These two stages and the individual steps are shown in Tab.10. Anaerobiosis begins with the disappearance of O_2 and the microbial reduction of NO_3^- to N_2 and N_2O. Manganese and Fe is then reduced to Mn^{2+} and Fe^{2+} respectively in accordance with the slight drop in the redox potential in the soil. Fe^{3+} reduction is to a large extent a biological process, brought about by microorganisms which use the ferric oxides as e^- acceptor for respiration (Munch & Ottow, 1983). Fe^{3+} reduction is an analogous process to nitrate reduction in which the NO_3^- is used as an e^- acceptor in bacterial respiration. This first stage of reduction is not detrimental to rice plants provided that Fe^{2+} and Mn^{2+} concentrations do not reach toxic levels. The second stage of reduction is associated with a substantial drop of redox potential indicating that reducing substances have been produced.

At this stage sulphate is reduced to sulphide and at an even lower redox potential molecular H_2 and methane are formed. Accumulation of additional toxic substances such as butyric acid and fatty acids also occur at this low redox potential. Russell (1973) quotes estimates that 10^{-2} M acetic acid and 10^{-4} M butyric acid are injurious to rice and that, after readily decomposable organic matter has been added to the soil, these concentrations may be exceeded to an extent which makes the land unsuitable for planting the crop until the acids have been largely removed by leaching or other processes. There is evidence also that these substances contribute to the creation of unfavourable conditions when massive quantities of animal waste are added to the paddy soil (Cooper & Smith, 1975).

Tab. 10 Steps of microbial metabolism in waterlogged soil (TAKAI *et al.* [1957])

Step	Main Reaction	Initial Redox Potential (volts)
	First stage	
1st	O_2 disappearance	+0.6 ~ +0.5
2nd	Nitrate reduction	+0.6 ~ +0.5
3rd	Mn^{2+} formation	+0.6 ~ +0.5
4th	Fe^{2+} formation	+0.5 ~ +0.3
	Second Stage	
5th	Sulphide formation sulphate reduction	0 ~ −0.19
6th	H_2 formation	−0.15 ~ −0.22
7th	CH_4 formation	−0.15 ~ −0.19

The effects of phenolic acids derived from plant debris, including stubble mulches, have been considered particulary by Tousson et al. (1968) and McCalla & Norstadt (1974). The former workers concluded that these compounds were responsible for some 60 % of the toxicity in ether extracts from such soils. McCalla et al. have attributed toxicity both to phenoxy acids and to patulin, an antibiotic, but there appears to be little information on the concentrations in which this latter substance occurs.

The second stage (Tab.10) should be avoided in rice cultivation. Soils to which organic matter has been applied or which are naturally high in organic matter are prone to low redox potentials due to the fact that the organic matter favours the growth and metabolism of anaerobic microorganisms (Ponnamperuma, 1965). Low redox potentials may lead to very high Fe^{2+} concentrations which are harmful to rice plants. According to Trolldenier (1973), rice plants suffering from Fe toxicity are characterized by extremely high Fe contents (290–1000 micrograms g^{-1} dry weight) as well as high Mn contents (1000 micrograms g^{-1} dry weight). The appearance of this disease, known as suffocation disease, depends on the "oxidizing power" of the rice root. This oxidizing power results from the excretion of O_2 which induces a rise in the redox potential in the rhizosphere, and hence a decrease of the Fe^{2+} level (Trolldenier, 1973). The Fe^{3+} is partially precipitated as oxides of Fe at the root surface giving the roots a red brown coulor. This colour is indicative of healthy roots. Under anaerobic conditions FeS is precipitated at the root surface and the roots are black as shown in Fig.19.

In paddy soils a characteristic profile may be observed as shown in Fig.20. At the uppermost surface of the flooded soil there is a thin zone with a maximum depth of 1 cm. This is known as the oxidized layer as aerobic conditions prevail due to oxygen from the water. The layer has a reddish coulor, Fe beeing present mainly in the Fe^{3+} form. This tendency to oxidation is also indicated by a rather high redox potential (> + 0.4 V) and N is present as NO_3^-. Underlying this layer is a broader zone which is exclusively anaerobic and is blue grey in colour due to the presence of Fe^{2+}. It is here that NO_3^-, originating from the oxidized layer is reduced to N_2 or the oxides of N. As these compounds are volatile they may be lost from the system. It is for this reason that NO_3^- fertilizers are not recommended for paddy soils (Matsubayashi et al., 1963). Ammonium-N regardless of whether applied as fertilizer or produced during the decomposition of organic N containing compounds, can also be lost via denitrification. Patric & Reddy (1977) have demonstrated that NH_4^+ may diffuse from the lower layer to the oxidized thin surface soil layer where it can be oxidized to NO_3^-. If this NO_3^- is then transported back into the reducing deeper soil zone it can be denitrified and thus lost.

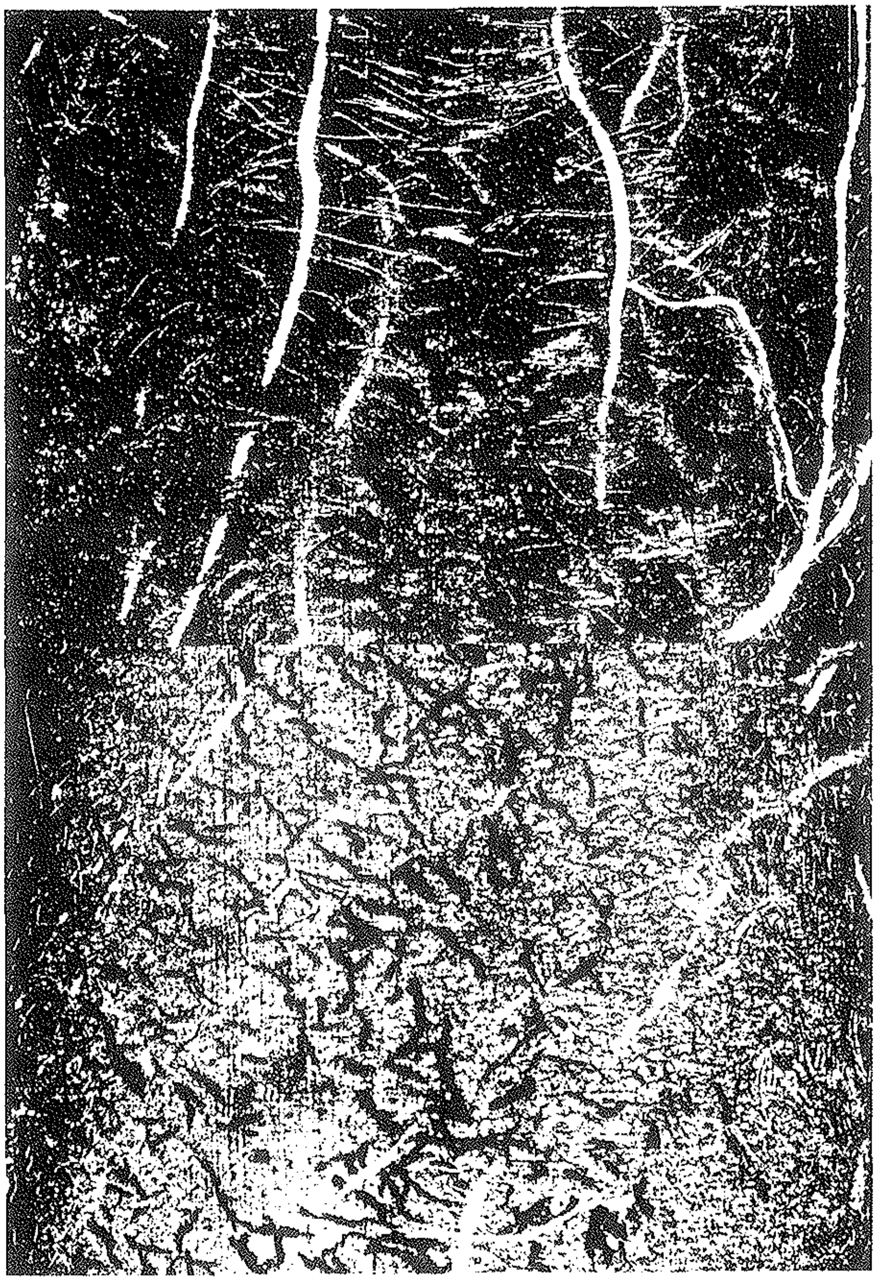


Fig. 19 Upper part, normal rice roots growing under an optimum redox potential; lower part, rice roots affected by too low a redox potential, lateral roots are covered with a black coating of FeS. (Photo: TROLLDENIER)

(After Mengel & Kirkby, 1987)

Submergence also influences the availability of plant nutrients other than N (Ponnamperuna, 1978). Generally phosphate availability increases. This is due partially to the release of occluded phosphates after the reduction of Fe^{3+} to Fe^{2+} on the Fe oxide skin and also partially due to hydrolysis of $Fe(OH)_3$. The content of soluble cations rises as a result of cation exchange induced by soluble Fe^{2+} and Mn^{2+}. Hydrogen sulphide produced under reducing conditions forms precipitates (sulphides) with Fe, Cu, Zn and Mn and thus affects the availability of these nutrients. By the formation of FeS, plants are protected from toxic levels of Fe^{2+}. The formation of sulphides has no major influence on S availibility, as sulphides can be oxidized in the rhizosphere by bacteria (Ponnamperuma, 1972). As mentioned before, flooding results in an increase in soil pH. Calcareous soils and sodic soils, however, decrease in pH when submerged and this decrease results from the dissolution of CO_2 (Mengel et al., 1987). High accumulations of CO_2 may be toxic to the rice plant (Cho et al., 1971). According to Mikkelsen et al. (1978) the pH of the flooding water shows a diurnal rhythm. pH values as high as 10 may be attained during the day, whereas at night a drop of about 2 pH units can be observed. It is supposed that the pH increase in the day time results from CO_2 uptake by algae. Such high pH values during the day may lead to high losses of NH_3 by volatilization especially under favourable wind and high temperature conditions (Savant & DeDatta, 1982).

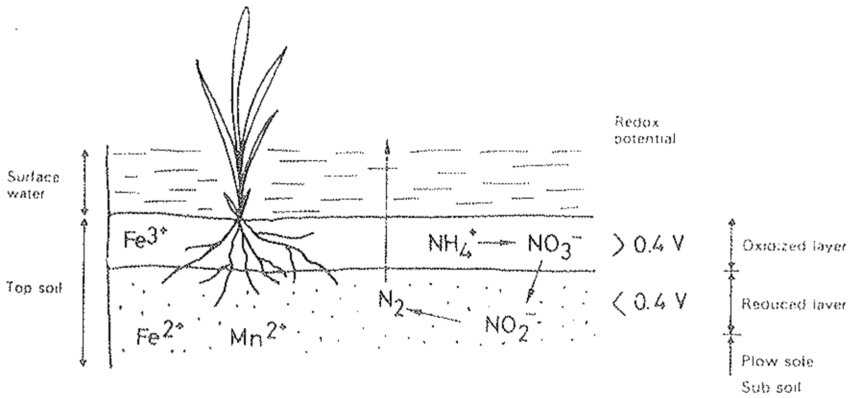


Fig. 20 Soil profile of a submerged paddy field soil (after MATSUBAYASHI *et al.* [1963]).

RESPONSE OF PLANTS TO ANAEROBIC SOILS

Species vary widely in their sensivity to injury in anaerobic soils and in any one species the effect may change depending on its stage of growth and on the environment (Russell, 1973).

Morphological and physiological effects

In sensitive plants, symtoms of injury can become evident rapidly, not only in roots but also in shoots. Within a few hours leaves may wilt or show epinasty (the downward curvature of petioles) (Fig.21). Subsequent leaves can become chlorotic and senesce prematurely and the elongation of stems is often reduced and root growth is also restricted (Erickson & van Doren, 1961). Exposure to anaerobic conditions for quite short periods, e.g. twenty four hours, can sometimes lead to permanent reduction in plant growth and longer exposure may lead to death. If plants survive anaerobiosis morphological changes can occur, e.g. the development of aerenchyma in roots (Bryant, 1934).

Anaerobic conditions can cause a switch from aerobic to anaerobic metabolism with the consequent production of ethanole (Crawford, 1967). He also found that the concentrations of ethanole were higher in sensitive plants, this beeing associated with increased activity of alcohol dehydrogenase.

Fig. 21 *Development of epinastic curvature in shoots of tomato plants* (Lycopersicom esculentum). *Left: control plant, Right: waterlogged for two days. (Photograph, Dr M. B. Jackson.)*

(After Russell, 1973)

As research has proceeded on the effects of anaerobic rooting media, increasing attention has been given to hormonal mechanisms. The reduction of the concentration of gibberelins in the xylem sap and in the roots and shoots of tomato plants has been demonstrated under anaerobic conditions (Reid & Crozier, 1971). Burrows & Carr (1969) showed that the transport of cytokinins to shoots could be restricted under anaerobic conditions. There is evidence also of the involvement of auxin in the response of plants to anaerobic soil conditions (Phillips,1964b). Its concentration in shoots increases as epinasty develops. The production of abscisic acid can also be affected by anaerobic rooting media. Wright & Hiron (1972) found increased concentrations in shoots and considered this might be due to incipient wilting.

However, ethylene is perhaps the endogenous growth substance which appears most closely associated with the response of plants to anaerobic soil. Its concentration throughout susceptible plants often increases markedly (Jackson & Campell, 1976a). Some results of these workers are shown in Tab.11. If the supply of oxygen in the rooting medium of tomato plants *(Lycopersicom esculentum)* is reduced, the concentration of ethylene in the leaves and also the degree of epinastic curvature can increase drastically.

Tab. 11 *Effects of waterlogging for four to five days on the concentrations of ethylene in the shoot system of various species.*

	ppm in the gas phase (v.v.)			
	Tomato (*Lycopersicon esculentum Mill*)	Pea (*Pisum sativum L.*)	Field bean (*Vicia faba L.*)	Dwarf bean (*Phaseolus vulgaris L.*)
Waterlogged	1·17	0·93	0·50	1·36
Control	0·34	0·25	0·37	1·08

(Jackson and Campbell, 1976b.)

Transient waterlogging of crops

Except under special circumstances, of which the cultivation of paddy rice is the obvious example, agricultural problems due to anaerobic soil conditions are usually transient, beeing the consequence of the soil beeing nearly or completely waterlogged for periods ranging from days to weeks, when precipitation is high and evapotranspiration low; at other times of the year water may be deficient.

The injury caused by transient waterlogging can vary much depending on the stage of growth when it is experienced (Fig.22). Part of this variation may be due to seasonal differences in oxygen consumption in the soil which influence the rate by which anaerobic conditions develop, but there is much evidence of changes in the sensitivity of plants during their life cycle (Russell, 1973). Germinating seeds are commonly regarded as particulary sensitive to injury because they are totally dependent on the surrounding soil for oxygen. Damage to young seedlings in waterlogged soil can be intesified if they are in close proximity to plant debris which is saturated with water (McCalla & Norstadt, 1974).

Fig. 22 *Plants of garden peas* (Pisum sativum) *which had been grown in continuously well aerated soil (C) or exposed to waterlogging for five days at the following stages of growth. T1–early vegetative growth (47), T2–pre flowering (7), T3–flowering (24), T4–pod filling (30). The figures in brackets are the yield of peas expressed as a percentage of that of unwaterlogged controls (C). The T1 plants were stunted but otherwise healthy, T2–T4 died prematurely (Cannell* et al., *1976).*

It is commonly observed that after plant shoots have emerged from the soil their tolerance to transient waterlogging can vary greatly. In general, it appears that the yield of cereals is depressed to the greatest extent if the soil is waterlogged when the reproductive organs are developing (Swartz, 1966). Erickson & van Doren (1961) reached similar conclusions with peas (Fig.22). However in maize Lal & Tailor (1969) found transient waterlogging to be particulary damaging early in the season.

EFFECTS OF SOIL COMPACTION ON ROOT GROWTH, CROP DEVELOPMENT, NUTRIENT UPTAKE AND CROP YIELD

Monocots

Effects of compaction on nutrient uptake by roots have received much less attention than effects on growth itself. While compaction might be expected to increase the movement of ions to roots by diffusion (Kemper et al., 1971) restricted growth of roots generally results in smaller amounts of nutrients beeing absorbed from compacted than from uncompacted soil (Boone & Veen, 1982). However, where only part of the root system or other root members (e.g. axes) are subjected to unfavourable conditions, the growth of other parts of the root system or particular root members (e.g. laterals) may be enhanced (Crosset et al., 1975). Hence, compaction of the soil need not necessarily result in decrease in the total amount of nutrients absorbed, although the location from which the nutrients are derived may vary.

In a laboratory experiment, Shierlaw & Alston (1984) investigated *Zea mays* L. and *Lolium rigidum* Gaud., grown for 18 and 33 days respectively in pots containing three layers of a loam soil each weighing 1 kg. The top and bottom layers were 100 mm deep and they had a bulk density of 1200 kg^{-3}, while the central layer of soil was compacted to one of 12 bulk densities between 1200 and 1750 kg^{-3}. The soil was labelled with ^{32}P and ^{33}P so that the contribution of the different layers of soil to the phosphorus content of the plant tops could be determined. Soil water potential was maintained between −20 and −100 kPa (Fig.23).

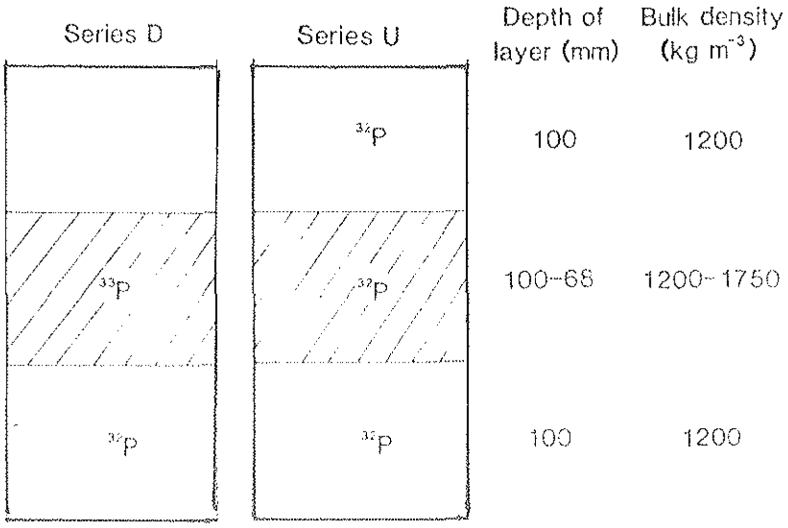


Fig. 23
(After Shierlaw & Alston, 1984)

There was a significant (P<0.05) negative correlation between the dry weight of the ryegrass plants and the bulk density of the central compacted layer of soil (Fig.24). The corresponding correlation with maize was positive, although in this case the level of significance was <0.10. The phosphorus content of the plant tops followed a similar pattern to that of dry weight.

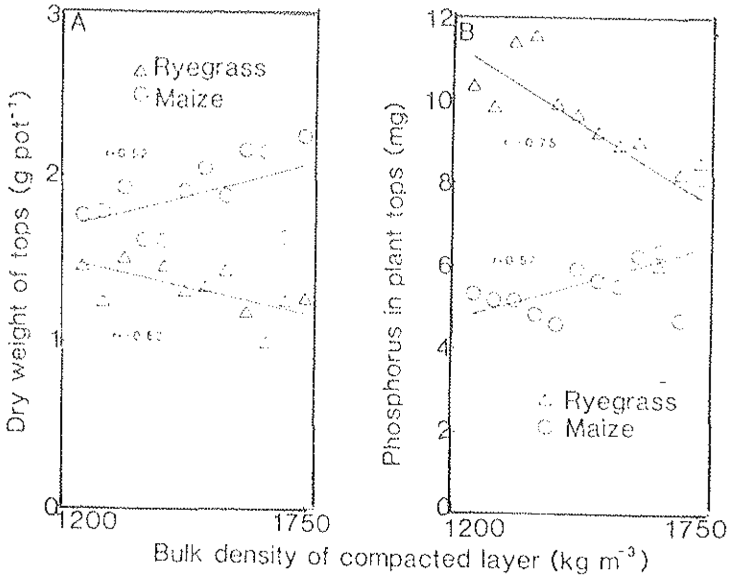


Fig. 24 Dry weight (A) and phosphorus content (B) in the tops of annual ryegrass (△) and maize (○). (Correlation coefficients of 0.50, 0.58, 0 71 and 0.82 correspond to probabilities of 0.10, 0 0.01 and 0.001 respectively, where there are ten degrees of freedom for error.)
(After Shierlaw & Alston, 1984)

The fractions of the phosphorus in the tops of the plants which came from the different layers of soil are shown in Fig.25. The greater the compaction of the central layer of soil, the greater was the fraction of phosphorus in the tops of both species which came from the surface soil. About half of the phosphorus in the maize seed was present in the tops of the plants at the time of harvest, and this accounted for just over one third of the phosphorus in the tops.

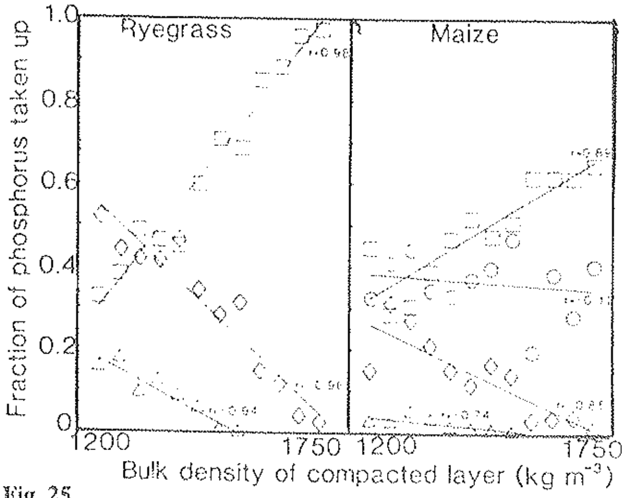


Fig. 25 Fraction of phosphorus in the plant tops derived from the upper (□), central compacted (◇) and lower (△) layers of soil; and from maize seed (○).
(After Shierlaw & Alston, 1984)

The treatments had no effect on the total length of root of either species, but the distribution of the roots was substantially altered by compaction of the soil (Fig.26). Some roots of both species grew into the most dense soil, but the roots were unable to penetrate completely these layers of soil with bulk densities more than or equal to 1550 kg m^{-3} and grow into the uncompacted soil below. Roots proliferated in the overlying soil when growth was restricted in the compacted layer.

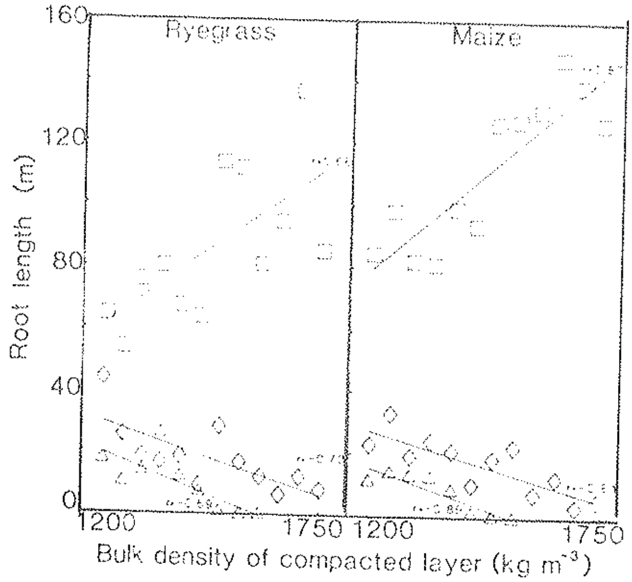


Fig. 26 Total root length in the upper (□), central compacted (◇) and lower (△) layers of soil.
(After Shierlaw & Alston, 1984)

The diameters of both the main axes and first order lateral roots of ryegrass were substantially larger in compacted than in uncompacted soil (Fig.27). The compaction treatments had little effect on the diameters of the roots in the top and bottom layers of soil, although the diameter of the first order lateral roots in the surface layer and the bulk density of the compacted layer were significantly correlated ($P<0.05$). The diameters of the maize roots responded to the compaction treatments in a manner similar to those of ryegrass, except for roots in the bottom uncompacted layer. In this case, the diameters of the maize roots were significantly affected by the compaction treatment; the roots were noticeably thicker where bulk density was high.

The concentrations of carbon dioxide and oxygen in the soil atmosphere shortly before the plants were harvested are shown in Fig.28. Gas concentrations in the surface layer of soil varied only slightly with the compaction treatments, but very large differances in the composition of the soil atmosphere occurred in the rest of the soil. Oxygen accounted for less than 0.1 m^3m^{-3} of the soil atmosphere in the central and bottom layers where the bulk density of the compacted soil was 1550 kg m^{-3} or greater.

The concentrations of oxygen shown in Fig.28 probably represent close to the minimum concentrations that occurred, since plant growth was at its maximum and the samples were collected during the day when temperature and presumably respiration were high. Results on measurements made on samples collected the previous night followed a similar pattern, but the soil atmosphere contained 0.01 to 0.02 m^3 m^{-3} more oxygen.

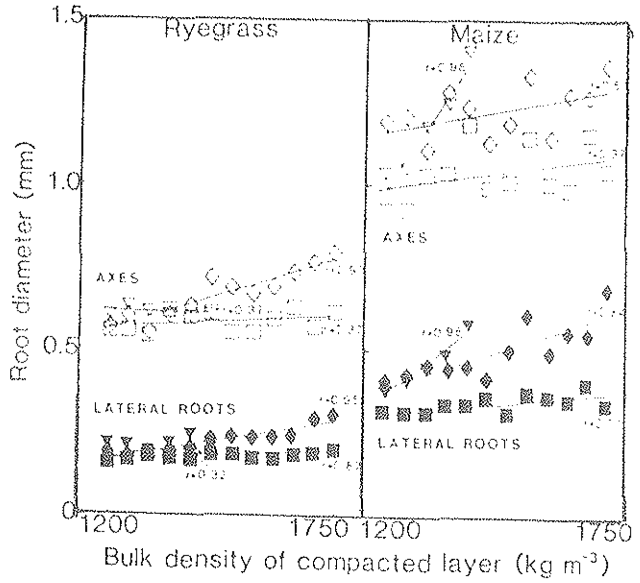


Fig. 27

Diameters of axes and first order lateral roots in the upper (□, ▩) central compacted (◇, ◆) and lower (▽, ▼) layers of soil.

(After Shierlaw & Alston, 1984)

The effects of compaction on volumetric water content and penetrometer resistance at water potential of −20 and −100 are shown in Fig.29. The relative effect on soil strength of a change in water potential was slightly greater at high than at low bulk density.

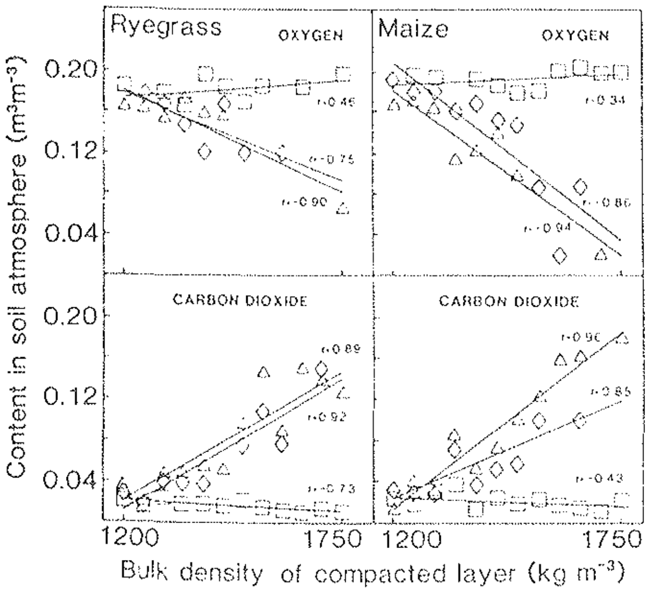


Fig. 28 Concentrations of oxygen and carbon dioxide in the atmosphere in the upper (□), central compacted (◇) and lower (△) layers of soil

(After Shierlaw & Alston, 1984)

The relationship between the root length and penetrometer resistance is shown in Fig.30. Although resistance was probably the main factor influencing root growth in compacted soil up to a bulk density of about 1550 kg m^{-3}, poor aeration was also involved in higher densities. Although there are variations in the reported values of oxygen concentration in the soil atmosphere below which anoxia may occur (Greenwood, 1970), root growth generally appears to be unrestricted by poor aeration when the oxygen concentration in the soil atmosphere is greater than 0.01 m^3 m^{-3}. Concentrations lower than this value were measured where bulk density was greater than 1550 kg m^{-3}. Moreover, the air-filled porosity of the soil at that density varied from 0.05 to 0.14 over the range of water potentials encountered. The latter value is close to the lower limit of 0.12 to 0.15 for air-filled porosity which has been suggested as necessary to provide sufficiently rapid diffusion of oxygen in soil (Greenwood, 1970). It was not possible to determine from the data available the relative importance of mechanical stress and poor aeration in controlling root growth in the highly compacted soil.

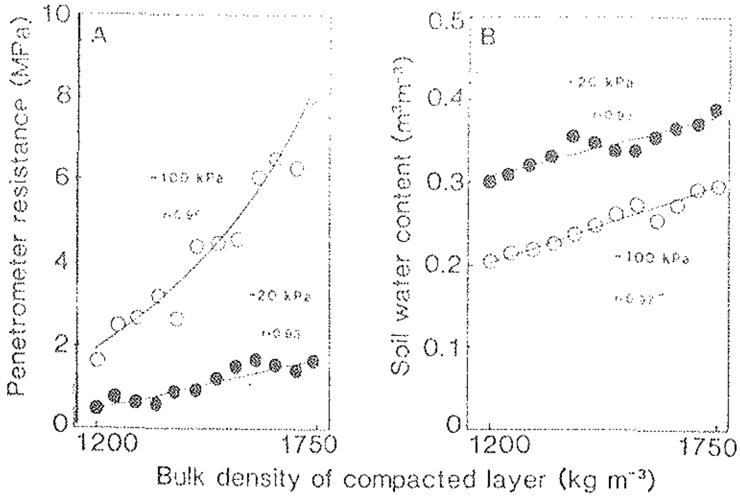


Fig. 29 Relation of penetrometer resistance (A) and volumetric water content (B) to the bulk density of the soil at water potentials of −20 and −100 kPa.
(After Shierlaw & Alston, 1984)

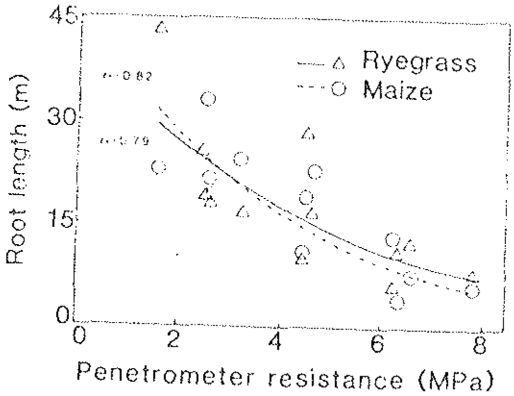


Fig. 30 Relation between root lengths of annual ryegrass (△) and maize (○) and penetrometer resistance of the soil at a water potential of −100 kPa

(After Shierlaw & Alston, 1984)

As shown above, the two species differed in ability to absorb phosphorus. The ryegrass had higher concentrations of phosphorus, and uptake from the surface layer of soil per unit length of root was about twice that of maize. The slightly greater volume of soil exploited by the ryegrass as a concequence of their longer root hairs (Tab.12) may have contributed to this effect.

Tab. 12 Root hair development of annual ryegrass and maize in a soil with a bulk density of 1200 $kg\ m^{-3}$

	Mean length of hairs, μm		Number of hairs mm^{-1} root section	
Plant	Axes	Lateral roots	Axes	Lateral roots
Ryegrass	666 ± 22	630 ± 25	84 ± 2.5	85 ± 3.3
Maize	558 ± 12	516 ± 8	64 ± 2.1	55 ± [illegible]

(After Shierlaw & Alston, 1984)

The results support previous observations on the effect of compaction on root growth, and on the ability of plants to compensate when part of the root system is subjected to stress by enhancing root growth in volumes of the soil where more favourable conditions exist (Goss, 1974). They also show that the main effect of compaction was on root growth. Where nutrient and water supply were adequately maintained, the plants were able to compensate for the lack of rooting depth caused by compaction by producing more roots in the surface layer.

Under field conditions, restriction of roots by compact layers may have severe effects on growth if the surface soil dries and the water supply to the plants is limited by the inability of the roots to tap reserves of water in the subsoil (Elkins et al., 1977). In such circumstances, action may need to be taken to disrupt the compact layers by deep ripping or perhaps by making use of plant species whose roots are able to penetrate the compact soil (Elkins et al., 1977).

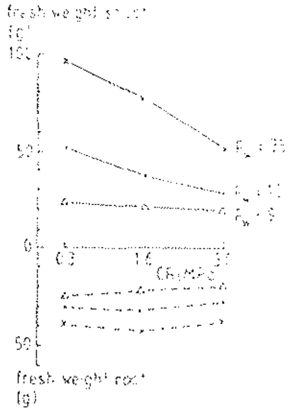
In another experiment with maize, Boone & Veen (1982) studied the influence of mechanical resistance on root growth and morphology and subsequent ion uptake and shoot growth.

The experiment soil was taken from the C horizon (subsoil) of a marine sandy loam with a clay content of about 11 %. P was added as superphosphate and the P availability was measured as P_w value (mg P_2O_5 dm^{-3} soil; van der Paauw, 1971).

The pots were filled in layers of 3 cm and compacted with a hydraulic press to the desired pore volume. Five pore volumes were used: 60, 51, 46, 44 and 42 %, which resulted, at a soil moisture content of 18 % (w/w), in a penetrometer resistance of 0.3, 0.9, 1.6, 2.3 and 3.0 MPa respectively. Maize seeds were sown in cylindrical pots in the compacted soil. Shoot fresh and dry weight were measured and N, P and K content of the shoot was analysed. Root lengths were measured by the line intersect method of Newman (1961) and root diameters with a binocular.

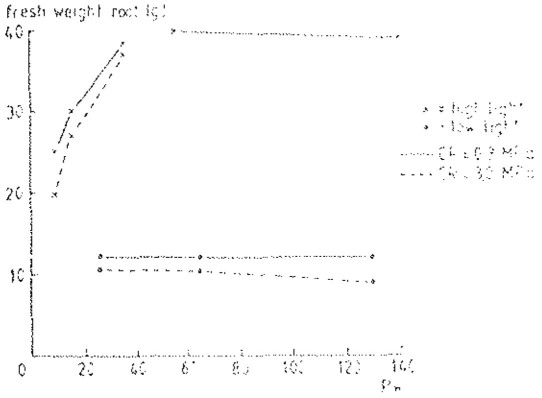
Effects on root growth

The fresh weight of the root system was hardly influenced by the mechanical resistance of the soil (Figs.31 and 33). At a high light intensity the positive effect of phosphate on root weight was very clear (Fig.32). The relation between root fresh weight and phosphate availability is a saturation curve. At a low light intensity root weight was much smaller, both absolute and relative to shoot weight as can be concluded from a comparison of Fig.31 and Fig.34. Moreover there was no visible influence of phosphate supply on root fresh weight at a low light intensity (Fig.33), which means that root growth is more limited by light than by phosphate.



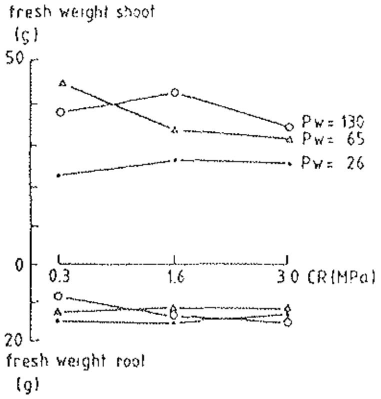
Influence of soil mechanical resistance (CR) on fresh weight of shoots and roots of maize three weeks after emergence at three levels of phosphate availability (P_w) under optimal light conditions

Fig. 31
(After Shierlaw & Alston, 1984)



The fresh weight of maize roots in relation to phosphate availability at two light intensities and two mechanical resistances

Fig. 32
(After Boone & Veen, 1982)



Influence of soil mechanical resistance (CR) on fresh weight of shoots and roots of maize, three weeks after emergence at three levels of phosphate availability (P_w), under low light conditions.

Fig. 33
(After Boone & Veen, 1982)

At a low mechanical resistance in the soil there was a fairly even distribution of roots with depth, but at a high mechanical resistance roots accumulated in the upper soil layers and most roots failed to penetrate into deeper layers (Fig.34). As a consequence there was hardly any roots at the bottom of the pot. Partly this can be explained by a low root growth velocity at a high mechanical resistance of the soil (Fig.35) which was determined by measuring the extension growth rate of the primary root axes. Especially at moderate mechanical resistance root growth is very sensitive to changes in mechanical resistance. Between a cone resistance of 0.9 and 1.6 MPa there was a 50 % decrease in root elongation. At higher or lower cone resistance the effect was much weaker. A second phenomenon influencing the distribution of roots in soil was their growth directions. The primary axes grew vertically but the other seminal axes and the lateral roots initially grew at an angle to the vertical which depended on the environmental conditions. The average angle to the vertical of the main axes was calculated from the length of segments of main root axes from a 3-cm thick upper soil layer. Tab.13 shows that roots grew steeper downwords in a loose soil than in a dense soil. Thirdly, root distribution was also influenced by relative differences in mechanical resistance. There is a preference of roots to grow in a layer with a low mechanical resistance which is clearly demonstrated in Fig.36.

Although fresh weight of the root system was not influenced by the mechanical resistance, root morphology changed considerably (Fig.37). Unimpeded roots were much thinner than roots grown at a high mechanical resistance. Near the bottom of the pot differences were much smaller because here young unbranched root tips accumulate. There was no distinct influence of phosphate supply on root morphology. Just like the total weight, the weight of laterals per gram root was not influenced by the mechanical resistance (Tab.14).

Tab. 13 Influence of mechanical impedance on the inclination of main root axes of maize

Penetrometer resistance (MPa)	Number of root segments	Average length (cm)	Angle to vertical (°)
0.3	42	6.0	60
3	45	9.0	70.5

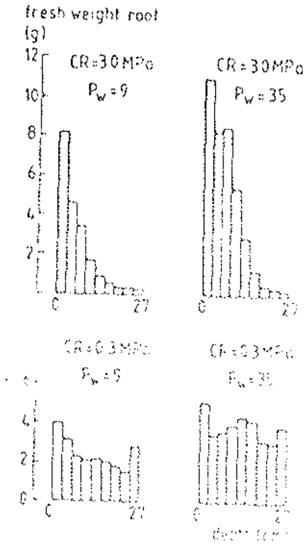
(After Boone & Veen, 1982)

The total length of the laterals per gram root, however, was strongly decreased concomitantly with an increased diameter. The decrease in total lateral root length per cm main axis at increased mechanical resistance is mainly caused by a decreased lateral root number whereas the length of the individual laterals is not influenced.

Tab. 14 Influence of mechanical resistance on the development of lateral roots of maize.

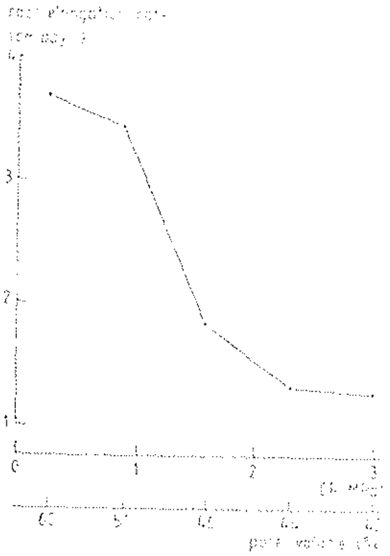
First order laterals per gram total root			First order laterals per cm main axis	
resistance (MPa)	weight (g)	total lenght (cm)	number	total length (cm)
0.3	0.40	1205	9.9	14.4
3.0	0.47	499	6.1	9.3

(After Boone & Veen, 1982)



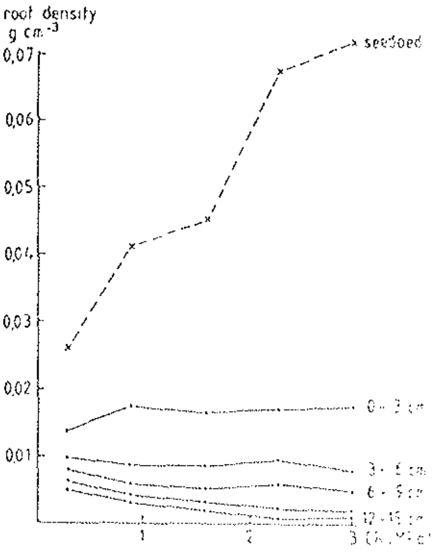
Root distribution of maize roots, three weeks after emergence, in relation to soil mechanical resistance (CR) and phosphate availability (Pw)

Fig. 34
(After Boone & Veen, 1982)



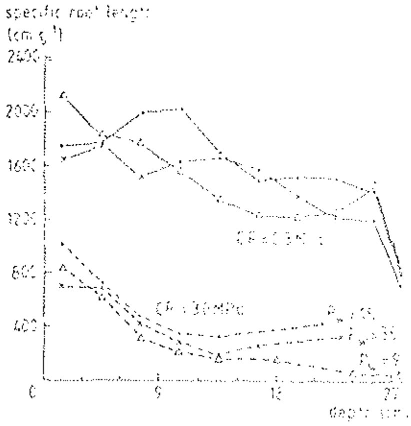
Relation between the elongation rate of main roots of maize and the mechanical resistance (CR) of the soil

Fig. 35
(After Boone & Veen, 1982)



Root density of maize in different soil layers in relation to cone resistance below the seedbed

Fig. 36
(After Boone & Veen, 1982)

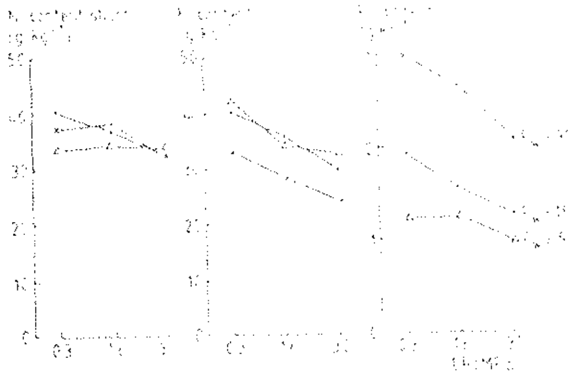


Influence of mechanical resistance (CR) on root length of maize per unit root weigth at different soil depths, and different phospate availabilities (P_w)

Fig. 37
(After Boone & Veen, 1982)

Mineral content and shoot growth

Except at low phosphate supply, total nitrogen content of the shoot was somewhat higher at a low mechanical resistance than at a high mechanical resistance (Fig.38).



Mineral content of maize shoots three weeks after emergence of plants grown in soil with different mechanical resistance (CR) and different phosphate supply (P_w)

Fig. 38
(After Boone & Veen, 1982)

The potassium content of the shoot was much stronger influenced by soil density than the nitrogen content; the higher the mechanical resistance, the lower the potassium content. Also the phosphate supply had a clear effect; a high phosphate supply decreased the potassium content of the shoot.

The phosphate content of the shoot was strongly influenced by the phosphate supply of the soil. At a low phosphate supply there was hardly any influence of soil density, but at a high phosphate supply the mechanical resistance had a clear negative effect on the phosphate content.

Raghavan & McKyes (1978) have carried out a comprehensive study how water content and root distribution in the soil is affected by different levels of compaction pressures and number of passes in maize, according to following experimental plan:

A. Zero traffic
B1–B4. 1, 5, 10 and 15 passes at 32 kPa
C1–C4. 1, 5, 10 and 15 passes at 42 kPa
D1–D4. 1, 5, 10 and 15 passes at 65 kPa

They found that the water content in the upper 20 cm soil layer increased with increasing compaction, which was related to the fact that the water uptake of the roots in the shallow soil layer was limited and that the water transportation due to water applied at the surface was restricted by the compaction. The root distribution was also to a great extent affected despite relatively small compaction pressures. Figs. 39, 40, 41 and 42 illustrate the influence of different treatments on root distribution.

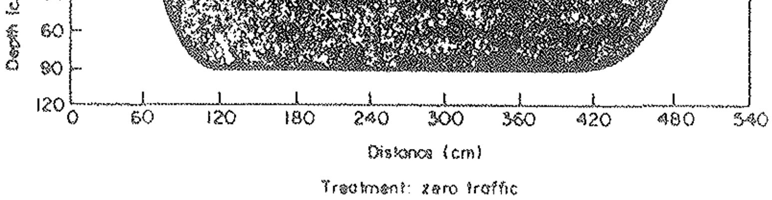


Fig. 39 Rotfördelningen hos majs i jord som ej packats.

(After Raghavan & McKyes, 1978)

In a laboratory experiment conducted by Lindberg & Petersson (1985) with barley (*Hordeum vulgare* L. v. Salve) root and shoot development and concentrations of K, Ca, N and P at different times during growth of young barley plants was studied. Experiments with glass beads of different sizes, representing different sizes of soil pores, and subject to different external pressure were performed and compared to experiments with sand of different compaction.

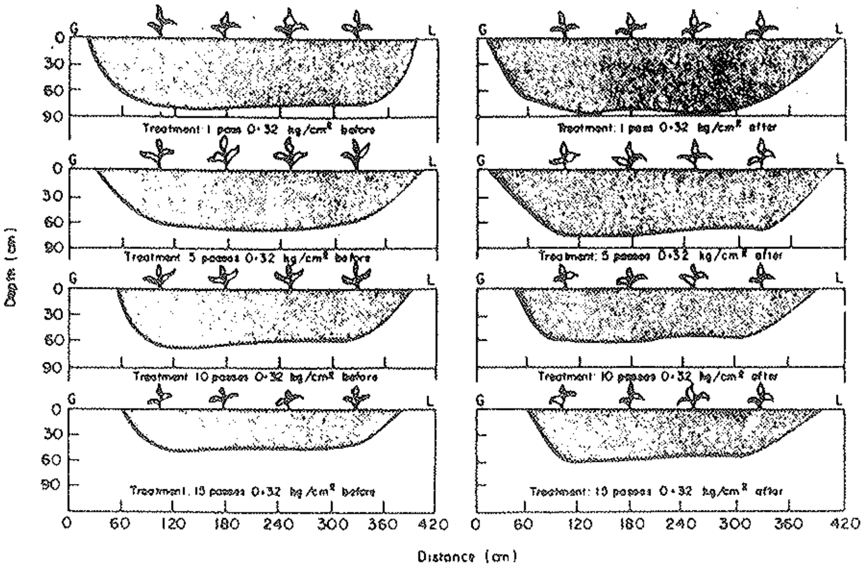


Fig. 40 Rotfördelningen hos majs i jord som packats med 1,5, 10 och 15 överfarter vid 32 kPa tryck.

(After Raghavan & McKyes, 1978)

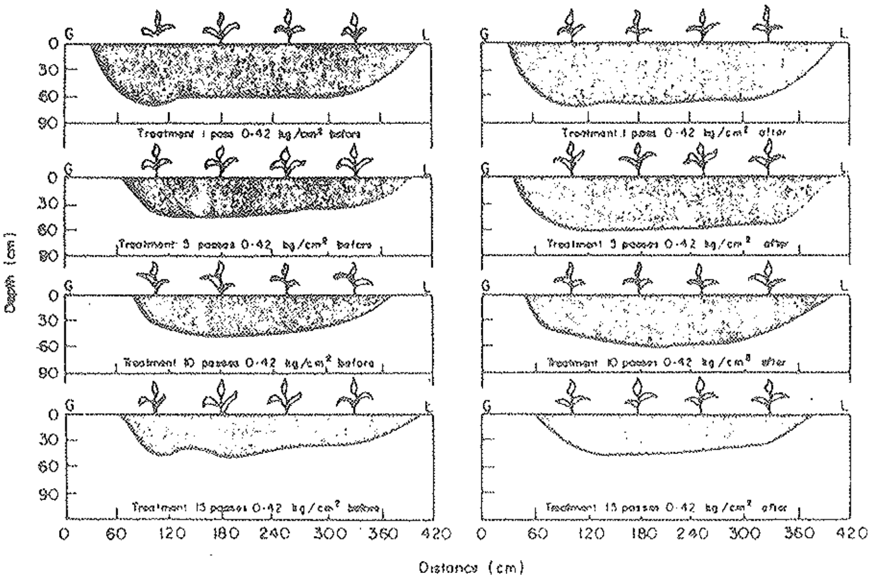


Fig. 41 Rotfördelningen hos majs i jord som packats med 1, 5, 10 och 15 överfarter vid 42 kPa tryck.

(After Raghavan & McKyes, 1978)

Culture cells were filled with glass beads of different sizes (4.0, 1.0 or 0.4 mm diameter). The glass beads with 4.0 mm diameter in close packing formed pores with a smallest diameter of 700 micrometers. This was well in excess of the cross section of the seminal root axis, and thus allowed free root penetration. The pores between glass beads with 1.0 mm diameter exceeded 160 micrometers and they impeded seminal roots but not the penetration of laterals. Packing of glass beads with 0.4 mm diameter formed pores with a smallest diameter of 70 micrometers. This impeded the growth of all root members.

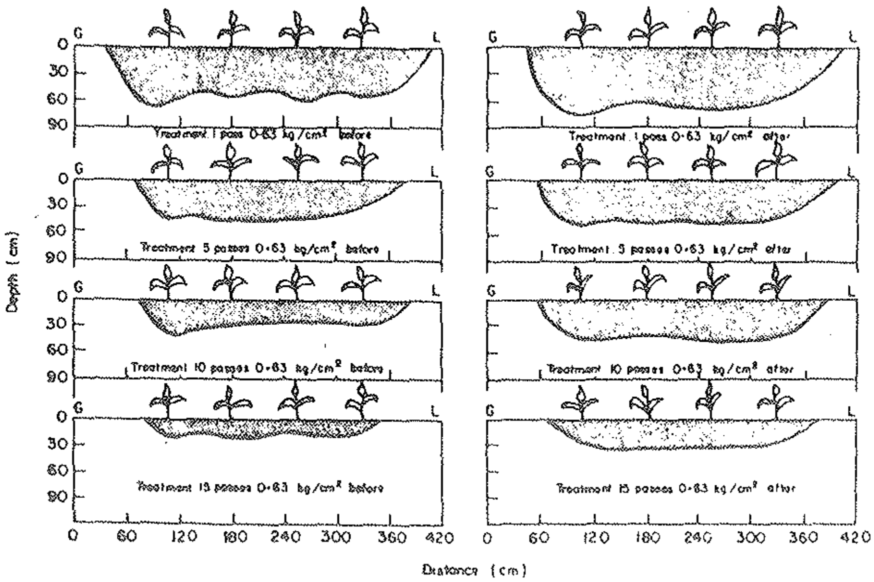


Fig. 42 Rotfördelningen hos majs i jord som packats med 1,5, 10 och 15 överfarter vid 65 kPa.

(After Raghavan & McKyes, 1978)

According to Fig.43, root length increased exponentially both with and without applied external pressure. Root elongation was inhibited by mechanical stress (20 kPa) in beds of glass beads which formed pores 70 micrometer in diameter (Fig.43A) and in compressed sand cultures (Fig.43B). Extrapolation of root length curves indicated that the inhibation appeared approximately on day 4, which is on the day after pressure application. The inhibation in glass bead culture was about 40 % compared with controls and in sand culture about 30 %.

Effects of sand compaction on fresh weight increase are shown in Fig.44. For both shoots and roots the relative growth rates are constant during the experimental period. No effects of the application of pressure could be detected.

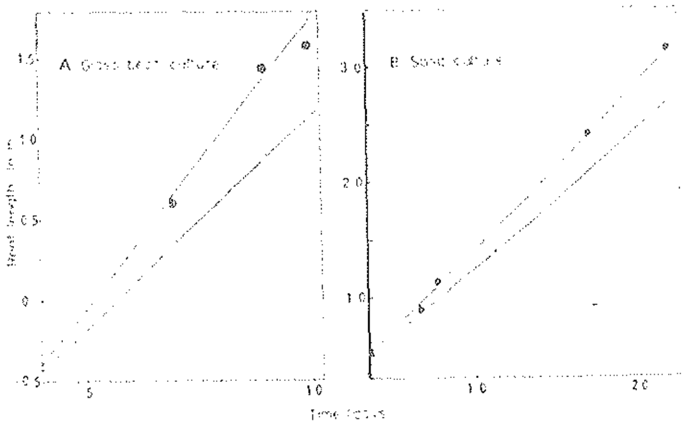


Fig. 43 Inhibition of root length growth (per 5 plants) by applied pressure with time (ln root length on y-axis). A. *Filled symbols*: controls, glass beads 4.0 mm diameter, no pressure, *open symbols*: glass beads 0.4 mm diameter, pressure 20 kPa. B. *Filled symbols*: controls; *open symbols*; pressure applied. Pressure applied on day 3.

(After Lindberg & Petersson, 1985)

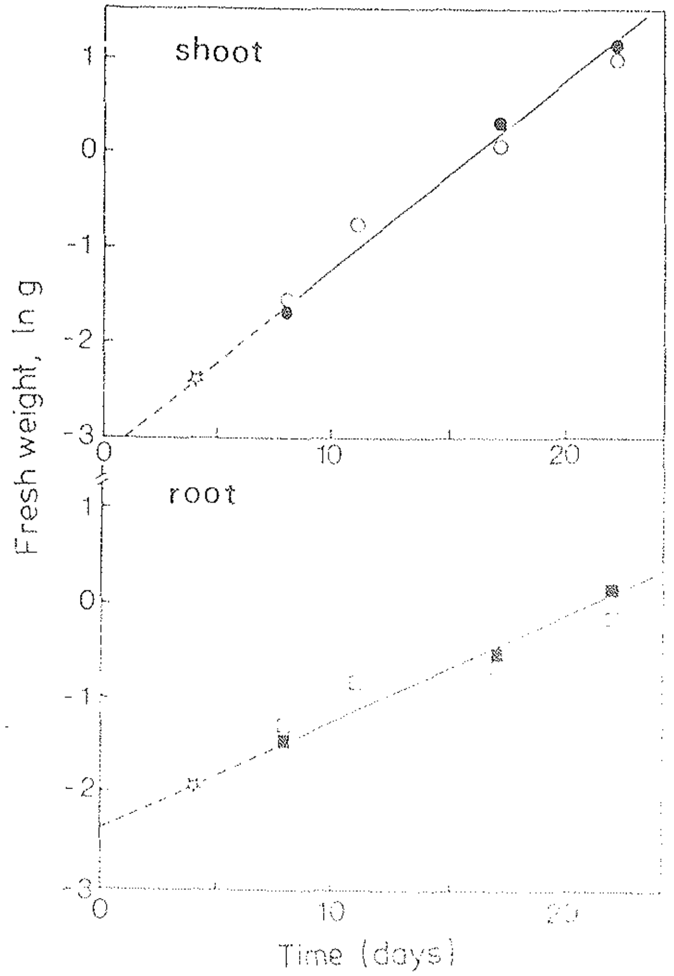


Fig. 44 Effects of sand compression on plant fresh weight increase with time (ln fresh weight on y-axis). *Filled symbols*, controls; *open symbols*, pressure applied; *stars*, estimated fresh weights at start of application of pressure

(After Lindberg & Petersson, 1985)

Dry matter of roots grown in beds of glass beads with restricted root elongation increased considerably (Tab.15). Dry matter of shoots remained unaffected.

Tab. 15 Effects of pore size in beds of glass beads and applied pressure on dry matter of shoots and roots. Plants 9-day-old. Mean values ± SDM, N > 5

Bead diameter (mm)	Pore size (µm)	Pressure (kPa)	Shoots (mg)	Roots (mg)
4.0	700	0	18.3 ± 1.28	4.9 ± 0.93
1.0	160	20	17.9 ± 0.85	7.5 ± 0.37
0.4	76	0	17.3 ± 1.70	10.1 ± 1.20
0.4	76	20	18.6 ± 0.55	13.6 ± 1.70

(After Lindberg & Petersson, 1985)

Changes in the morphology of roots grown in glass beads and in sand cultures were determined by estimation of "specific root length" (m/g fresh weight). This variable decreased where roots were exposed to mechanical stress mainly associated with fewer roots (Fig.45). The pattern was the same for roots grown in sand (Fig.45A) and in glass bead culture (Fig.45B). The irregularities of the curves in the time interval 7–9 days appeared in all cultures and were related to the emergence of a further order of laterals.

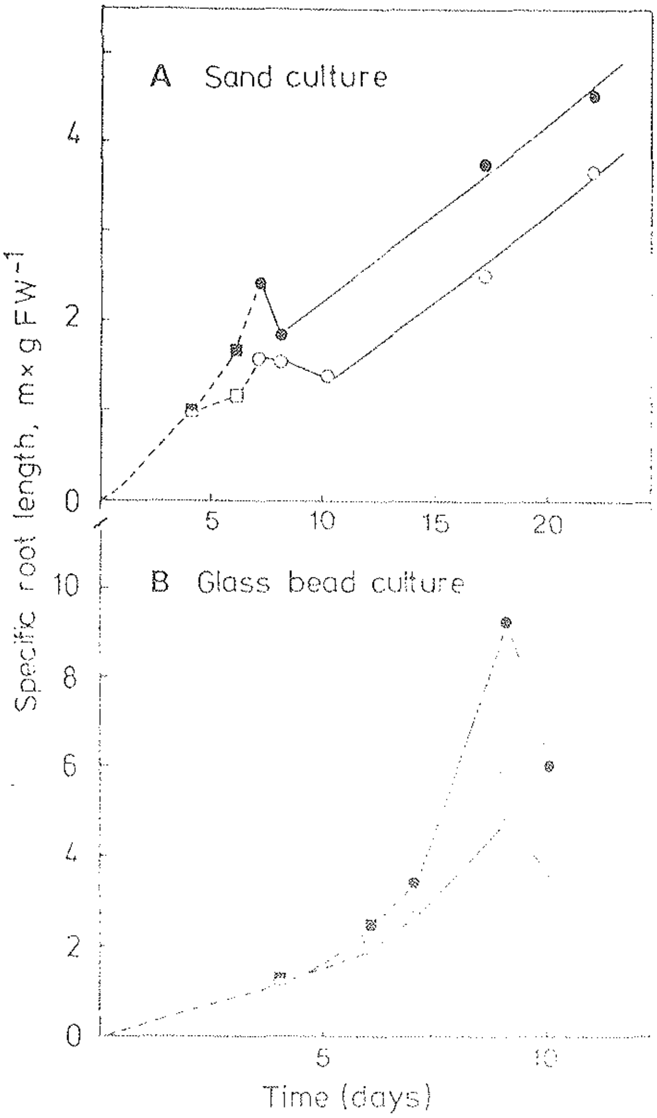


Fig. 45 Effects of pressure on specific root length (m g fresh weight^{-1}) with time. *Filled circles*, controls, *open circles*, pressure applied. In B: Controls: glass beads 4 mm diameter; pressure applied, glass beads 0.4 mm (20 kPa). Squares: Values computed after regression analysis and extrapolation of data from Figures 2 and 3. Pressure applied on day 4.

(After Lindberg & Petersson, 1985)

The concentration of nitrogen on a fresh weight and dry matter basis in shoots and roots from glass bead cultures is shown in Fig.46. In the shoots the concentration of nitrogen was only about 50 % of the controls when the roots were grown in beds of glass beads which formed pores 70 micrometer in diameter and pressure (20 kPa) was applied (Fig.46A, C). The corresponding roots contained even less nitrogen; about 20 % of controls on fresh weight basis (Fig.46B) and 15 % on a dry matter basis (Fig.46D).

In beds with 70 micrometers pore diameter, without pressure, a reduction in concentration of N appeared in roots (50–70 % of controls). In the corresponding shoots, however, the reduction was insignificant.

The concentration of Ca in roots decreased after pressure was applied to glass bead cultures for 7 days (Fig.47A), to sand cultures for 7 days (Fig.47B) and to sand cultures for 20 days (Fig.47C). The reduction was nearly the same when glass beads forming pores with 70 micrometer or with 160 micrometer diameter were used. The content of Ca in shoots was little affected by pressure application.

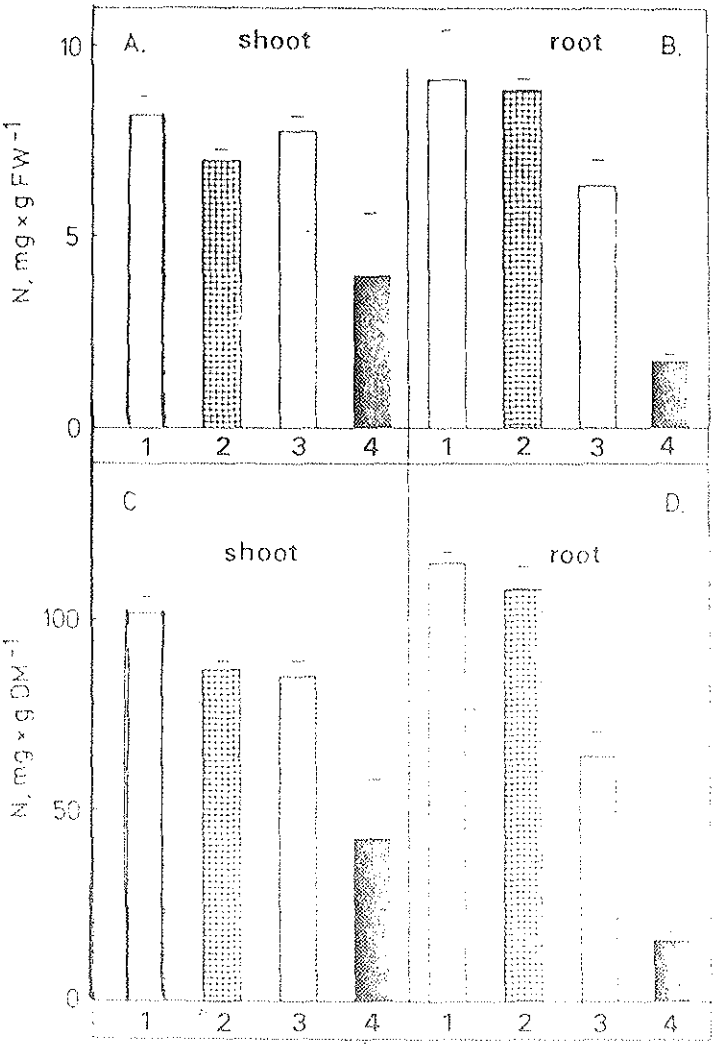


Fig. 46 Effects of pressure on concentration of N in plants grown in glass bead cultures for 9 days. Growth conditions 1. bead size 4.0 mm diameter, no pressure, 2. 1.0 mm, 20 kPa, 3. 0.4 mm, no pressure; 4. 0.4 mm, 20 kPa. *Dashes* show ± SEM.

(After Lindberg & Petersson, 1985)

Seven days old seedlings had the same concentration of P irrespective of pressure and different glass bead sizes (Fig.48A). After 10 days in standard nutrient solution in beds of glass beads forming pores with 160 micrometer the concentration of P in shoots was higher than in controls (Fig.48B). This effect disappeared when a nutrient solution with 1/30 of full strength was used (Fig.48C). Seedlings from compressed sand cultures contained more P than controls after 7 days (Fig.48D)

The concentration of K in shoots and roots was not affected by different pressure treatments in beads of glass beads after 7 days (Fig.49A). Small effects appeared after 10 days in nutrient solution of full strength (Fig.49B) but not when the plants were supplied with solution diluted 1:30 (Fig.49C). Sand compaction lowered the K concentration slightly of both shoots and roots after a 20 day culture (Fig.49D).

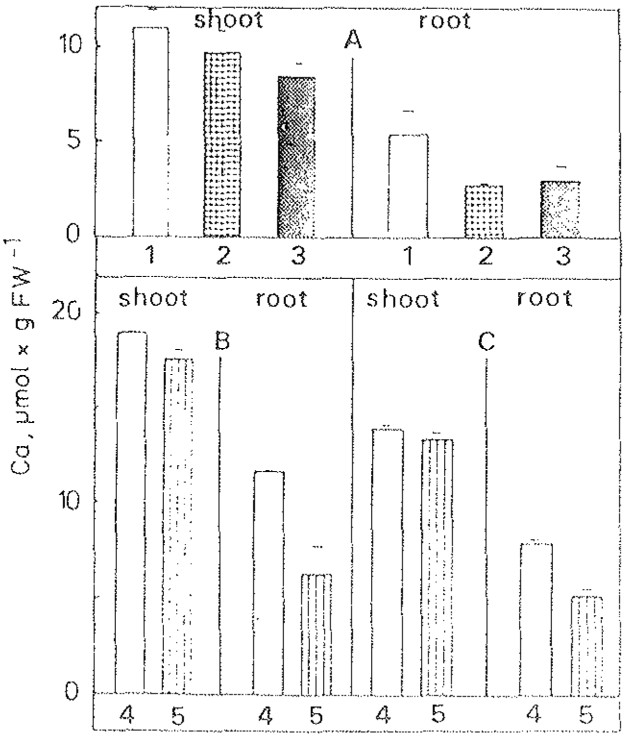


Fig. 47 Effects of pressure on concentration of Ca in plants grown in glass bead cultures for 7 days (A) and in sand cultures for 7 days (B) or 20 days (C). Growth conditions: 1. bead size 4.0 mm diameter, no pressure; 2. 1.0 mm, 20 kPa; 3. 0.4 mm, 20 kPa; 4. controls; 5. compressed sand. *Dashes* show ± SDM.
(After Lindberg & Petersson, 1985)

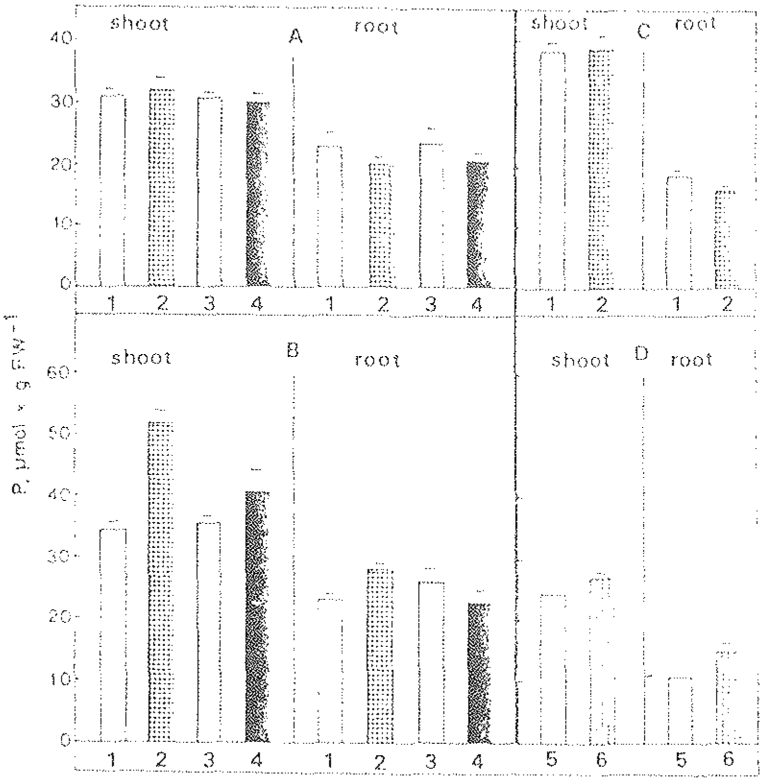


Fig. 48 Effects of pressure on concentration of P in plants grown in glass bead cultures for 7 days (A) or 10 days (B, C) and in sand cultures for 7 days (D). Growth conditions. In A, B, D the nutrient solution was supplied at full strength., in C diluted 1:30 1. bead size 4.0 mm diameter, no pressure, 2. 1.0 mm, 20 kPa; 3. 0.4 mm, no pressure; 4. 0.4 mm, 20 kPa. 5. controls, 6. compressed sand. *Dashes* show ± SDM.
(After Lindberg & Petersson, 1985)

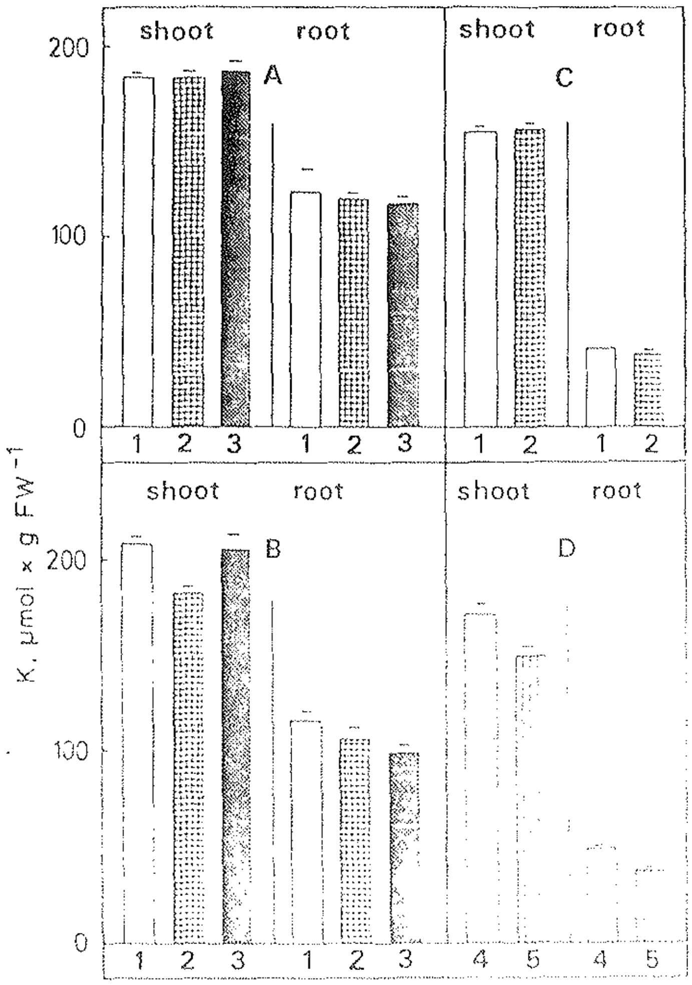


Fig. 49 Effects of pressure on concentration of K in plants grown in glass bead cultures for 7 days (A) or 10 days (B, C) and in sand cultures for 20 days (D). Growth conditions: In A, B, D the nutrient solution is supplied at full strength, in C diluted 1:30. 1. bead size 4.0 mm diameter, no pressure; 2. 1.0 mm, 20 kPa; 3. 0.4 mm, 20 kPa. 4. controls; 5. compressed sand. *Dashes* show ± SDM.

(After Lindberg & Petersson, 1985)

To sum up the results, the main effects of applied pressure were:

1) Elongation of roots was suppressed to 30–40 % of controls, 2) mean diameter of roots increased, 3) dry matter content of roots increased, 4) N concentration of whole plants decreased, 5) Ca concentration of roots decreased, 6) concentrations of P and K were mainly unaffected. The results indicated that the main part of N and P are absorbed by lateral roots but that Ca is taken up by seminal roots.

Pot experiments

The effect of soil structure (fine aggregate, coarse aggregate and compacted) on root growth, root morphology and P uptake of spring wheat (Triticum aestivum L.) was studied by Keita & Steffens (1989) in pot and split root experiments using three soils (2 x Alfisol–Udalf, Alluvium).

The experiment was designed according to:
A Fine structure (aggregates less than 5 mm in diameter) = control
B Coarse (aggregates 5–7 mm, 50 %, and aggregates less than 5 mm, 50 %)
C Compacted soil (aggregates less than 5 mm were saturated to 60 % of maximal water capacity. The pots were stratified in three layers comprising 4, 4 and 3 kg. Each layer was compacted by a hammer). The depths of the different layers are not stated in the report.
Clay and humus content, P concentration and pH–value of the soils are shown in Tab.16.

The influence of soil structure on bulk density, pore volume and pore size distribution is shown in Tab.17.

Tab. 16 : Ton-, Humus-, P-Konzentration und pH-Wert der Versuchsböden
Clay-, humus-, P concentration and pH-value of the used soils

Boden	Bodentyp	Horizont	Ton %	pH-Wert (In KCl)	Humus %	P *1) mg · kg^{-1} Boden
Wetterau	Parabraunerde	Ap	26	6.7	2.5	81.2
Trebur	Alluvium	Ap	33	6.5	2.4	62.7
Seelbach	Parabraunerde	Ap	29	6.9	n.b.	35.2(90.2)*2)

*1) CAL-Methode nach *Schüller* (1969)
*2) nach P-Düngung

(After Keita & Steffens, 1989)

Tab. 17 : Einfluß des Bodengefüges auf Lagerungsdichte, Gesamtporenvolumen und Porengrößenverteilung
Influence of soil structure on bulk density, pore volume, and pore size distribution

Porengröße (in μm)	1 <0.2	2 0.2-10	3 10-50	4 >50	5	Lagerungsdichte g/cm³
	Vol%					
Boden Trebur						
Feinaggr.	16.6	9.9	5.1	20.9	52.5	1.30
Grobaggr.	17.0	12.6	3.1	17.6	50.3	1.34
Verd. Gef.	18.2	21.0**	2.0	6.0***	47.2*	1.44
Boden Wetterau						
Feinaggr.	14.3	9.5	5.0	21.8	50.6	1.31
Grobaggr.	15.2	9.3	3.1	20.3	47.9	1.39
Verd. Gef.	16.3	12.8	2.4	14.0**	45.5	1.46

Signifikant mit * ($P \leq 5\%$), ** ($P \leq 1\%$) und *** ($P \leq 0.1\%$) im Vergleich zur Kontrolle (Feinaggregat)
1 = Feinporen; 2 = Mittelporen; 3 = enge Grobporen; 4 = weite Grobporen; 5 = Gesamtporenvolumen.

(After Keita & Steffens, 1989)

As can be seen in Fig.50 and Tab.18, both root FW, root length and root surface area were markedly decreased compared to control.

Beside these root parameters there was an evident reduction of both root diameter and root hair length (Tab.19). The reduction of the root diameter is a little contradictory due to the fact that this parameter normally is increased in compacted layers and also because root surface area is reduced more than root length (pers. comment).

The influence of soil structure on shoot weight of spring wheat is shown in Fig.51. There is a visable decrease in dry matter in B and C compared to the control. It can also be seen that the relative differences increase with plant development.

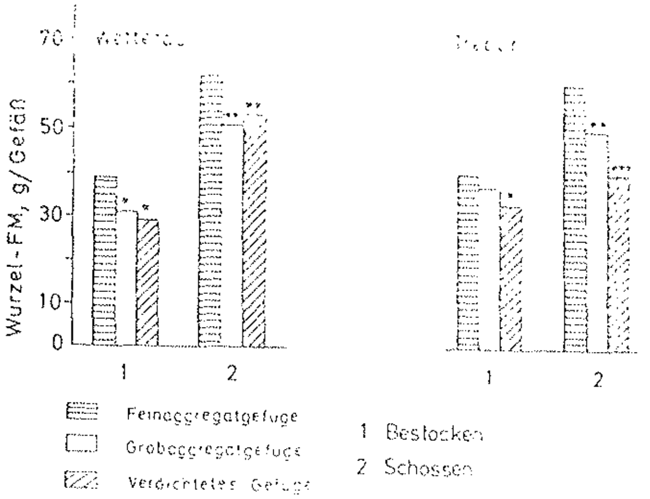


Fig. 50 Einfluß verschiedener Gefügeformen auf die Wurzelfrischmasse von Sommerweizen (signifikanter Unterschied zum Feinaggregatgefüge: °P ≤ 5%; °°P ≤ 1%; °°°P ≤ 0.1%)

Influence of soil structure on root fresh weight of spring wheat (significant difference to fine aggregate structure: °P ≤ 5%; °°P ≤ 1%; °°°P ≤ 0.1%)

(After Keita & Steffens, 1989)

Tab. 18 Einfluß des Bodengefüges auf die Wurzellänge und die Wurzeloberfläche von Sommerweizen

Influence of soil structure on root length and root surface area of spring wheat

			Wurzellänge (m · Gefäß⁻¹)	
Boden	Trebur		Wetterau	
Zeitpunkt	Bestockung	Schossen	Bestockung	Schossen
Gefügeform				
Feinaggregatgefüge	155	397	128	390
Grobaggregatgefüge	96**	316**	109*	298*
Verdichtetes Gefüge	86***	301*	94**	208***

			Wurzeloberfläche (m^2 · Gefäß⁻¹)	
Boden	Trebur		Wetterau	
Zeitpunkt	Bestockung	Schossen	Bestockung	Schossen
Gefügeform				
Feinaggregatgefüge	0.26	0.74	0.24	0.74
Grobaggregatgefüge	0.14**	0.46**	0.17*	0.47**
Verdichtetes Gefüge	0.12**	0.46**	0.16*	0.35**

Signifikanter Unterschied mit * P ≤ 5%, ** P ≤ 1% zur Feinaggregat-Variante

(After Keita & Steffens, 1989)

The influence of soil structure on P concentration in shoots and grain is shown in Tab.20. Plants grown in a coarse structure or under compacted conditions show lower concentrations of P compared to plants grown in a fine textured soil. This applies to all recorded plant development stages.

The influence of soil structure on P uptake is shown in Tab.21. Due to higher yield of shoots and increased concentration of P in shoots the highest P uptake was observed in the control.

The influence of soil structure on grain and straw yield can be seen in Tab.22. For both soils there is a more or less significant reduction in grain and straw yield relative the fine textured soil.

Tab. 19 Einfluß des Bodengefüges auf die Wurzeldurchmesser und die Wurzelhaarlänge von Sommerweizen

Influence of soil structure on root diameter and root hair length of spring wheat

			Wurzeldurchmesser (mm)	
Boden	Trebur		Wetterau	
Zeitpunkt	Bestockung	Schossen	Bestockung	Schossen
Gefügeform				
Feinaggregatgefüge	0.54	0.59	0.60	0.60
Grobaggregatgefüge	0.46**	0.46**	0.49**	0.50
Verdichtetes Gefüge	0.41**	0.49	0.53**	0.54**

			Wurzelhaarlänge (mm)	
Boden	Trebur		Wetterau	
Zeitpunkt	Bestockung	Schossen	Bestockung	Schossen
Gefügeform				
Feinaggregatgefüge	0.44	0.41	0.40	0.41
Grobaggregatgefüge	0.28**	0.23	0.20**	0.21
Verdichtetes Gefüge	0.28**	0.24	0.25**	0.20

* Signifikanter Unterschied mit $P \leq 1\%$ zur Feinaggregat-Variante

(After Keita & Steffens, 1989)

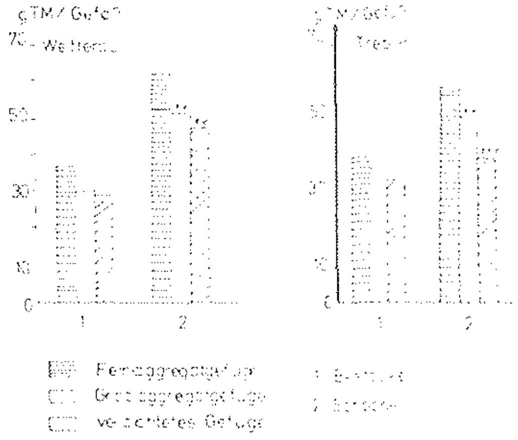


Fig. 51 Einfluß verschiedener Gefügeformen auf die Sproßmasse von Sommerweizen (signifikanter Unterschied zum Feinaggregatgefüge. $^{**}P \leq 1\%$; $^{***}P \leq 0.1\%$)

Influence of soil structure on the shoot weight of spring wheat (significant difference to fine aggregate structure: $^{**}P \leq 1\%$; $^{***}P \leq 0.1\%$)

(After Keita & Steffens, 1989)

Tab. 20 Einfluß des Bodengefüges auf die P-Konzentration in oberirdischen Pflanzenteilen
Influence of soil structure on P concentration in the shoot and grain

Boden		Trebur			Wetterau	
	Bestockung	Schossen	Korn	Bestockung	Schossen	Korn
Gefügeform		mg P · g^{-1} TS			mg P · g^{-1} TS	
A	5.29	4.57	3.29	6.57	4.57	3.89
B	5.00	3.71**	2.57**	6.07	3.71**	2.43**
C	4.86*	3.29***	1.57***	5.86**	3.00***	2.14**

A = Feinaggregatgefüge; B = Grobaggregatgefüge; C = Verdichtetes Gefüge.
Signifikanter Unterschied mit * $P \leq 5\%$; ** $P \leq 1\%$; *** $P \leq 0.1\%$ zur Feinaggregat-Variante

(After Keita & Steffens, 1989)

Tab. 21 Einfluß des Bodengefüges auf die P-Aufnahme von Sommerweizen
Influence of soil structure on P uptake of spring wheat

Boden		Trebur			Wetterau	
	Bestockung	Schossen	Korn + Stroh	Bestockung	Schossen	Korn + Stroh
Gefügeform		mg P · $Gefäß^{-1}$			mg P · $Gefäß^{-1}$	
A	290	480	1264	249	490	1137
B	215*	370**	875**	190	400**	794***
C	219*	305**	703**	180	310***	438***

A = Feinaggregatgefüge; B = Grobaggregatgefüge; C = Verdichtetes Gefüge
Signifikanter Unterschied mit * $P \leq 5\%$; ** $P \leq 1\%$; *** $P \leq 0.1\%$ zur Feinaggregat-Variante

(After Keita & Steffens, 1989)

Tab. 22 Einfluß der Bodenstruktur auf die Korn- und Stroherträge von Sommerweizen
Influence of soil structure on grain and straw yield of spring wheat

Boden	Trebur		Wetterau	
	Korn	Stroh	Korn	Stroh
	g · $Gefäß^{-1}$		g · $Gefäß^{-1}$	
Feinaggregatgefüge	47.0	24.3	59.0	30.0
Grobaggregatgefüge	43.0*	14.3**	45.0*	15.7***
Verdichtetes Gefüge	31.0**	11.4**	42.0**	14.3***

Signifikanter Unterschied mit * $P \leq 5\%$; ** $P \leq 1\%$, *** $P \leq 0.1\%$ zur Feinaggregat-Variante

(After Keita & Steffens, 1989)

Split – root experiment

The experimental technique used by Keita & Steffens is shown in Fig.52. The pots consisted of two from each other independent chambers, one filled with 800 g of soil and the other with a nutrient solution, consisting of all nutrients necessary except P in order to force the P uptake from the soil. 7 days old spring wheat seedlings were planted with half of the roots in the soil and half in the nutrient solution and then placed in a climate chamber for 5 weeks.

The influence of soil structure on bulk density, shoot and root dry matter yield is shown in Fig.53. Especially under compacted conditions there was an observable reduction of both shoot and root dry matter yield compared to control. Root length and root surface were strongly affected in both coarse aggregate structure and in compacted soil (Tab.23).

Influence of soil structure on P concentration and P uptake can be seen in Tab.24. Both P concentration and P uptake were significantly reduced in compacted soil compared to fine aggregate structure.

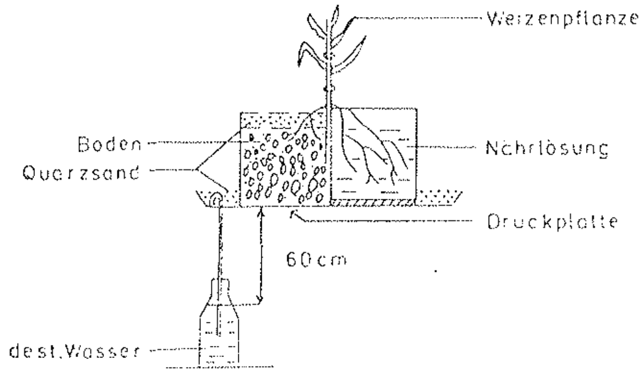


Fig. 52 Split-root-Technik
Split-root technique

(After Keita & Steffens, 1989)

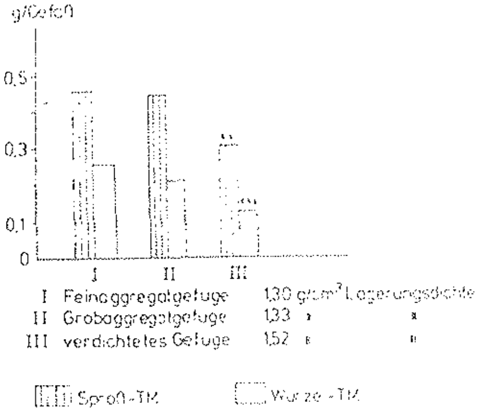


Fig. 53 Einfluß verschiedener Gefügeformen auf die Lagerungsdichte sowie die Sproß- und Wurzeltrockenmasse. Split-root-Versuch (signifikanter Unterschied zum Feinaggregatgefüge: $^{**}P \leq 1\%$; $^{***}P \leq 0.1\%$)

Influence of soil structure on bulk density, shoot and root dry matter yield. Split-root-experiment (significant difference to fine aggregate structure: $^{**}P \leq 1\%$; $^{***}P \leq 0.1\%$)

(After Keita & Steffens, 1989)

Tab. 23 Einfluß der Bodenstruktur auf die Wurzellänge und -oberfläche von Sommerweizen, Split-root-Experiment

Table 8: Influence of soil structure on root length and root surface of spring wheat. Split-root-experiment

	Wurzellänge $cm \cdot Gefäß^{-1}$	Wurzeloberfläche $cm^2 \cdot Gefäß^{-1}$
Feinaggregatgefüge	1123	1904
Grobaggregatgefüge	849**	1226**
Verdichtetes Gefüge	632***	833***

Signifikanter Unterschied mit ** $P \leq 1\%$; *** $P \leq 0.1\%$ zur Feinaggregat-Variante

(After Keita & Steffens, 1989)

Tab. 24 Einfluß der Bodenstruktur auf die P-Konzentration im Sproß und die P-Aufnahme von Sommerweizen. Split-root-Versuch

Influence of soil structure on P concentration in the shoot and P uptake of spring wheat. Split-root-experiment

	P-Konzentration mg P · g^{-1} TS	P-Aufnahme mg P · $Gefäß^{-1}$
Feinaggregatgefüge	4.48	3.09
Grobaggregatgefüge	4.43	2.84
Verdichtetes Gefüge	3.89**	1.59**

Signifikanter Unterschied mit ** $P \leq 1\%$ zur Feinaggregat-Variante

(After Keita & Steffens, 1989)

Dicots except for leguminous plants

Potatoes (*Solanum tuberosum* L.). The effects of soil compaction are direct as well as indirect. The growth of runners as well as tubers is reduced in compacted soil and the harvest is made more difficult due to an increased amount of clods and by an increased need of tractive power (Soane et al., 1982). Potatoe cultivation under compacted conditions also give rise to a more dirty product. The frequency of surface injuries is often enhanced parallel to an increasing need of cleaning when clods and stones are to be separeted. According to Voorhees (1977), this often leads to pathogen attacks and greater storage losses. Harvest of late potatoes often occurs when soil water content is high and because of the heavy implements used, an increased compaction may have a detrimental effect on subsequent crops.

Guren (1985) observed that the occurrence of small and burst potatoes increased with the degree of compactness. The experiments also showed that the negative influence of compaction to a certain extent could be avoided by deep cultivation. Tab.25 describes the yield reduction due to different compaction intensities and tillage implements compared to uncompacted soil. A deep sub-surface application of fertilizers positively affected the yield.

Tab. 25 Avkastningsreduktion (i %) vid olika kombinationer av redskap och packningsintensitet (gäller potatis i storlek 35 - 60 mm) (efter Guren, 1985).

Behandling efter packning	Packat 2 ggr	Packat 4 ggr
S-pinneharv (20)	18 (15)	34 (10)
Fräs (26)	28 (13)	49 (11)
Vibroflex (25)	- 1 (22)	3 (18)
Vibroflex + djupmyllning av gödselmedel	- 4 (22)	- 8 (18)

( ) = arbetsdjup i cm

(After Guren, 1985)

Vegetable crops, especially root crops are very sensitive to soil compaction. A loose surrounding soil is needed for a satisfactory crop development. Under compacted conditions roots often give rise to different kinds of deformations- they become bent, branched and reduced in length. Even physiological injuries can occur like lettuse tipburn. Flower development disturbances in cauliflower and "thick neck"-establishment in onion constitue examples of injuries caused by soil compaction (Luddington, 1979).

Cauliflower (*Brassica oleracea* var. *botrytis* L.)

Tatham (1972) describes experiments with 0, 50, 100 and 200 % of the experimental plot area compacted by wheels. The emergence was favoured by the compaction due to a finer structure in the seedbed. Anyhow, both head size and weight was reduced in compacted plots compared to control (Tab.26).

Tab. 26 Inverkan av jordpackning på uppkomst, huvudstorlek och huvudvikt hos blomkål (efter Tatham, 1972)

	Packningsintensitet			
	0 %	50 %	100 %	200 %
Uppkomst	78	89	87	100
Huvudstorlek	100	87	93	83
Huvudvikt	100	96	96	66

relativtal på icke skördefärdig kultur.

Cucumber (*Cucumis sativus* L.)

In an experiment where the influence of size graded seed and soil compaction was studied on yield of cucumber, soil compaction was observed to have the greatest impact. From Tab.27 it can be seen that a big size graded seed increases yield, but that the influence of soil compaction in a greater extent affects yield. The average yield in the spring culture is more than double the size in uncompacted treatment compared to compacted.

Tab.28 points out how yield varies with an increased dose of nitrogen (NO_3–N). As can be seen, differences in yields between uncompacted and compacted plots, at all N–levels, were very apparent. Anyhow, the yield increase in compacted soil is insignificant when increasing the N–dose from 22 to 33 kg ha^{-1}, while there was a significant gain in uncompacted soil.

Tab. 27 Inverkan av jordpackning och fröstorlek på saludoglig skörd (t/ha) för gurka (efter Smittle & Williamson, 1978)

Jord	Fröstorlek	Vårskörd	Höstskörd
Opackad	Osorterat	32	18
	Lätt	27	15
	Tungt	37	20
Packad	Osorterat	15	10
	Lätt	13	10
	Tungt	18	10

Tab. 28 Inverkan av jordpackning och stigande kvävegiva på avkastningen (t/ha) av gurka (efter Smittle & Williamson, 1977)

Kvävegiva (kg N/ha)	Avkastning	
	Opackad jord	Packad jord
11	17,7	8,4
17	19,2	12,5
22	20,3	13,8
33	23,9	13,9

Onion (*Allium cepa* L.)

In an experiment with onions, Birkenshaw (1981) investigated effects of 0, 2 and 4 passes on yield and thick necks. A 12 % yield reduction was obtained with 4 passes compared to control and the share of thick necks increased correspondently with 4 % (Tab.29).

Tab. 29 Inverkan av jordpackning på avkastning och andel halslök hos kepalök (efter Luddington, 1979)

Behandling	Avkastning (t/ha)	Halslök (%)
Opackad	52	17
2 hjulspår intill varandra	53	18
4 hjulspår intill varandra	45	22

Carrots (*Daucus carota* L.)

In an experiment at Kise Experimental Station in Norway (Kise Försöksstation, 1983) the soil was exposed to very high axle loads. Four intensity levels were used:

A. No compaction
B. 1 pass with a 26 ton heavy dumper
C. 4 passes with a 14 ton heavy dumper
D. 4 passes with a 26 ton heavy dumper

The soil type consisted of a clayey till and had a water content of 28 % w/w at the time of compaction. After compaction the experiment was spring ploughed, harrowed 3 times and rotovated in order to obtain a satisfactory seed bed.

The yield decreased with 11, 21 respectively 23 % relative to the uncompacted treatment and for treatments C and D results were significant. The percentage of saleable carrots were 75, 69, 59 and 62, and treatments C and D showed significant differences.

Carrots grown in peat soil are also exposed to compaction damages which is shown by Strandberg & White (1979), who cultivated carrots in pots where the peat soil was exposed to different compaction intensities. Fig.54 and Tab.30 show how root length, root diameter and root weight is changed due to different compaction pressures.

Tab. 30

Inverkan av jordpackning på tillväxten hos morot 78 dagar efter sådd (efter Strandberg & White, 1979)

Kompakteringstryck (kPa)	Rotlängd (cm)	Rotvikt (g torrvikt)	Rotdiameter (mm) 2 cm	Rotdiameter (mm) 10 cm
			under bladkrona	
45	12.7	1.14	1.15	0.36
112	12.3	1.65	1.26	0.36
151	7.4	0.96	1.10	0.17
223	5.3	0.58	0.68	0.10

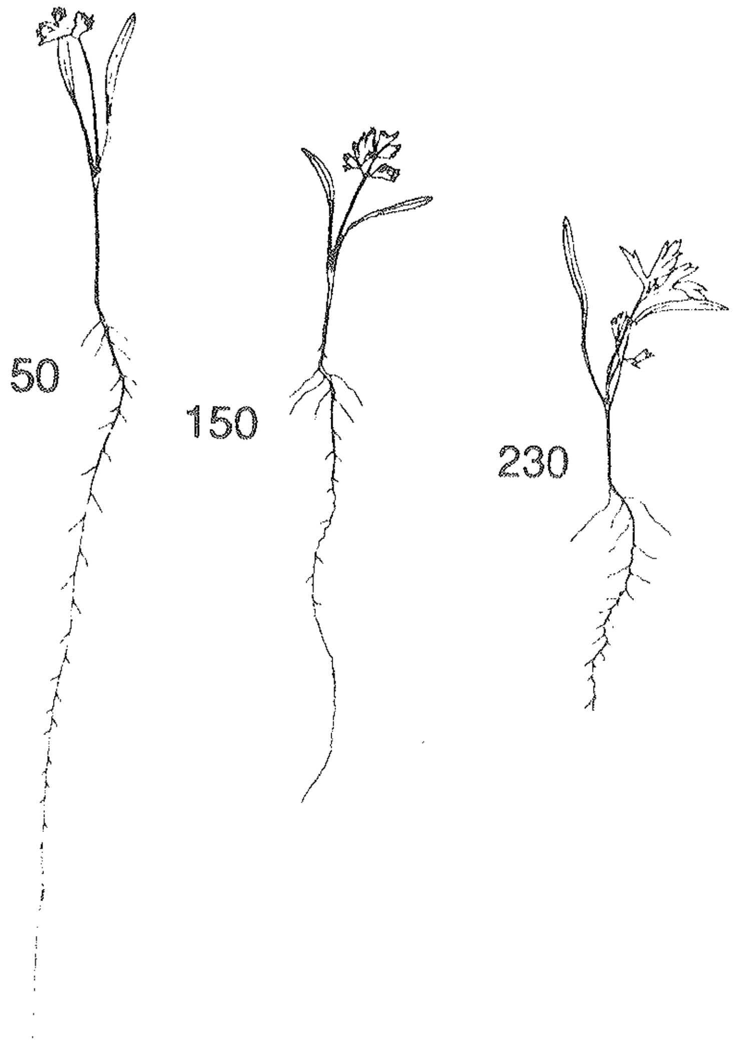


Fig. 54 Inverkan av jordpackning med 50, 150 och 230 kPa på rottillväxten hos morot (16 dagar efter sådd).
(After Strandberg & White, 1979)

Growth and root diseases in leguminous crops

White beans (*Phaseolus vulgaris* L.) **and soybeans** (*Glycine max* L.). Research has shown that compacted soil not only reduces the biomass and yield of leguminous crops but also increases root rot incidence and severity (Miller & Burke, 1974).

The objective of a study by Tu & Tan (1988) was to determine the effect of soil compaction on photosynthesis, root rot severity and growth in white beans under controlled environmental conditions so that soil conditions (such as water, temperature, aeration and fertility) as well as atmospheric environments (such as air temperature, wind speed, humidity and light quality and intensity) could be strictly controlled.

The investigation was conducted in a controlled environment to standardized growing conditions. The soil water was maintained at field capacity to provide adequate water without flooding or reducing gas exchange. Photosynthesis of leaves from plants grown on compacted and noncompacted soil was compared under these conditions.

For each experiment, 120 20-cm plastic pots were used, 60 of which were allotted to sterile soil and the other 60 to naturally infested soil obtained from a nursery heavily infested with root-rotting fungi (*F. solani, P. ultimum, R. solani*). For each soil preparation, the pots were divided into two groups, noncompacted and compacted with a bulk density of 1.3 and 1.6 g cm^{3-}, respectively. Each level of compaction had 30 pots and they were subdivided to accomodate two cultivars, 15 pots per cultivar.

Two white bean cultivars (PI-165.435 and Seafarer) with similar plant type and growth habit were used. The former and latter were resistant and susceptible, respectively, to the root-rotting pathogen complex (*Fusarium solani, Pythium ultimum* and *Rhizoctonia solani*)(Tu & Tan, 1985).

The results of the photosynthetic measurements (Fig.55A, B) showed that photosynthetic rates in leaves of plants grown in compacted soil were significantly lower than those grown in noncompacted soil.

In healthy soil, regardless of compaction, Seafarer had a significantly higher photosyntetic rate than PI-165.435. The reduction in photosynthetic rate attributable to soil compaction was 46 and 35 % for PI-165.435 and Seafarer, respectively (Fig.55A). In root-rot diseased soil, notwithstanding the soil compaction, PI-165.435 had a significantly higher photosynthetic rate than Seafarer (Fig.55B) and the reduction of photosynthetic rate due to soil compaction was 34 % for PI-165.435 and 36 % for Seafarer. The differance was not significant (Fig.55B).

Although PI-165.435 (root-rot tolerant) was more susceptible to soil compaction, it still fared better than Seafarer (root-rot susceptible) in a root-rot diseased soil under compaction soil conditions.

In general, plant biomass (both roots and shoots) and total leaf area (Tab.31) were reduced significantly in both sterilized and root-rot diseased soil because of compaction. Similary, the plant height was significantly reduced, flowering occurred earlier and lower leaves senesced earlier as a result of soil compaction. The results of analyses (Tab.32) showed all aforementioned effects were significantly greater in root-rot diseased soil than in sterilized soil (Tab.31).

Between the two cultivars, PI-165.435 was more susceptible to soil compaction than Seafarer. In sterilized soil, the reduction in biomass for PI-165.435 and Seafarer was 53 and 24 %, respectively; in root-rot diseased soil, however, the reduction was 32 and 39 % respectively, reflecting the root rot resistance of PI-165.435 (Tab.31).

Plants grown in sterilized soil had little or no root rot while those grown in root-rot infested soil developed root rot symptoms (Tab.31). The average root rot index for PI-165.435 and Seafarer grown in noncompacted root-rot soil was 0.2 and 2.1, respectively, compared with 1.3 and 2.1, respectively, for those grown in compacted root-rot diseased soil. The results indicate that soil compaction increased root rot, even for PI-165.435. The root rot index for PI-165.435, however, was significantly lower than Seafarer.

The results showed a significant decrease in photosynthetic rate in bean plants grown in compacted soil. Since soil water was in ample supply, and gas exchange was not a limiting factor in the leaves, the decrease of photosynthetic rates could be attributed to the effect of soil compaction on aeration which resulted in reduction of water and gas transmission in the root system. The restriction of root growth may reduce demand for photosynthetic products from roots. Consequently, this leads to a drop in photosynthetic rate and the increase in shoot:root ratio for plants grown in compacted soil attests to such improportional growth (Tab.31).

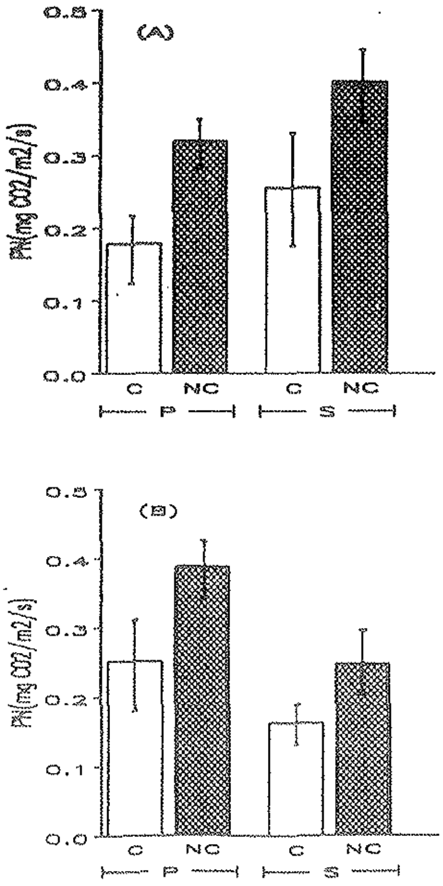


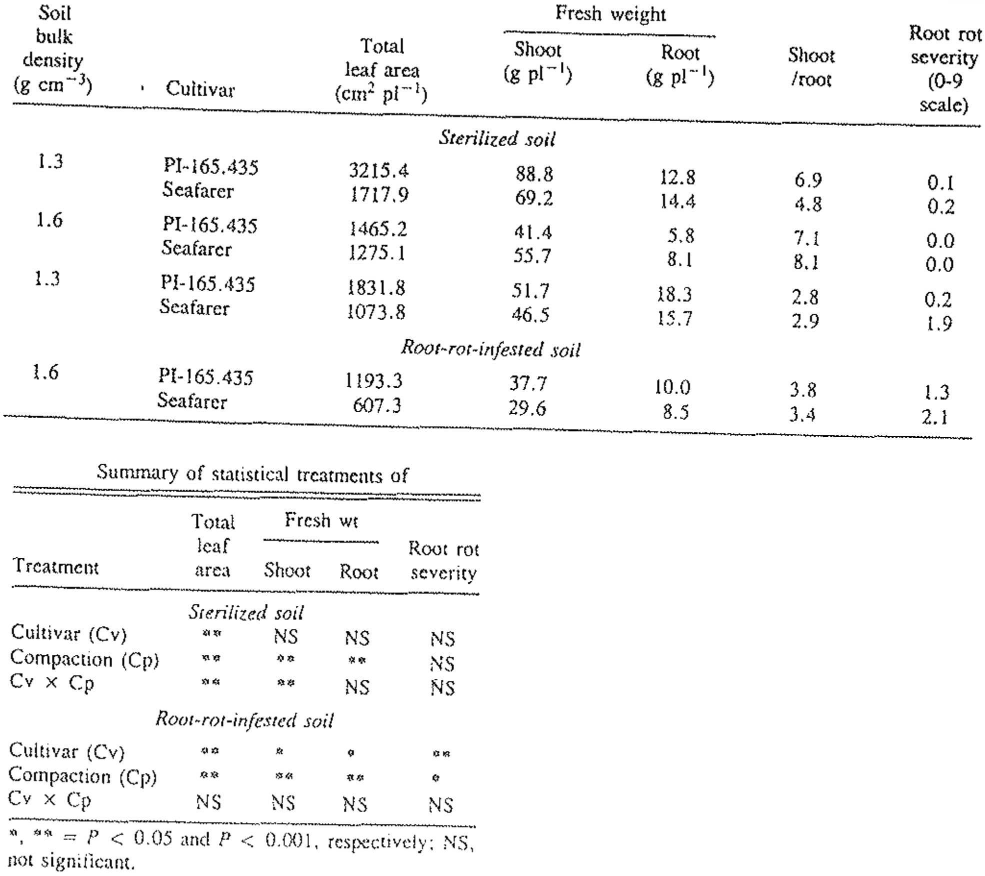
Fig. 55 Measurement of photosynthetic activities of PI-165.435 (P) and Seafarer (S) grown in healthy (A) and root-rot-diseased (B) soil under compacted (C) and noncompacted (NC) conditions, with SE of means given on each bar in figure. The measurements were performed on the fully expanded first trifoliate while the plant was at the early second trifoliate stage.

(After Tu & Tan, 1988)

Miller & Burke (1973) report a laboratory study of the effects of soil water matric potential and root impedance by soil layers on injury to bean growth by *Fusarium solani* f. sp. *phaseoli*.

Bulk soil was obtained from the surface (0–15 cm) and subsoil (60–75 cm) of a loam that had been cropped to beans for about 15 years. The surface soil contained 48 % sand and 12 % clay; the subsoil was a silt loam with 23 % sand and 14 % clay. Dilution plate counts showed that the surface soil was heavily infested (200–500 propagules/gram) with *Fusarum solani* f. sp. *phaseoli*, but the population was negligible in the subsoil. A portion of each soil was fumigated (1.5 g methyl bromide/kg of soil) to eliminate the pathogen.

Tabs. 31 & 32 Effect of soil compaction on plant growth and root rot severity. Data were collected 8 wk after sowing



Soil bulk density (g cm^{-3})	Cultivar	Total leaf area (cm^2 pl^{-1})	Fresh weight Shoot (g pl^{-1})	Fresh weight Root (g pl^{-1})	Shoot /root	Root rot severity (0-9 scale)
			Sterilized soil			
1.3	PI-165.435	3215.4	88.8	12.8	6.9	0.1
	Seafarer	1717.9	69.2	14.4	4.8	0.2
1.6	PI-165.435	1465.2	41.4	5.8	7.1	0.0
	Seafarer	1275.1	55.7	8.1	8.1	0.0
1.3	PI-165.435	1831.8	51.7	18.3	2.8	0.2
	Seafarer	1073.8	46.5	15.7	2.9	1.9
			Root-rot-infested soil			
1.6	PI-165.435	1193.3	37.7	10.0	3.8	1.3
	Seafarer	607.3	29.6	8.5	3.4	2.1

Summary of statistical treatments of

Treatment	Total leaf area	Fresh wt Shoot	Fresh wt Root	Root rot severity
	Sterilized soil			
Cultivar (Cv)	**	NS	NS	NS
Compaction (Cp)	**	**	**	NS
Cv × Cp	**	**	NS	NS
	Root-rot-infested soil			
Cultivar (Cv)	**	*	*	**
Compaction (Cp)	**	**	**	*
Cv × Cp	NS	NS	NS	NS

*, ** = $P < 0.05$ and $P < 0.001$, respectively; NS, not significant.

(After Tu & Tan, 1988)

The surface soil was fertilized with appropriate nutrients and the soil was thereafter mixed with sufficient water to bring the water content to 16–17 % by weight. It was then packed in slabs between two plates, one of which was the porous ceramic side of a suction chamber (Fig.56). The bottom 14 cm of the slabs was subsoil at a bulk density of 1.2 g cm^{-3}. Immediately above was a 4–cm layer of surface soil packed to bulk densities of 1.2, 1.4 or 1.55 g cm^{-3}. 3 bean seedlings were transplanted into each slab and then covered with sand to reduce evaporation and the units were then placed under controlled climatic conditions.

All units were maintained at –200 mb (–20 kPa) potential until the roots approached the 4–cm layer. At this time a matric potential of –800 mb (–80 kPa) was applied to every other unit, and these two values were maintained throughout the growth period.

The study was set up in a factorial design with 3 replications with the main factors as:
Soil: Fusarium–infested or fumigated
Water potential: –20 or –80 kPa
Layer bulk density: 1.2, 1.4 or 1.55 g cm^{-3}

Plant growth (tops and roots) was consistently reduced by decreasing water potential from –20 to –80 kPa (Tab.33). Water stress symptoms were often visable in the plants grown at the lower potential. Averaged over all the other variables, decreased potential decreased top yields about 40 %. There were no interactions between potential and the other variables. Water use rates also dropped as potential decreased (Tab.34).

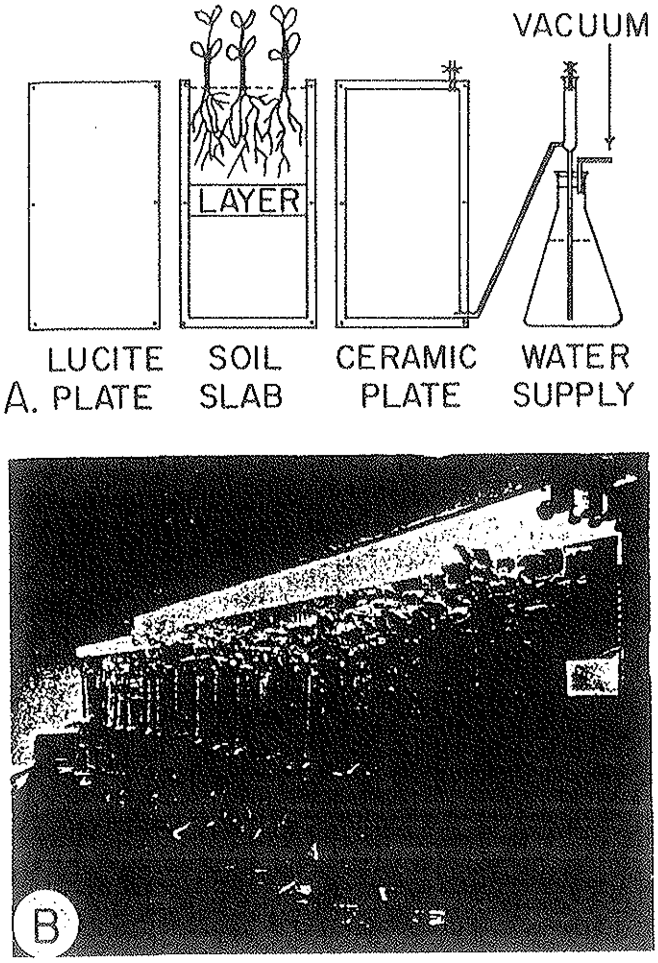


Fig. 56 A) Diagram of apparatus used to evaluate effects of soil water matric potential, soil layer bulk density, and root rot infestation on growth of beans. Soil slab is clamped between the lucite and ceramic plates and water potential in the ceramic plate is controlled by regulated vacuum. B) The assembled units in use.

(After Miller & Burke, 1974)

Yields of tops and of roots within or above the central layer were significantly less in the infested soil than in the fumigated soil (Tab.35). When roots penetrated through the layer, however, they grew equally well in both soils.

Tab. 33 Fresh weights of bean tops and roots as affected by soil water potential[a]

Water potential	Bean tops	Bean roots with respect to subsurface layer			
		Above	Within	Below	Total
mb	------------grams per unit------------				
-800	15	7	1	4	12
-200	25**[b]	9**	2**	8**	19**

[a] Each value is the average from two soil and three bulk density variables 28 days after planting.
[b] Significantly different, $P = 0.01$.

(After Miller & Burke, 1974)

Tab. 34

. Effect of soil water potential and bulk density of a subsurface layer on water use rates by beans in *Fusarium*-infested vs. fumigated soil at 10, 19, and 27 days after planting

Water potential of soil (mb)	Bulk density of subsurface layer (g/cm^3) Fumigated soil 1.2	1.4	1.55	Fusarium-infested soil 1.2	1.4	1.55
	———grams per unit per 24 hours———					
	10 Days after planting					
−800	45	36	32	41	37	33
−200	59	70	67	66	47	56
	Potentials**[a]					
	19 Days after planting					
−800	87	80	58	64	58	54
−200	122	108	128	119	80	98
	Potentials**					
	27 Days after planting					
−800	78	115	89	82	62	40
−200	160	161	185	130	95	129
	Soils**; Potentials**					

[a] Significantly different, $P = 0.01$.

Tab. 35

. Effect of soil water potential and bulk density of a subsurface layer on fresh weights of bean tops and roots in *Fusarium*-infested vs. fumigated soil

Water potential of soil (mb)	Bulk density of subsurface layer (g/cm^3) Fumigated soil 1.2	1.4	1.55	Fusarium-infested soil 1.2	1.4	1.55
	————Bean tops (g/unit)————					
−800	19	20	17	13	12	11
−200	31	28	32	22	16	20
	Soils**[a]; Bulk density N.S.					
	——Roots above layer (0 to 14 cm) (g/unit)——					
−800	7	9	11	4	4	6
−200	10	9	15	6	6	7
	Soils**; Bulk density**; Soils × bulk density*					
	——Roots within layer (14 to 18 cm) (g/unit)——					
−800	2	1	0	1	0	0
−200	2	2	2	2	1	1
	Soils**; Bulk density**					
	——Roots below layer (18 to 32 cm) (g/unit)——					
−800	7	7	0	6	4	0
−200	9	9	7	11	7	8
	Bulk density**; Soils N.S.					
	——Total roots (0 to 32 cm) (g/unit)——					
−800	16	17	11	11	9	6
−200	22	20	24	19	13	15
	Soils**; Bulk density N.S.					

[a] ** = Significant differences at 1% probability; * = Significant differences at 5% probability; N.S. = Not significantly different at 5% probability.

(After Miller & Burke, 1974)

Water use rates were nearly the same from infested and fumigated soil 10 and 19 days after planting (Tab.34). By 27 days after planting, however, root rot was severe enough to interfere with water absorption, and water use rates were less in the infested than in the fumigated soil. The lowest water use rates were from those plants with root rot, subjected to low water potential and a layer bulk density of 1.55 g cm^{-3}. Under these conditions, roots did not penetrate the layer and the plants were forced to extract water from the restricted volume above the layer through injured roots.

The bulk density of the central layer had little effect on yield of plant tops (Fig.57). Although the 1.55-g cm^{-3} layer restricted root penetration, the plants obtained sufficient water and nutrients from above the layer for adequate top growth. Roots penetrated the layer at a bulk density of 1.4 g cm^{-3} nearly as well as at 1.2 g cm^{-3}.

In root growth above the restricted layer there was a significant interaction between layer bulk density and soil treatment. The growth above that layer was greater in the fumigated soil at the highest bulk density than at the lowest bulk density, but in the *Fusarium* infested soil root growth above the layer was not affected by layer bulk density (Tab.35).

At the low water potential, no roots penetrated the layer of *Fusarium* infested soil compacted to 1.55 g cm^{-3} and only one root penetrated the fumigated soil layer. When the impedance was lowered by increasing the potential or decreasing the bulk density, roots penetrated the layer and grew profusely in the subsoil, whether or not it had been fumigated (Tab.35, Fig.58). Fig.58 indicates greater root growth at −20kPa potential below a dense layer in infested soil than in fumigated soil.

Fig. 57 Effect of soil compaction on plant growth. Left to right indicates three levels (i.e. control Co, medium C1 and heavy (C2) of soil compaction and top to bottom refers to three cultivars, Seafarer (S), Kentwood (K) and Fleetwood (F).
(After Tu & Tan, 1988)

Conclusions. The detrimental effects of water potential, *Fusarium* infestation and layer bulk density on plant growth were additive. Plant damage was greatest in infested soil maintained at low potential and with the most compact layer. Conversely, plant yields were highest in fumigated soil without a restrictive layer and maintained at high potential. Penetration of the most compact layer was negligible at low potential, whether or not the *Fusarium* was present. Root penetration was increased by decreasing impedance, either by reducing bulk density or increasing water potential and those roots that penetrated the layer into the subsoil appeared healthy.

In a previous study, Burke et. al (1972) found that subsoiling had little effect on plant yields when soil water was maintained near optimum. The data in Tab.33 support these findings in that the yields of tops were not significantly influenced by the bulk density of the soil layer, under conditions where water was not deficient. In the field, soil above a compact layer may dry out enough to cause water stress injury to plants with roots confined above the layer, especially if root density and functions are reduced by root rot. Under such conditions, an interaction between soil water status above the layer and the root impedance by the layer may be expected. Serious water stress injury may be prevented, however, even in Fusarium infected plants, if the soil is kept moist enough. Moisture status of the soil above the layer will be less important when roots can penetrate the layer than when they cannot. Furthermore, roots extending into the subsoil encounter fewer *Fusarium* propagules.

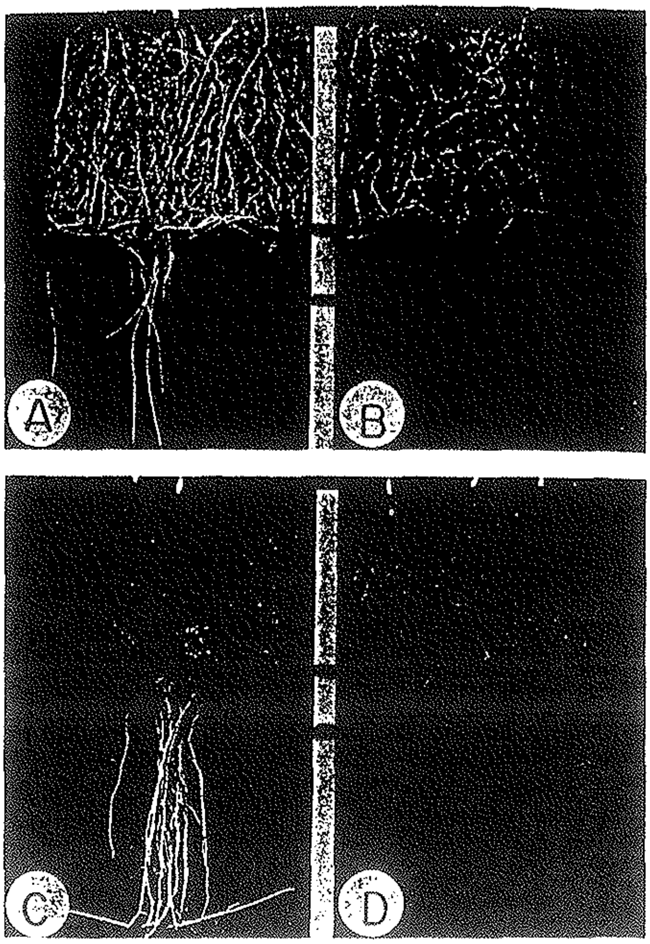


Fig. 58 Effect of soil water matric potential and infestation with *Fusarium solani* f. sp. *phaseoli* on root growth of bean plants. A and B are fumigated soil held at −200 and −800 mb matric potential, while C and D are infested soil held at −200 and −800 mb matric potential, respectively. Location of soil layer with a bulk density of 1.55 g/cm^3, is indicated by the marker. Distance between marks is 4 cm.

(After Miller & Burke, 1974)

The objectives of a growth chamber study by Frederick et al., (1982), were to assess the influence of three soil compaction levels, as determined by bulk density, and four N fertilizer treatments on growth, nodulation and N_2 fixation of *Phaseolus vulgaris* in minesoils.

Since minesoil is practically void of available N (Reeder & Berg, 1977a), plant growth is often severily retarded if no fertilizer is applied at seeding. Because of low indiginous N level in minesoils, rates in excess of 100 kg N ha^{-1} may be applied at the time of hydroseeding. It is well established that plant available N can depress nodulation in legumes (Hardy & Gibson, 1977). The problem, therefore, is to provide sufficient inorganic nitrogen during seed germination and early plant growth without having exsess amounts to depress nodulation of legumes.

Because legume establishment is an important step in the revegetation of drastically disturbed land such as minesoil, this study was undertaken to determine the influence of minesoil compaction and N fertilization at seeding on legume shoot, root and nodule mass and potential for nitrogen fixation.

Four-year-old, sparsely vegetated minesoil from Wise County, Virginia was collected and placed in polyethylene-lined 15-cm diameter plastic pots. The experiment was arranged in a randomized complete block design with inoculated and uninoculated (control) plants maintained in separate growth chambers programmed at standardized climatic conditions. Unamended minesoil was highly compacted, averaging 1.55 g cm^{-3}. Acid-washed sand was mixed with minesoil at 3 levels: 0:1, 1:3 and 1:1 (v/v) sand:soil ratios resulting in bulk densitiy values of 1.55, 1.46, 1.40 g cm^{-3}, respectively. Seeds of *P. vulgaris* were sown in pots containing minesoil and thinned to 2 plants per pot after germination and treatments were inoculated with freshly prepared peat culture. Nitrogen fertilizer, as NH_4NO_3, was applied in solution at seeding at rates equivalent to 25, 50, and 100 kg N ha^{-1}. Appropriate controls consisted of uninoculated and inoculated plants without nitrogen fertilizer addition.

There was no interaction between bulk density and N fertilizer rates for any parameter measured with the exception of percentage root N. With uninoculated plants, nodulation was absent, reduction of acetylene to ethylene ($N_2(C_2H_2)$ fixation) was not detected, and root and shoot mass was minimal. Therefore, the data presented in Tab.36 and Tab.38 represent the increase over the uninoculated control plants.

Ameliorating the minesoil with sand increased root and shoot mass but decreased nodule mass (Tab.36). The highly significant inverse correlation (r= -0.70**, Tab.37) between compaction and root mass is particularly relevant to shoot growth and stabilization of disturbed lands. The reduced root growth in unamended minesoil undoubtedly contributed to reduced shoot growth (r= 0.67** for shoot x root, Tab.37). The data are consistent with other reports (Tisdale & Nelson, 1975) and (Whisler et al., 1965) that have shown soil compaction to reduce root growth of plants.

In the study, nodules were predominantly found near the soil surface clustered at the base of the plants in all treatments. Lateral root nodulation was found only in minesoil amended with 50 % sand. Since root growth was restricted mainly to the upper surface of unamended minesoil, N fertilizer uptake was probably stimulated in this zone. Thus, the greater nodule production in unamended minesoil possibly resulted in part from rapid N depletion in the upper soil surface. Available N is known to adversely affect nodulation (Hardy & Gibson, 1977).

There was no consistent effect of bulk density on N_2 fixation during the 49-day growing season (Tab.38). Although nodule mass at harvest was greatest in unamended minesoil (Tab.36), apparently other factors interacted with changes in compaction to influence N_2 fixation. No significant overall correlations between minesoil compaction and nodule mass or N_2 fixation were found (Tab.37).

Shoot and root mass increased in proportion to the amount of N fertilizer added (Tab.36). Nodule mass was greatest at 25 kg N ha^{-1}. However, there were no significant differences in root N and only a slight increase in shoot N among N fertilizer rates. Apparently, the bean plants obtained adequate amounts of N for growth irrespective of the source- applied fertilizer or symbiotically fixed N. This demonstrates the important potential of symbiotically fixed N in the maintainance of plant N levels.

Tabs. 36 & 37

Effect of Bulk Density and N Fertilization on Dry Weight Yields of P. Vulgaris Harvested at 49 Days From Seeding

Treatment	Shoot mass	Root mass	Nodule mass	Shoot N	Root N
	- - -	- g -	- - -	- - %	- -
Bulk density					
(g/cm^3)					
1.55	2.21b[z]	0.66b	0.20a	1.58b	1.25b
1.46	2.20b	0.77b	0.17ab	1.69ab	1.45a
1.40	2.98a	1.60a	0.15b	1.78a	1.35ab
N fertilization[y]					
(kg N/ha)					
0	1.83c	0.69b	0.18b	1.54b	1.28a
25	2.35b	1.00ab	0.28a	1.82a	1.30a
50	2.56b	1.09a	0.13bc	1.67ab	1.38a
100	3.10a	1.25a	0.11c	1.69ab	1.43a

[z] Mean separation within columns by Duncan's multiple range test, 5% level.

[y] Indigenous N level was 8.3 ppm NO_3.

Correlation Coefficients (r) for Relationships Among Bulk Density, N Fertilizer Rates, and Growth Parameters

	Shoot mass	Root mass	Nodule mass	Shoot N	Root N	N_2 (C_2H_2) fixation (35 days)
Bulk density	-0.42*	-0.70**	0.26	-0.33	-0.25	0.17
N fertilizer rate	0.65**	0.36	-0.51*	0.11	0.30	-0.60**
Shoot mass	--	0.67**	-0.27	0.19	0.23	-0.24
Root mass	--	--	-0.45*	0.18	0.05	-0.23
Nodule mass	--	--	--	0.15	-0.14	0.87**
Shoot N	--	--	--	--	0.37	0.15
Root N	--	--	--	--	--	-0.25

*Significant at 5% level. **Significant at 1% level.

(After Sundstrom et al., 1982)

For plants receiving N fertilizer, the maximum rates of N_2 fixation occurred at 35 days after seeding, which corresponded to the pod filling stage (Tab.38). At 0 kg N ha^{-1}, however, N_2 fixation was greater at 25 days than at 35 days, illustrating the repressive nature of available soil N on nodule formation and nitrogenase activity.

Addition of 25 kg N ha^{-1} increased N_2 fixation compared to the inoculated plants to which no N fertilizer was added. Increasing the rate of N fertilizer to 50 and 100 kg ha^{-1} reduced N_2 fixation. High rates of fertilizer N have been recognized for a number of years to depress N_2 fixation, although low amounts applied at seeding have been reported to be beneficial (Harper, 1974). Introduced species of legumes in a revegetation study of spent oil shales showed increased N_2 fixation potential by addition of moderate amounts of N (Sorensen et al., 1981).

Tab. 38
Influence of Bulk Density and N Fertilization on $N_2(C_2H_2)$ Fixation Rates of P. Vulgaris at 21, 35, and 49 Days From Seeding[z]

Mean effects	Days from seeding		
	21	35	49
Bulk density	- µmoles C_2H_4 produced/plant/hr -		
(g/cm^3)			
1.55	0.63ab[y]	1.31a	0.20a
1.46	0.42b	.81b	0.08a
1.40	1.04a	.98ab	0.21a
N fertilization			
(kg N/ha)			
0	1.54a	1.13b	0.19ab
25	0.91ab	2.26a	0.33a
50	0.26bc	0.60c	0.10ab
100	0.07c	0.14c	0.03b

[z] Ethylene production was not detected at 7 days from seeding.

[y] Mean separation within columns by Duncan's multiple range test, 5% level.

(After Sundstrom & et al., 1982)

Effective nodulation is important for establishing a permanent stand of legumes on minesoils. Since surface deposited overburden generally lacks symbiotic nitrogen fixing microorganisms, revegetation recommendations for disturbed sites (McCart, 1973) should emphasize the need for seed inoculation similar to that recommended for agricultural soils (Hardy & Gibson, 1977).

There was a strong positive relationship ($r= 0.87^{**}$, Tab.37) between nodule mass and N_2 fixation, as would be expected. A low relative amount of applied N fertilizer (25 kg ha^{-1}) increased both nodule mass and N_2 fixation; however nitrogenase activity was enhanced proportionately more (100 %) than nodule mass (55 %). The data would indicate that the addition of 25 kg N ha^{-1} increased plant vigor in a manner beneficial to N_2 fixation. Whether this was due to increased carbon transport or greater photosynthetic activity was not known. However, it is well known that N_2 fixation requires a substantial input of energy that must be supplied to the nodule by the plant as oxidizable carbon (Hardy & Gibson, 1977). Thus, the relative size and vigor of the young plant at time of infection by the symbiont may conceivably affect subsequent plant growth and relative N_2 fixation potential.

In an investigation by Tu & Tan (1991), the objective was to determine the effect of soil compaction on plant growth, yield and root rot severity in white beans under field conditions so that improved tillage and cultural practices could be implemented to alleviate these constraints.

The experiments were conducted for 4 years at 2 different Research Stations in England. The soil texture, moisture retention and bulk densities are summarized in Tab.39. Both fields were heavily infested with root rot fungi, e.g. *Rhizoctonia solani* (Rs) and *Fusarium solani* f. sp. *phaseoli* (Fs). The ratios of Rs:Fs were 10:6 and 10:4 at the 2 Research Stations, respectively.

Tab. 39 . Summary of soil texture, moisture retention characteristics and bulk density at different levels of compaction of Brady sandy loam at Harrow and Thames silty clay loam at Chatham in 1984

Depth (cm)	Sand (%)	Silt (%)	Clay (%)	FC[b] (%)	PW[c] (%)	Bulk density		
						Ck	C1	C2
Harrow								
0–7	82.3	14.1	3.6	16.1	5.2	1.35 ± 0.02[a]	1.46 ± 0.01	1.54 ± 0.02
7–14	80.3	14.5	5.2	17.3	5.9	1.51 ± 0.02	1.51 ± 0.01	1.52 ± 0.01
Chatham								
0–7	9.3	60.3	30.4	32.0	13.0	1.22 ± 0.02	1.31 ± 0.02	1.41 ± 0.02
7–14	9.5	60.0	30.5	32.5	14.7	1.52 ± 0.03	1.56 ± 0.03	1.55 ± 0.03

[a] Standard error (SE).
[b] FC = field capacity on an oven-dry wt basis.
[c] PW = permanent wilting point on an oven-dry wt basis.

(After Tu & Tan, 1985)

Three white bean cultivars were used in this experiment and all of them were highly susceptible to root rots.

Soil compaction was studied for 3 years (1983–1985) in the same fields. Conventional seedbed preparation included one fall plowing, two spring discings and one harrowing.

Each field was divided into three blocks for control (non–compaction), compaction 1 (C1) and compaction 2 (C2). C1 and C2 were obtained by two runs of continous tyre marks of a 1.6 ton golf cart and a 2.6 ton tractor, respectively.

Plant growth and development were observed weekly and fresh weight of shoots and roots were taken end of July just before the onset of natural senescence. Washed roots were rated for disease severity on a 0–9 scale in which 0= no symptoms and 9= 81 % or more root discolored.

Yield was determined by harvesting 5 m of the two center rows per treatment of each plot during end of August when beans matured.

The 3–year results showed similar trends in white bean response to soil compaction even though a year–to–year variation of up to 15 % in yield did exist (Tab.40). This variation was attributable to differences in rainfall and temperature.

Tab. 40 Average daily high, low and mean temperatures and total precipitation at the two field locations (Harrow and Chatham) during the growing seasons (May–September inclusive) and average yield per two 5 m-rows of three cultivars (Fleetwood, Kentwood and Seafarer) in check plot from 1982 to 1985

Location	Year	Temperature (°C)			Precipitation (P) (mm)	T × P	Yield[a] (g)
		High	Low	Mean (T)			
Harrow	1982	23.9	13.9	18.9	286.0	5,405.4	382.5
	1983	24.6	14.6	19.6	437.0	8.565.2	573.3
	1984	23.4	13.6	18.5	378.0	6,993.0	435.6
	1985	23.8	13.9	18.8	348.5	6,551.8	401.1
	r^b			0.65	0.83	0.97	
Chatham	1982	23.4	12.4	17.9	459.4	8,233.3	381.6
	1983	24.7	13.5	19.1	633.0	12,090.3	468.1
	1984	23.3	13.7	18.5	416.0	7,696.0	357.8
	1985	23.9	13.7	18.8	572.5	10,763.0	427.8
	r^b			0.59	0.99	0.99	

[a] At 18% moisture. Yield 5 m rows.
[b] r = correlation coefficient in relation to yield.

(After Tu & Tan, 1985)

Plant biomass (roots and shoots) and plant height were reduced as the degree of compaction increased from C1 and C2 (Tab.41 and Fig.59). It was also observed that uniformity of plant growth was reduced, maturity was delayed, and variability in size increased with soil compaction.

Comparison of plant growth in clay soil and sandy soil revealed that clay soil supported better biomass production than that of sandy soil at the same degree of soil compaction (Tab.42 and 43).

Tab. 41 Effect of soil compaction on various measures of plant growth and severity of root rot of white bean in 1984

Location	Category	Yield[b] (g)	Fresh wt[a] (g)	Height[c] (cm)	Root rot (0–9 index)
Harrow (sandy loam)	Cultivars means				
	Fleetwood	442.8a	21.7a	30.5a	2.7c
	Kentwood	217.5b	12.0b	23.5b	3.9b
	Seafarer	197.8b	7.4c	21.5b	3.8b
	Soil compaction means				
	Ck	367.0a	17.4a	31.0a	2.1c
	C1	285.4b	14.7b	24.3b	3.2b
	C2	205.8c	9.0c	20.5c	5.1a
	Significance of *F*				
	Cultivar (cv.)	**	**	**	*
	Compaction (CP)	**	**	**	**
	CV × CP	NS	**	NS	NS
Chatham (clay loam)					
	Fleetwood	464.3a	28.6a	31.3a	1.8b
	Kentwood	300.3b	25.0ab	23.8b	2.2ab
	Seafarer	251.0c	21.3b	21.0b	2.4a
	Soil compaction means				
	Ck	426.4a	31.2a	35.0a	1.4c
	C1	350.5b	26.0b	23.0b	1.9b
	C2	238.6c	17.7c	18.0c	3.0a
	Significance of *F*				
	Cultivar (CV)	**	**	**	*
	Compaction (CP)	**	**	**	**
	CV × CP	*	NS	NS	NS

[a] Data taken on 16 August 1984.

[b] Yield of 5 m row at 18% moisture, plants harvested on the first week of September 1984.

[c] Measurements were taken from soil level to the tip of plant on 16 August 1984.

a–b means within column followed by the same letter are not significantly different ($P \geq 0.05$) according to Duncan's multiple range test.

*Significant at 5% level, **significant at 1% level.

(After Tu & Tan, 1985)

Tab. 42 Yield of white bean in field plots of different soil compaction in relation to soil types in 1984

		Yield at different degrees of soil compaction				
Location	Cultivar	Control (Ck) (g)	Medium (C1) (g)	High (C2) (g)	C1.Ck	C2.Ck
Harrow	Fleetwood	554.1a[a]	427.1a	347.3a	77.1	62.7
	Kentwood	284.9b	225.4b	140.6b	79.1	49.2
	Seafarer	262.1b	201.9b	129.5b	77.0	49.4
	F-test	**	**	**		
Chatham	Fleetwood	560.0a	452.0a	380.9a	80.7	68.0
	Kentwood	413.8b	304.3b	182.9b	73.5	44.2
	Seafarer	350.5c	295.3b	152.1b	84.3	43.4
	F-test	**	**	**		

[a] Yield of 5 m row at 18% moisture. Plants harvested in the first week of September. a–b means within column followed by the same letter are not significantly different ($P \geq 0.05$) according to Duncan's multiple range test.

**Significant of *F*-test at 1% level.

(After Tu & Tan, 1985)

Tab. 43 Growth, yield and root rot severity of white bean in sandy loam and clay loam soil based on average of three cultivars[a] and three degrees of compaction[b]

Soil type	Yield[c] (g)	Fresh wt[d] (g)	Height[e] (cm)	Root rot (0–9 index)
Sandy loam (Harrow)	286.1b	13.7b	25.3a	3.5a
Clay loam (Chatham)	338.5a	25.0a	25.3a	2.1b

a–b means within column followed by the same letter are not significantly different ($P \geqslant 0.05$) according to Duncan's multiple range test.

[a] Fleetwood, Kentwood and Seafarer.

[b] Refer to text.

[c] Yield of 5 m row at 18% moisture. Plant harvested in the first week of September

[d] Data taken on 16 August 1984.

[e] Plant height measured from soil level to the tip of plant. Data were taken on 16 August 1984.

(After Tu & Tan, 1985)

The three cultivars differed considerably in their growth rate and canopy size. Fleetwood had the largest plant biomass and highest yield followed by Kentwood and Seafarer. Their responses to soil compaction were similar both in sandy soil and in clay soil (Tab.41). However, plant growth and bean yield of all three cultivars fared better in clay soil than sandy soil. The percentage growth or yield reduction due to heavy soil compaction was considerably less in Fleetwood than Kentwood and Seafarer (Tab.42).

Notwithstanding the differance in cultivars, root rot severity increased with soil compaction. The root rots were more severe in sandy soil than clay soil. Among the cultivars, Fleetwood appeared more resistant to root rot than Kentwood, and Kentwood more resistant than Seafarer (Tab.41).

The relationship between white bean yield and soil compaction (Tab.42) was clearly shown in the reduction of bean yield as soil compaction increased. Yield reduction from C1 to C2 was greater than from Ck to C1 in both sandy and clay soils. Bean yield of the three cultivars had C1-to-Ck ratios ranging from 77.0 to 79.1 and 73.5 to 84.3 in sandy soil and clay soil, respectively, and their differences were small. However, at heavy compaction (C2), these three cultivars had a large difference in C2-to-Ck ratios showing that some cultivars were more susceptible to heavy compaction than others (Tab.42).

The results of these field experiments confirmed a previous work by Tu & Tan (1988), conducted in a greenhouse. In both cases, soil compaction reduced plant biomass and yield of white bean, and increased the root rot index. No doubt, soil compaction increased physical restraint of root growth and reduced soil aeration and water accessibility. The latter restricts delivery of nutrients to plants and consequently affects the efficiency of photosynthesis (Tu & Tan, 1988). Clearly, soil compaction imposed not only physical but also physiological constraints to plant growth. The poor plant growth due to soil compaction may predispose these plants to more severe root rots.

Plants grew better and yielded higher in clay loam soil than in sandy loam soil at the same traffic treatment (Tab.43), possibly because clay loam has more nutrients, organic matter and better moisture holding capacity than sandy soil. It is noteworthy that throughout the experiments, the soils were compacted only in the top 7 cm. From 7 to 14 cm, the bulk density measurements showed little or no difference among treatments (Tab.39). Thus, it was safe to assume that tillage of top soil during the growing season may effectively reduce soil compaction in the field and improve plant growth and yield.

A study by Kahnt et al. (1986) was done to observe the effects of soil compaction on field bean and soybean growth in greenhouse. Plastic cylindrical tubes were filled with silty loam soil with 3 bulk densities viz., low (1.25 g cm^{-3}) medium (1.45 g cm^{-3}) and high (1.65 g cm^{-3}) either in the whole profile= (homogenous) or in combination of low/medium (level 1), low/high (level 2) and medium/high (level 3) as topsoil/subsoil densities= (heterogenous).

The homogeneous bulk densities in 0–50 cm soil profile were as under:

Bulk densities	Total pore volume (%)
1.25 g cm^{-3}	49.6 (Low)
1.45 g cm^{-3}	46.4 (Medium)
1.65 g cm^{-3}	44.1 (High)

To create heterogeneous soil profile the following combinations of soil bulk densities were taken:

low (1.25 g cm^{-3}) upper 20 cm soil
(level 1; control)
med. (1.45 g cm^{-3}) lower 30 cm soil

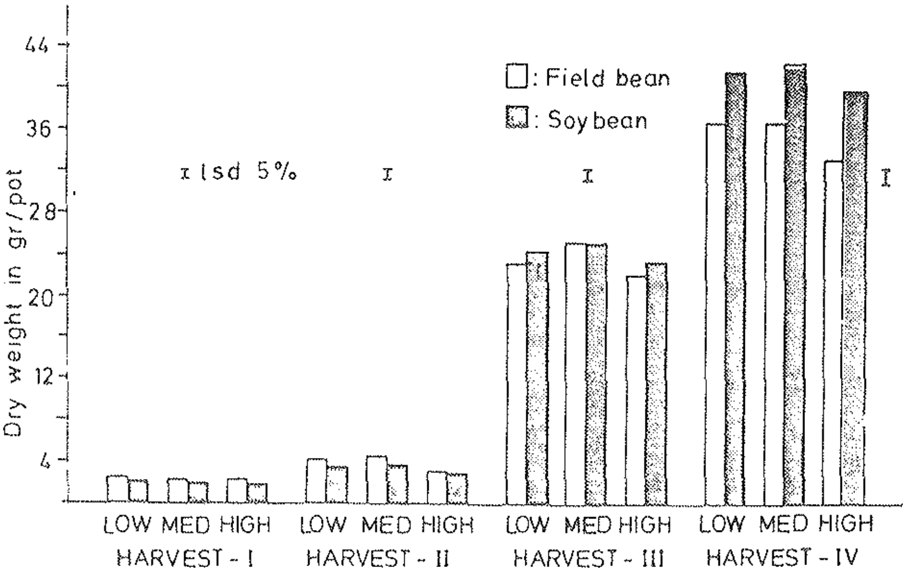
low (1.25 g cm^{-3}) upper 20 cm soil
(level 2)
high (1.65 g cm^{-3}) lower 30 cm soil

med. (1.45 g cm^{-3}) upper 20 cm soil
(level 3)
high (1.65 g cm^{-3}) lower 30 cm soil

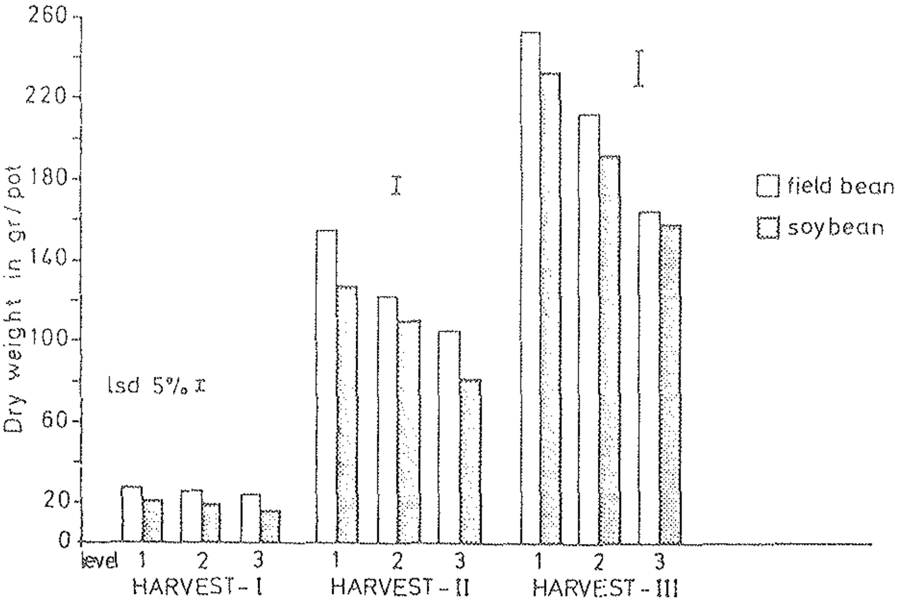
The plants were harvested after 4, 5, 7 and 12 weeks after sowing in homogeneous and 4, 8 and 12 weeks after sowing in heterogeneous soil. Watering was done at 70 % field capacity. The treatments were replicated 4 times.

The results in Fig.59 showed the first decrease in dry matter yield due to high density to occur at second harvest i.e. after 5 weeks. This decrease was observed until the last harvest. No appreciable differences between low and medium density treatments were found. In heterogeneous soil profile (Fig.60) compaction combinations also caused a decrease in weight, which became greater with time.

To establish the zones of the root concentration, soil profile was divided into 3 parts i.e. 0–20 cm (layer a), 20–40 cm (layer b) and 40–50 cm (layer c). At first 2 harvests only field bean showed a decrease in root weight due to high compaction (Fig.61). The effect of compaction at 3rd harvest was not very clear in any. At the final harvest an evident decrease in total weight due to compaction was registered for both crops.



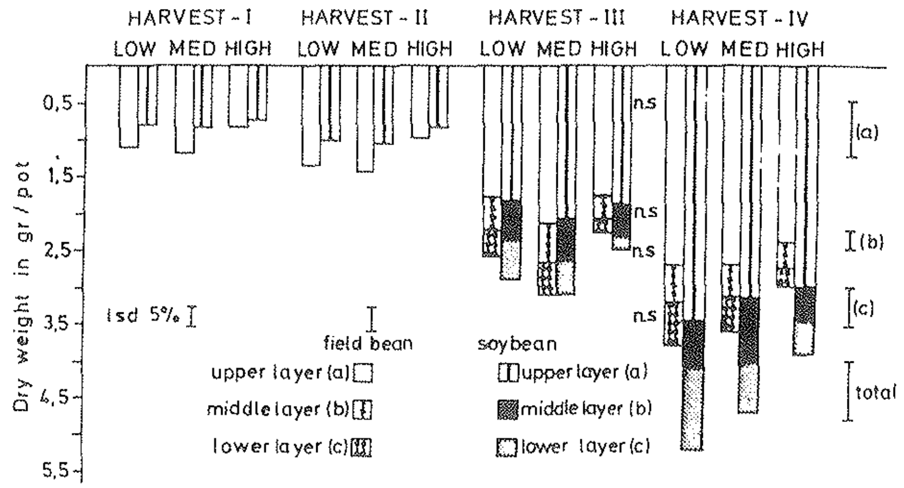
Effect of homogeneous soil compaction on the dry matter production of field bean and soybean at four different harvests



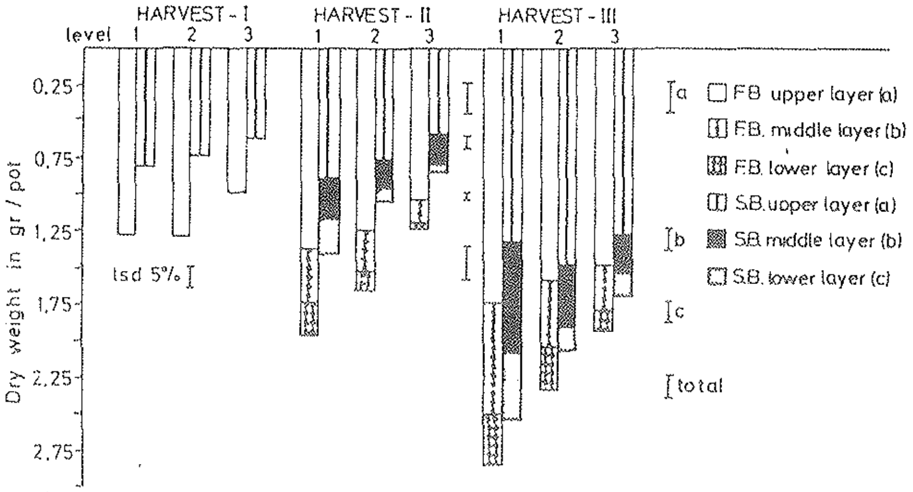
Figs. 59 & 60 Effect of heterogeneous soil compaction on the dry matter production of field bean and soybean at three different harvests

(After Kahnt et al., 1986)

The adverse effect of compaction showed itself in heterogeneous soil profile too (Fig.62). In the first harvest the effect was only seen at 3rd level, but it became notacieable at all levels from 2nd harvest and onwards. At 2nd harvest a decrease was registered in total dry matter at level 2.



Effect of homogeneous soil compaction on the dry root weight in upper (a), middle (b) and lower (c) layer and the total root dry weight of field bean and soybean at four different harvests



Figs. 61 & 62 Effect of heterogeneous soil compaction on the root dry weight in upper (a), middle (b) and lower (c) layer and total root dry weight of field bean and soybean at three different harvests

(After Kahnt et al., 1986)

The effect of compaction on root volume started becoming clear at 2nd harvest (Fig.63). At 3rd harvest in the upper layer an increasing trend was found with the increase in bulk density. No differences were observed in the middle layer. In the lower layer increase in bulk density decreased the root volume. At final harvest higher bulk density increased the root volume of both crops in the upper layer. In the middle layer increasing the density from low to medium increased the root volume, but a further increase caused a decrease in root volume.

In heterogeneous soil profile (Fig.64) both crops reacted differently to soil compaction. At all harvests field bean showed a decrease in root volume due to compaction, whereas in soybean it was produced only at level 3.

At 1st harvest an increase in bulk density from 1.25 cm to 1.65 cm^{-3} caused both field bean and soybean to reduce its total root length (Fig.65). This effect went through 2nd harvest. At 3rd harvest no effect of compaction was found in the upper layer. In the middle and lower layer root length was greatly decreased. At final harvest an increase in bulk density from level 2–3 especially reduced root length in both crops.

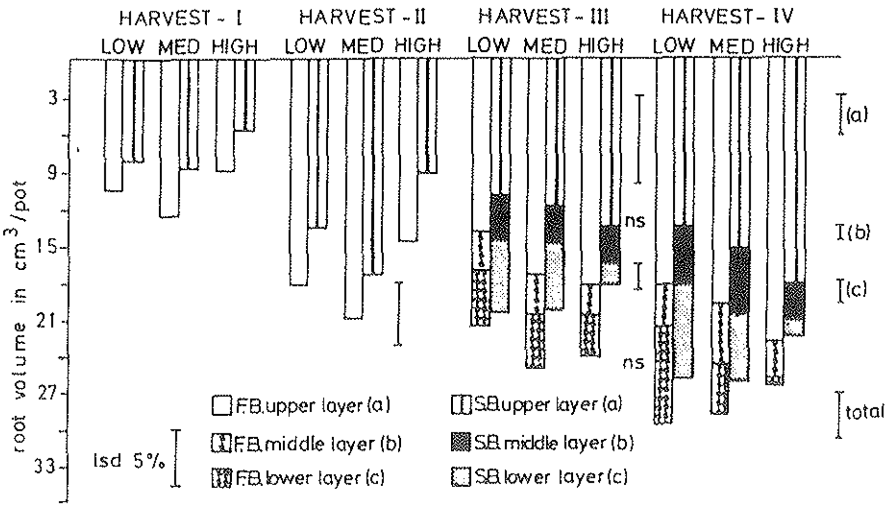


Fig. 63 Effect of homogeneous soil compaction on the root volume in upper (a), middle (b) and lower (c) layer and the total root volume of field bean and soybean at four different harvests

(After Kahnt et al., 1986)

The effect of heterogeneous soil profile in Fig.66 shows no clear cut effect of compaction at 1st harvest, but at 2nd harvest total root length of both field beans and soybeans decreased.

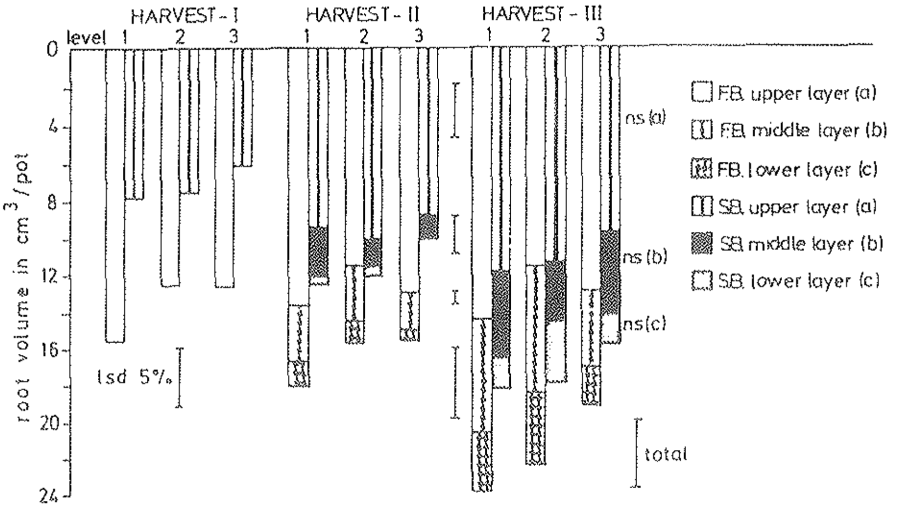


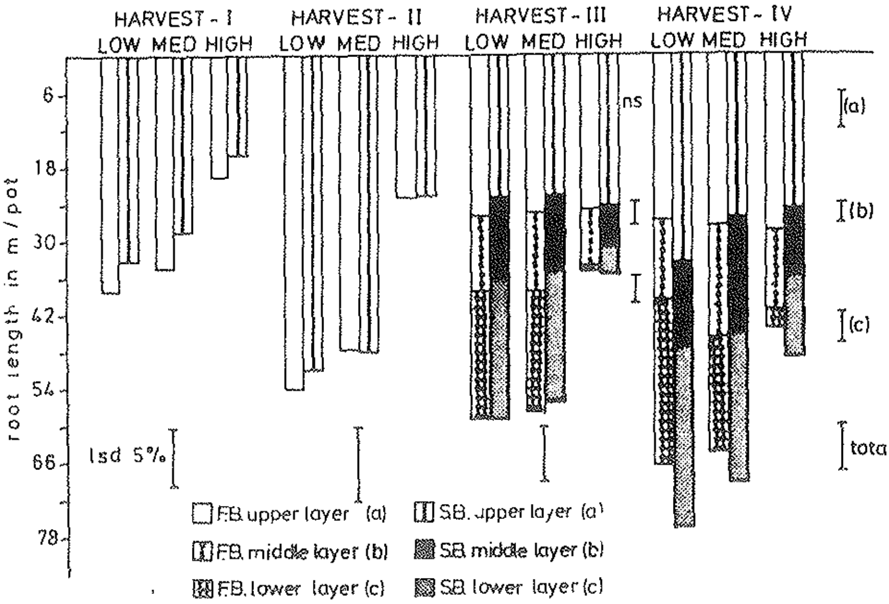
Fig. 64 Effect of heterogeneous soil compaction on the root volume in upper (a), middle (b) and lower (c) layer and total root volume of field bean and soybean at three different harvests

(After Kahnt et al., 1986)

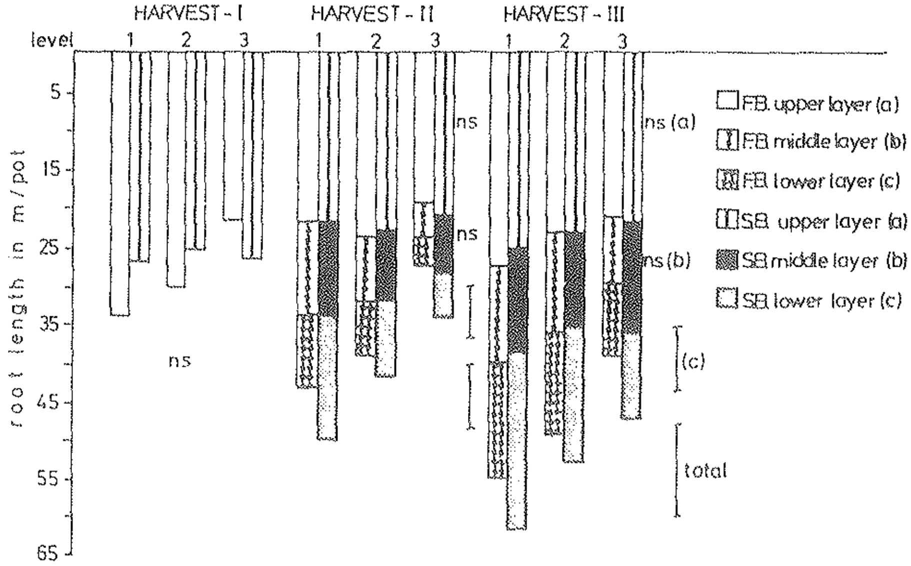
As noted earlier in this review, roots grown in compacted media fail to elongate but expand radially causing the roots to thicken. This might have prevented the reduction of root volume in some high density profile in this study (Pers. comment).

In an investigation by Borges et al. (1988), growth of soybean varieties in response to soil compacted layers were studied. The study was conducted to evaluate the capacity of roots of 5 soybean varieties to grow into compacted soil layers and the effect of soil compaction on plant growth and nutrient concentrations.

Containers were made up by superimposing three PVC rings. Lime and fertilizer, in proper quantities, were mixed with a sample of a Dark Red Latosol. Pressure was applied to the soil in order to obtain the following bulk densities: 0.85, 1.15, 1.25 and 1.35 g cm^{-3}.



Effect of homogeneous soil compaction on the root length in upper (a), middle (b) and lower (c) layer and the total root length of field bean and soybean at four different harvests



Figs. 65 & 66 Effect of heterogeneous soil compaction on the root length in upper (a), middle (b) and lower (c) layer and total root length of field bean and soybean at three different harvests

(After Kahnt et al., 1986)

The growth of the aerial part of the tropical variety (Tab.44) showed most sensitivity to the increase of soil compaction. A drastic decrease of root growth is observed in the 1.25 and 1.35 g cm^{-3}, respectively.

Phosphorus, potassium and magnesium concentrations in plant shoots increased with the compaction up to nearly 1.0 g cm^{-3}, decreasing for higher densities (Tab.45). However, calcium concentrations decreased linearly with the increase in the soil compaction. In general, the behaviour of all varieties was similar in response to the treatments tested.

The objective of a study by Lindemann et al. (1982) was to investigate the effects of soil compaction applied in spring prior to planting on soybean nodulation, N_2 (C_2H_2) fixation and seed yield.

Tabs. 44 & 45 Produção de matéria seca da parte aérea e das raízes de cinco variedades de soja, submetidas à densidade aparente de 0,85 g/cm^3 nos anéis superior e inferior e a diferentes densidades no anel intermediário do vaso

Variedades	Densidade aparente (g/cm^3)(1)										
	0,85	1,05	1,15	1,25	1,35	Média	0,85	1,05	1,15	1,25	1,35
	Parte Aérea										
	g/vaso						Crescimento Relativo(%)				
IAC-8	8,77 a	8,40 a	8,41 a	7,45 a	7,22 a	8,05	100,0	95,8	95,8	84,9	82,3
Bossier	8,12 ab	8,17 ab	8,16 ab	7,26 a	6,96 ab	7,73	100,0	100,6	100,4	89,4	85,7
Tropical	8,28 ab	7,26 c	7,86 abc	6,22 b	6,26 c	7,18	100,0	87,7	94,9	75,1	75,6
Doko	8,38 ab	7,60 bc	7,40 c	6,83 ab	6,83 abc	7,41	100,0	90,7	88,3	81,5	81,5
Cristalina	7,92 b	7,66 bc	7,62 bc	7,06 a	6,54 bc	7,37	100,0	96,7	96,2	89,2	82,6
Média	8,29	7,82	7,89	6,96	6,76	-	100,0	94,3	95,2	84,0	81,5
	Raízes										
IAC-8	2,527	2,417	2,508	1,768	1,707	2,186 cd	100,0	95,6	99,2	70,0	67,6
Bossier	2,633	2,586	2,498	1,675	1,951	2,269 bc	100,0	98,2	94,9	63,6	74,1
Tropical	2,519	2,394	2,410	1,463	1,537	2,065 d	100,0	95,0	95,7	58,1	61,0
Doko	2,760	2,604	2,786	1,775	1,846	2,354 b	100,0	94,3	100,9	64,3	66,9
Cristalina	2,849	2,909	3,093	2,027	2,151	2,606 a	100,0	102,1	108,6	71,1	75,5
Média	2,658	2,582	2,659	1,742	1,838	-	100,0	97,1	100,0	65,5	69,1

(1) Densidade aparente do anel intermediário.

Médias seguidas da mesma letra, na coluna, não diferem estatisticamente entre si, pelo teste de Tukey, a 5% de probabilidade

Concentração de fósforo, potássio, cálcio e magnésio na parte aérea de cinco variedades de soja, submetidas à densidade aparente de 0,85 g/cm^3 nos anéis superior e inferior e a diferentes densidades no anel intermediário do vaso

Nutriente	Densidade aparente(1)	Variedades					Média
		IAC-8	Bossier	Tropical	Doko	Cristalina	
	g/cm^3	%					
Fósforo	0,85	0,13	0,14	0,14	0,13	0,14	0,14
	1,05	0,14	0,14	0,13	0,14	0,15	0,14
	1,15	0,14	0,13	0,13	0,13	0,14	0,13
	1,25	0,13	0,13	0,13	0,12	0,12	0,12
	1,35	0,12	0,12	0,12	0,13	0,11	0,12
	Média(2)	0,13 a	0,13 a	0,13 a	0,13 a	0,13 a	-
Potássio	0,85	1,68	1,76	1,82	1,94	1,62	1,76
	1,05	1,82	1,84	1,93	1,99	1,86	1,89
	1,15	1,91	1,88	1,92	1,86	1,29	1,77
	1,25	1,40	1,54	1,42	1,39	1,31	1,41
	1,35	1,08	1,26	1,19	1,11	1,05	1,14
	Média(2)	1,58 ab	1,66 a	1,66 a	1,66 a	1,43 b	-
Cálcio	0,85	0,95	1,18	1,07	1,13	1,05	1,08
	1,05	0,87	1,08	1,06	1,15	1,13	1,06
	1,15	0,98	1,00	1,05	1,09	1,04	1,03
	1,25	0,84	1,00	1,04	1,07	0,99	0,99
	1,35	0,91	0,91	0,92	1,05	0,93	0,94
	Média(2)	0,91 b	1,03 a	1,03 a	1,10 a	1,03 a	-
Magnésio	0,85	0,42	0,41	0,41	0,40	0,43	0,41
	1,05	0,42	0,45	0,42	0,43	0,45	0,43
	1,15	0,42	0,42	0,41	0,39	0,40	0,42
	1,25	0,40	0,45	0,42	0,40	0,44	0,40
	1,35	0,40	0,40	0,37	0,40	0,37	0,39
	Média(2)	0,41 a	0,43 a	0,41 a	0,40 a	0,42 a	-

(1) - Densidade aparente do anel intermediário.
(2) - Médias seguidas da mesma letra, na linha, não diferem estatisticamente entre si, pelo teste de Tukey, a 5% de probabilidade.

(After Borges et al., 1988)

Field experiments were conducted on a clay loam soil for 2 years in Minnesota. Prior to planting, compaction treatments were imposed on the plot area by driving a tractor over each plot once, twice or three times. The control plot was not compacted. After compaction, bulk density and soil moisture samples were taken. The experimental design was a randomized, complete block with 4 replications.

1976 and 1977 were quite different years with respect to precipitation at the experimental site. While 1976 was an extremely dry year (58 % of normal April to September precipitation), precipitation was greater than normal in 1977 (125 % of normal April to September precipitation).

Bulk density (Tab.46) in the upper 5 to 25 cm of soil was increased significantly by tractor compaction. Only in 1977 did additional tractor passes (2X and 3X) further increase bulk density over the one tractor pass.

According to the report, visual treatment differences were clearly evident in 1977, especially in June and July. As the number of tractor passes increased, plant growth decreased. Compaction decreased plant dry weight on the 1st July sampling date (Tab.47). At harvest, plant height was not significantly different, but the trend was apparent.

Soybean yields (Tab.48) were not affected significantly by tractor compaction in either year, although trends were present. There was a trend for compaction to increase yields in the dry year (1976) and to decrease yields in the wet year (1977). This is also in line with several years experiments by Håkansson (1989). These investigations show that the optimal degree of compactness and consequently the yield varies due to e.g. the weather situation during the growing season. A comparatively low degree of compactness was optimal in wet summers and a higher degree of compactness in dry summers.

Tab. 46 **Effect of compaction treatments on soil bulk density.**

Compaction treatment	Bulk density			
	1976		1977	
	Soil depth (cm)			
	5-15	15-25	5-15	15-25
	$g\ cm^{-3}$			
0	1.16 a*	1.24 a	1.25 a	1.46 a
1 tractor pass	1.26 b	1.37 b	1.46 b	1.49 b
2 tractor passes	1.25 b	1.39 b	1.55 c	1.53 c
3 tractor passes	1.28 b	1.33 b	1.54 c	1.56 d
Standard error	0.05	0.05	0.04	0.04

* Means followed by the same letter within each column are not significantly different at the 5% probability level as determined by Duncan's Multiple Range Test.

(After Lindemann et al., 1982)

Cumulative nodulation and acetylene reduction from 4 sampling dates in 1976 can be seen in Tabs.49 and 50. The 2 tractor pass treatment had significantly higher nodulation and acetylene reduction values for taproot samples only. A similar trend is seen in the lateral samples, but the differences are not statistically significant. In contrast to the 1976 data nodule number and weight in 1977 were greater in the control and 1 tractor pass treatments than in the more compacted plots (Tabs.51,52).

Phytophthora root rot, caused by *Phytophthora megasperma* f. sp. *glycinea* (Kuan and Erwin), is one of the most destructive soilborne diseases of soybean and the disease now occurs in most soybean producing areas of the U. S. and Canada (Kaufmann & Gerdemann, 1958). The pathogen may attack plants in all stages of growth with disease development favored by poorly drained soils and cool wet weather. Symptoms of the disease are preemergent or postemergent damping off of younger plants and stunting, wilting or death of older plants (Hildebrand, 1959).

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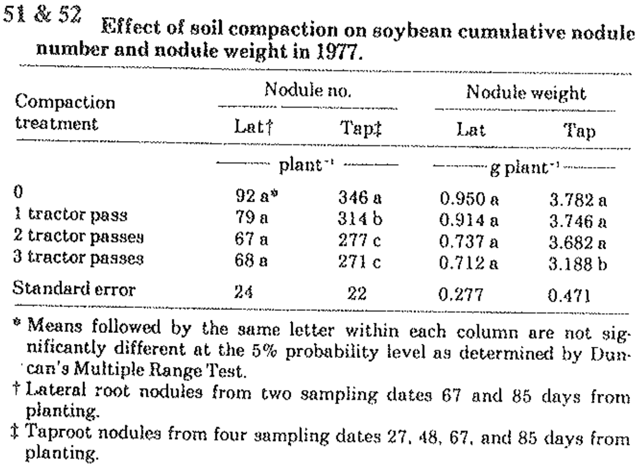
Tab. 51 & 52



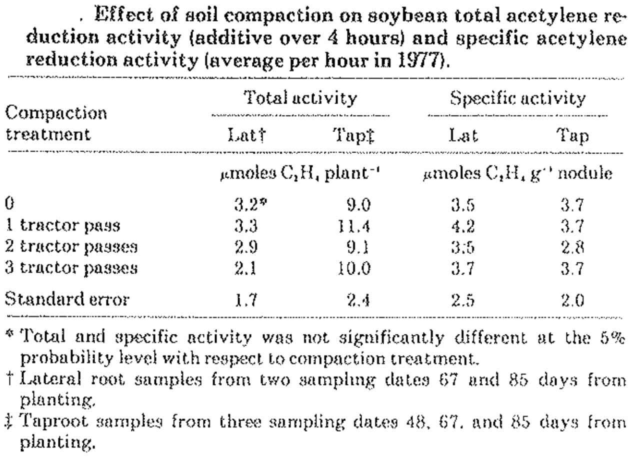
Effect of soil compaction on soybean cumulative nodule number and nodule weight in 1977.

Compaction treatment	Nodule no.		Nodule weight	
	Lat†	Tap‡	Lat	Tap
	plant^{-1}		g plant^{-1}	
0	92 a*	346 a	0.950 a	3.782 a
1 tractor pass	79 a	314 b	0.914 a	3.746 a
2 tractor passes	67 a	277 c	0.737 a	3.682 a
3 tractor passes	68 a	271 c	0.712 a	3.188 b
Standard error	24	22	0.277	0.471

* Means followed by the same letter within each column are not significantly different at the 5% probability level as determined by Duncan's Multiple Range Test.

† Lateral root nodules from two sampling dates 67 and 85 days from planting.

‡ Taproot nodules from four sampling dates 27, 48, 67, and 85 days from planting.



. **Effect of soil compaction on soybean total acetylene reduction activity (additive over 4 hours) and specific acetylene reduction activity (average per hour in 1977).**

Compaction treatment	Total activity		Specific activity	
	Lat†	Tap‡	Lat	Tap
	μmoles C_2H_4 plant^{-1}		μmoles C_2H_4 g^{-1} nodule	
0	3.2*	9.0	3.5	3.7
1 tractor pass	3.3	11.4	4.2	3.7
2 tractor passes	2.9	9.1	3.5	2.8
3 tractor passes	2.1	10.0	3.7	3.7
Standard error	1.7	2.4	2.5	2.0

* Total and specific activity was not significantly different at the 5% probability level with respect to compaction treatment.

† Lateral root samples from two sampling dates 67 and 85 days from planting.

‡ Taproot samples from three sampling dates 48, 67, and 85 days from planting.

(After Lindemann et al., 1982)

Resistance to the pathogen has been identified and effective disease control has been obtained by incorporating race specific, major gene resistance into adapted cultivars (Keeling, 1984).

Gray & Pope (1986) found that subsurface soil compaction increased the severity of Phytophthora root rot in the susceptible cultivar Corsoy. They observed an increase in the number of plants killed by the fungi and a seed yield decrease in compacted vs. uncompacted plots.

The objectives of a study by Moots et al (1988) were to determine 1) if soil compaction would help distinguish resistant from susceptible genotypes in field screening and 2) if isolines with varying degrees of resistance could be separated.

Soil compaction experiments were conducted in Illinois on a silty clay loam soil. The soil had a poor internal drainage and a natural infestation of *Phytophtora*. Compactions were made by tractor on strips by repeatedly driving the tractor over the plots. The compaction treatment increased bulk density from 1.13 to 1.28 g cm^{-3} in 1983 and from 1.15 to 1.27 g cm^{-3} in 1984. The treatments were replicated 3 times in a split-plot arrangement of a randomized complete block design in which the compacted or uncompacted treatments were main plots and cultivars were subplots.

Cultivar effects were highly significant for all variables measured. Disease incidence and number of dead plants increased with compaction while seed weight and total number of plants emerged decreased. Seed yield was not significantly affected by compaction.

Disease incidence (Tab.53) in 1983 and 1984 ranged from 0.0 to 7.67 in uncompacted plots and from 0.10 to 18.95 in compacted plots. Only the susceptible cultivar Sloan had significantly higher disease incidence than the other lines in uncompacted plots, while both susceptible cultivars Sloan and Corsoy had significantly higher values in compacted plots.

Tab. 53 Comparison of disease incidence in compacted and uncompacted plots averaged over planting dates in 1983 and 1984

	Disease incidence[1]					
	1983		**1984**		**2-Year means**	
Cultivar	Uncompacted (%)	Compacted (%)	Uncompacted (%)	Compacted (%)	Uncompacted (%)	Compacted (%)
BSR 201	0.17	0.85	0.33	3.83	0.25	2.34
Century	1.30	0.82	1.67	11.83	1.48	6.33
Corsoy	2.38	9.53	7.67	13.67	5.03	11.60
Corsoy 79	0.42	0.93	2.00	4.00	1.21	2.47
L27	0.00	0.35	0.33	2.83	0.17	1.59
L28	0.25	0.25	0.83	1.83	0.54	1.04
L77-1585	0.28	0.98	1.17	2.50	0.73	1.74
Multiline	0.57	1.0[illegible]	0.67	1.50	0.62	1.25
Sloan	5.92	18.95	7.17	9.67	6.54	14.31
Toku	0.27	0.10	...	...	...	...
Voris 295	0.08	1.20	...	...	...	...
LSD 0.05[2]	3.12	3.12	3.89	3.89	2.57	2.57
LSD 0.05[3]	4.42		5.52		2.57	
Mean	1.06	3.18	2.43	5.74	1.84	4.74

[1] Percent of dead plants to total plants emerged.
[2] LSD for within-compaction comparisons.
[3] LSD for within-cultivar comparisons.

(After Gray & Pope, 1986)

Despite the fact that peas descend from Asia Minor they have not especially high demand for high summer temperatures. This is also due to the fact that their areas of origin are located at rather high altitudes. Normally peas demand an average July temperature just below 20^{0}C in order to yield maximal. Too low summer temperatures, however, give rise to a lengthy vegetative development and weak flowering. Peas are relatively tolerant to low temperatures and are able to stand frost at seedling stage (Askerblad et al., 1984). They possess a high degree of hardiness and can germinate already at + 1^{0}C, which make an early sowing possible.

Concerning the need of precipitation, the situation is a bit more complicated. Peas demand a moderate water supply. During dry years, the root depth becomes a limiting factor and consequently the crop will not be sufficiently developed and yields become low. On the contrary, under wet conditions and especially when compaction is high, the crop can suffer from suffocation which in combination with root rots limits the N– fixation. The result is a stunted, prematuring crop giving rise to a low yield (Pers. observations). According to Berglund (1957) peas are yielding optimal when precipitation during the first two months after sowing amounts to approx. 100 mm (Fig.67) in combination with a normal distribution. Peas are very sensitive to excessive water during the rapening stage. Harvest becomes more complicated, pods splits and the seeds are attacked by fungi (Pers. observations).

Several workers in Britain have quoted marked yield reductions arising from soil compaction by tractor wheelings, especially on headlands, but they have not indicated clearly to what extent these reductions were due to adverse effects on plant population and plant distribution, or to the impaired growth of individual plants that have emerged (Battey & Davis, 1971).

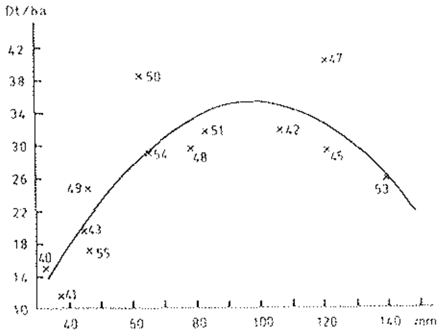


Fig. 67 *Samband mellan skörd och nederbörd 60 dagar efter sådden för Parvus foderärt (Berglund, 1957).*

In 1979 a survey was conducted (Tudor et al., 1981) to establish the importance of soil compaction to the pea industry in England. Several cases of severe compaction were examined and the physiological development of the crop recorded.

According to Tab.54, on average, plant population in wheelings were reduced by more than 50 %; the plants that grew were stunted and the yield of peas reduced by about 65 %.

When the strength of the soil is too great, pea roots are unable to penetrate and ramify through the soil or the hypocotyl may fail to emerge except through occasional large cracks. Fig.68 shows the effect of increasing bulk density on pea growth in a laboratory experiment. The number of lateral roots and plant height were notably reduced at a bulk density of 1.4 g cm^{-3} (Tudor et al., 1981).

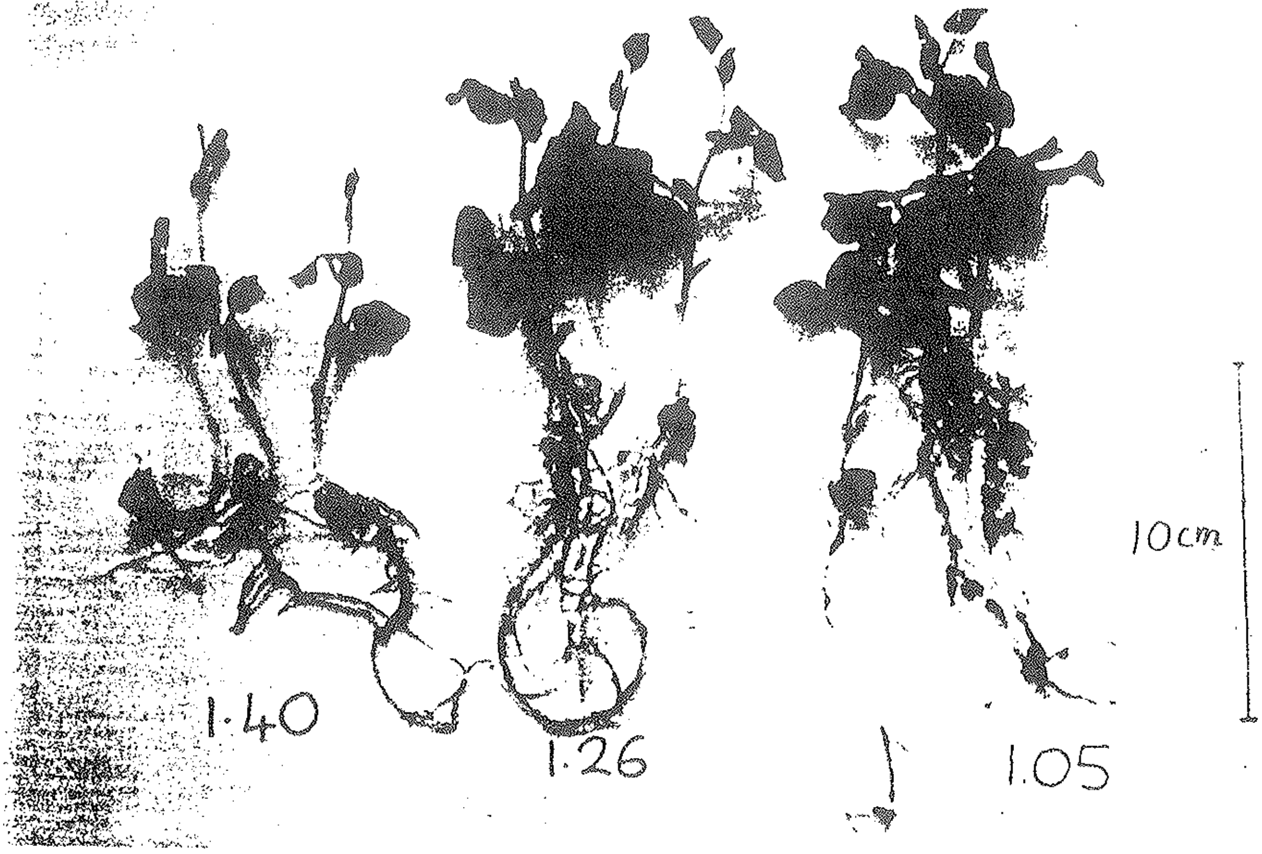


Fig. 68 *The effect of bulk density on pea growth.*

(After Tudor et al., 1981)

Tab. 54 Table of plant components on three dates under wheeled and non-wheeled areas from a commercial field site.

Non-wheeled site				Wheeled site			
Component	**28.5.79**	**13.6.79**	**7.7.79**	**Component**	**28.5.79**	**13.6.79**	**7.7.79**
Plants per m^2	117	117	117	Plants per m^2	52	52	52
Leaf dry wt/m^2 kg	0.062	0.203	0.192	Leaf dry wt/m^2 kg	0.005	0.031	0.058
Stem dry wt/m^2 kg	0.039	0.190	0.379	Stem dry wt/m^2 kg	0.003	0.028	0.096
Root dry wt/m^2 kg	0.019	0.035	—	Root dry wt/m^2 kg	0.002	0.015	—
Root length cm	10.7	—	—	Root length cm	6.3	—	—
Nodule number/m^2	2.644	—	—	Nodule number/m^2	1.258	—	—
Plants HTS cm	28.9	66.1	84.0	Plants HTS cm	9.9	31.7	50.9
Photosynthetic area index	1.8	5.9	7.9	Photosynthetic area index	0.15	0.92	1.91
Dry wt pods per m^2 kg	— —	0.005	0.226	Dry wt pods per m^2 kg	—	—	0.100
Peas/pod	—	—	8.27	Peas/pod	—	—	5.04
Yield peas/m^2 TR 105 kg	—	—	2.09	Yield peas/m^2 TR 105 kg	—	—	0.86

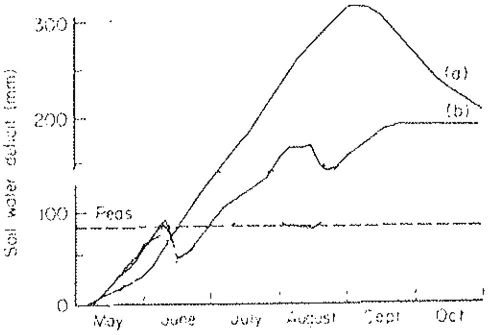
(After Tudor et al., 1981)

In an experiment where the influence of soil structure was investigated on yield of peas, a yield comparison was made between a soil which had been continuously cultivated for more than 100 years and an old pasture, which was newly ploughed (Low, 1973). Soil type, fertilizing and other conditions were equivalent. The new field yielded 4000 kg ha^{-1}, compared to the old field, which only yielded 1250 kg ha^{-1}. The difference in yield can probably not only be attributed to soil structure effects, since soil borne pathogens may have had a considerable influence (Pers. comment). However, the newly tilled soil showed a bulk density of only 1.1 kg cm^{-3} compared to 1.5 kg cm^{-3} in the old field. Aggregate stability showed to be nearly 4 times higher in the newly tilled soil.

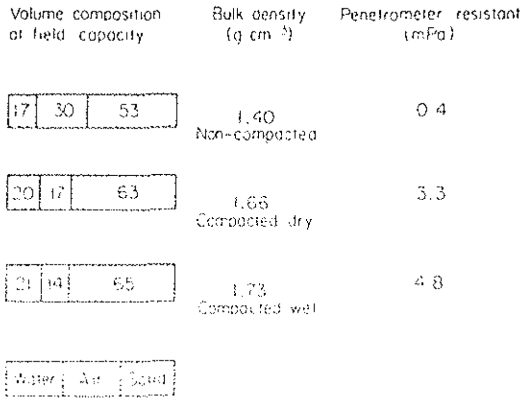
In an experiment by Hebblethwaite & McGowan (1980) the objectives were designed to study the ways by which compaction affected growth and development of peas in 1976–1977 from sowing through final harvest. Information was obtained on emergence, growth and development, water use and components of final yields. An additional treatment was included in which plants grown on non-compacted soil were thinned to population density and distribution similar to that of the compacted area, so that effects on final yields of altered population and performance of individual plants might be distinguished.

Shortly after sowing, a tractor was moved across strips of land to create plots which had been compacted by each rear wheel side by side comprising several passes. For the "dry compacted" treatment, the seedbed was compacted immediately after sowing before the soil was wetted by irrigation. For the additional "wet compacted" treatment, the soil was first irrigated after sowing and then compacted the following day. Thus, all treatments, including controls, received the same amount of water. Plots were then sheltered until full emergence. 3–6 weeks after emergence non-compacted thinned populations were prepared by thinning out non-compacted areas to a population and distribution similar to that of the compacted dry plots.

According to the report, the 1976 growing season was the driest, sunniest and hottest growing season at the Experimental site since records were first kept in 1916. Most crops suffered severe moisture and heat stress. In 1977, during the growing season, rainfall was generally equal to or greater than long term average. Fig.69 compares potential soil water deficits for 1976–1977 with the estimated soil water available within maximum root range of peas. Fig.70 shows the bulk density, pore space and penetrometer resistance for the 1977 pea crop.



Potential soil water deficits for three seasons and estimated soil water reserves for peas (a) 1976, (b) 1977.

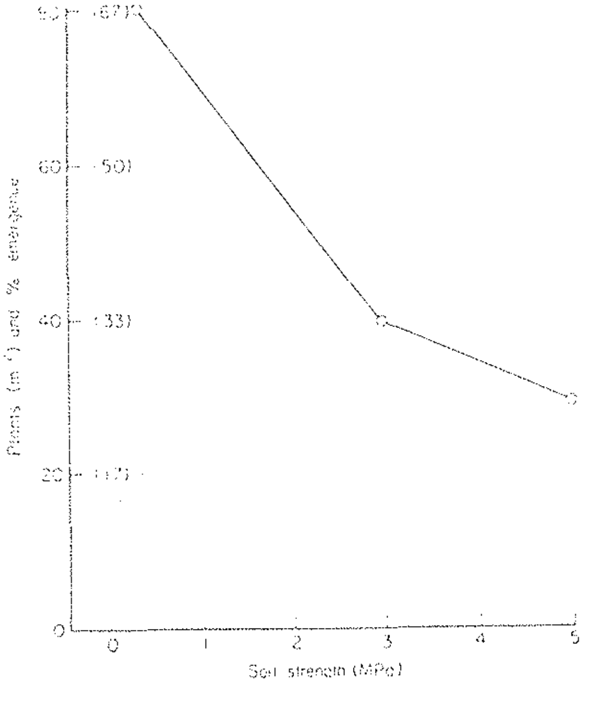


The effects of compaction treatments (1977) on soil physical conditions, 0-10 cm depth.

Figs. 69 & 70

(After Hebblethwait & McGowan, 1980)

According to Fig.71, emergence was closely related to penetrometer values. However, it is doubtful if this can be taken as a direct causal relationship. Taylor et al. (1966) found that the emergence of monocot plants were closely related to the strength of soil as determined using a penetrometer. Dicots, such as peas, have a larger surface area which has to be forced through the soil, which makes them more susceptible to soil compaction (Hanks & Thorpe, 1957).



Emergence of peas (1976) in relation to penetration resistance.

Fig. 71
(After Hebblethwait & McGowan, 1980)

Final yields of dried peas, per plant and per unit area, are given in Tab.55. Interesting to note is that compensation by tillering, and hence pods per plant, of the thinned population in non–compacted soil had proceeded to such a degree as to out–yield even the non–compacted control plots. Possibly plants in control plots were restricted by interplant competition. Had there been no data for non–compacted thinned treatments, one might have concluded that compaction reduced yield and its components through decreased population. However, comparison with non–compacted thinned treatments indicates that the inability of plants growing in compacted soils to make compensatory growth is also important.

Tab. 55 Dry yield and yield components at dried pea stage for Vedette in 1976 and Sprite in 1977

	Plants (m^{-2})		Pods per plant		Peas per pod		Pea weight (mg)		Dry yield of peas per plant (g)		Dry yield of peas ($g\ m^{-2}$)	
Treatment	1976	1977	1976	1977	1976	1977	1976	1977	1976	1977	1976	1977
Compacted wet	74	26	2.0	4.6	2.3	5.1	157	314	0.6	7.4	49	192
Compacted dry	100	30	2.4	5.2	2.3	5.8	139	288	0.8	8.5	82	256
Non-compacted thinned	—	34	—	12.4	—	5.6	—	303	—	21.5	—	731
Non-compacted control	112	64	2.4	5.2	2.6	4.6	150	279	0.9	6.8	99	423
l.s.d.[a]	16	12	0.5	4.1	0.4	1.0	36	39	0.3	2.1	9	251

[a] Least significant difference ($P < 0.05$).

(After Hebblethwait & McGowan, 1980)

While most studies report on effects of soil compaction on plant root and shoot growth and yield, few investigators have been concerned with plant nutrient uptake in compacted soils. Especially concerning leguminous crops there is an evident lack of information regarding interaction effects between soil compaction and plant nutrient uptake. Reports on combined effects between soil compaction, nutrient uptake and root rots in leguminous crops are more or less non– existing (Pers. comment).

Anyhow, in a laboratory study by Castillo et al. (1981) the objective was to determine if compacting soil around the roots of growing pea plants affected dry matter production, rooting characteristics and nutrient uptake.

Soil cores were formed from <2mm sieved aggregates of the 0–15 cm horizon of a loam soil and packed to bulk densities of 1.16 and 1.30 g cm^{-3} (Fig.72) and exposed to an external pressure of 0, 90, 179 and 269 kPa throughout the experimental period. The experimental design was a randomized block with 4 replications.

Final bulk densities after applying external pressures are seen in Tab.56. Shoot weight, root length and root weight were all decreased after applying stresses of 90, 179 and 269 kPa (Tab.56).

Data reported in Tab.57 show that K and Mg uptake were reduced when external pressures were applied to the root system. Calcium uptake followed a similar trend. No significant reduction in Mn uptake was observed at the highest level. Copper uptake, on the contrary, was increased with the application of mechanical stress. No significant effects were observed for B, Fe, P and Zn uptake.

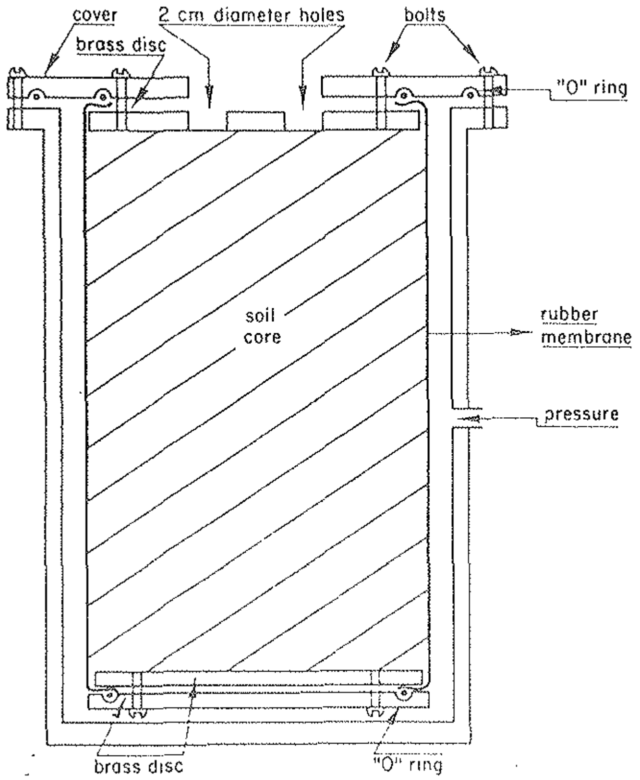


Fig. 72 Schematic diagram of pressure cell used to grow pea seedlings. (After Castillo et el., 1982)

Bradford (1980) showed a 50 % reduction in pea seedling root length when the soil water matric potential of soil cores with a silt loam was reduced from −10 to −33 kPa. Penetrometer resistance increased from 1240 to 1290 kPa at the same time. The elemental compositions of plant shoots from the experiment are reported in Tab.58. Significant decreases in uptake were shown by K and Fe but not by other elements.

Tabs. 56 & 57 **Effects of applied external stress and soil bulk density of pea shoot and root growth.**†

Applied stress	Soil bulk density Initial	Soil bulk density Final	Shoot weight	Root length	Root weight	Root length to root weight ratio
kPa	g/cm³	g/cm³	mg/core	cm/core	mg/core	m/g
0	1.16	1.16	115	478	26.3	190
	1.30	1.30	115	424	23.3	183
90	1.16	1.28	123	275	24.5	116
	1.30	1.35	118	233	22.3	107
179	1.16	1.38	75	66	14.3	46
	1.30	1.40	73	74	15.0	50
269	1.16	1.47	68	61	12.8	47
	1.30	1.46	65	58	13.8	43

† Each value is the average of four observations.

Effects of applied external stress and soil bulk density on the nutrient composition of pea shoots.†

Stress applied	Soil bulk density Initial	Soil bulk density Final	B	Ca	Cu	Fe	K	Mg	Mn	P	Zn
kPa	g/cm³	g/cm³	mg/g	mg/g	mg/g	mg/g	μg/g	μg/g	μg/g	μg/g	μg/g
0	1.16	1.16	211	19.6	254	1,550	2.92	0.73	27.8	0.56	51.1
	1.30	1.30	208	17.9	279	1,440	2.84	0.70	26.8	0.55	49.0
90	1.16	1.28	212	14.4	458	1,690	2.55	0.61	22.0	0.53	46.6
	1.30	1.35	225	14.3	436	2,560	2.51	0.61	23.0	0.58	52.6
179	1.16	1.38	231	12.1	390	1,700	2.18	0.49	21.4	0.51	47.9
	1.30	1.40	204	12.5	438	1,820	1.99	0.57	22.2	0.51	44.2
269	1.16	1.46	236	12.8	323	1,770	2.15	0.49	25.4	0.55	43.0
	1.30	1.47	218	12.8	342	1,560	1.99	0.49	25.7	0.52	41.7
SE‡			14.2	0.99	38	384	0.187	0.034	2.15	0.036	5.78

(After Castillo et al., 1981)

Tab. 58 Pea nutrient uptake as affected by soil water potential in natural cores of a B_3 silt loam soil.

Soil water potential	B	Ca	Cu	Fe	K	Mg	Mn	P	Zn
kPa	mg/g				µg/g				
0	198	15.6	104	6.780	1.07	0.41	51.1†	0.53	312†
−3	198	14.2	101	5.230	1.08	0.36	64.3	0.70	189
−10	208	14.9	108	4.960	1.02	0.36	68.7	0.68	109
−33	211	13.8	89	3.340	0.80	0.35	115.9	0.68	284
−100	217	13.9	86	3.000	0.79	0.38	118.5	0.67	144
F (ratio)	(NS)	(NS)	(NS)	6.5**	7.1**	(NS)	(NS)	(NS)	(NS)

** Significant at the 0.01 level.
† Great variability among observations in same treatment.

(After Bradford, 1980)

In a case study by Grath & Håkansson (1992), 11 fields in the province of Halland in southwestern Sweden were included. After a rainy period in first part of July pea fields developed a patchy, premature yellowing and wilting in a pattern pointing out machinery-induced soil compaction as a major reason. The highest frequency of yellow patches was observed on headlands, in wheel tracks of heavy machines or in small depressions where the soil had been relatively wet during seedbed preparation and sowing.

The sampling was carried out by the end of July, when the pea crop was in the middle of the pod-filling stage. In each sampled field one plot with healthy, green peas (G) and one with yellowing peas (Y) were selected as close to each other as possible. Within each plot core samples were taken out (depth 10–15 cm) for determination of total and air filled porosity. Number of nodules on main roots were counted and occurrence of nodules on lateral roots was assessed subjectively on a scale with 0 = no occurrence and 5 = very abundant occurrence. In five of the sites the above-ground part of the crop was harvested and analyzed regarding dry matter, nutrient uptake and concentration.

Based on Fig.73, it may be assumed that the plough layer in the investigated fields had a water content below field capacity during most of May and June. After heavy rainfalls in late June and early July the soil became fully saturated for a period of about two weeks. Especially in compacted plots with a low saturated hydraulic conductivity, the top soil for a period probably had a water content above field capacity.

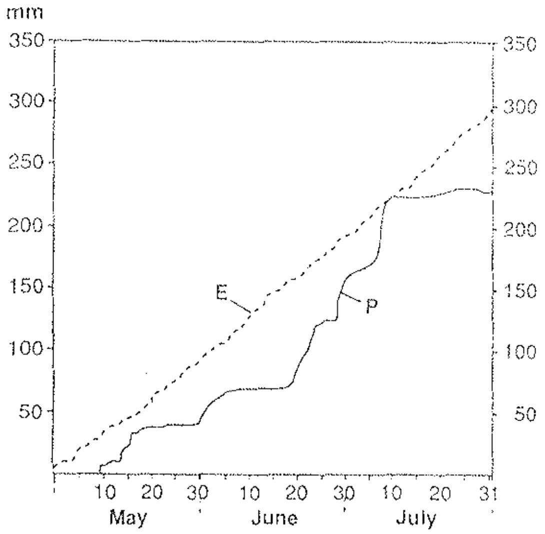


Fig. 73 Cumulative values of precipitation (P) at Halmstad and potential evaporation (E) at Torup for May, June and July, 1990.

(After Grath & Håkansson, 1992)

Total porosity was generally lower (Tab.59) in Y than in G, and in most cases, air-filled porosity was also considerably lower.

The number of *Rhizobium*-nodules both on main and lateral roots was significantly lower in Y than in G (Tab.60), which reduced N fixation (Tab.61). N concentration was reduced by more than 50 % and total amount of N, P, K and S was reduced by 70–37 %. Interesting to notice is that the Mn concentration increased in compacted plots (Rel. 144 in Y compared to G). The same was true in the experiment by Bradford (1980; Tab.58). This might be explained by the Mn Ox/Red situation in the soil during anaerobic conditions, which is discussed above. In all probability, differences in root disease infestation have occurred, which accentuated the effects, but this was not investigated.

Tab. 59 *Soil texture, total porosity (n, % v/v) and air-filled porosity (a, % v/v) at various matric water tensions in G and Y plots at the individual sites*

Site number, texture and crop appearance[1]		n	a at a tension of (hPa)		
			25	100	1 000
1. Sandy loam	G	51.1	13.8	19.3	23.5
	Y	39.9	4.4	6.1	12.1
2. Loam	G	51.3	7.0	14.3	21.1
	Y	50.6	7.3	11.6	20.4
3. Sandy loam	G	52.6	11.9	18.9	25.8
	Y	51.9	8.4	16.3	25.1
4. Sandy loam	G	43.3	7.5	10.7	14.0
	Y	40.4	6.1	7.1	10.3
5. Sa clay loam	G	52.3	15.0	17.4	21.4
	Y	43.8	4.9	6.6	10.5
6. Sa clay loam	G	49.0	7.0	10.4	15.7
	Y	42.3	3.9	5.7	11.7
7. Sandy loam	G	57.4	7.3	10.9	17.5
	Y	46.6	1.6	2.3	7.6
8. Sandy loam	G	45.5	3.0	4.6	9.1
	Y	46.1	4.8	7.0	10.7
9. Sandy loam	G	43.4	4.7	6.2	10.3
	Y	40.1	3.7	5.3	10.3
10. Loamy sand	G	56.8	10.4	12.1	16.7
	Y	52.0	11.1	14.3	18.5
11. Loamy sand	G	40.7	7.2	19.8	25.1
	Y	35.6	6.3	12.3	17.5
Mean values	G	49.4	8.6	13.1	18.2
	Y	44.5	5.7	8.6	14.1
LSD ($p < 0.05$)		2.7	2.7	3.4	3.4

[1] G = green peas; Y = yellowing peas.

(After Grath & Håkansson, 1992)

In another study by Grath & Håkansson (1992), the investigation was concentrated to a 37 ha field with a clay loam soil. The field became extremely patchy in July after heavy rainfalls during the second part of June with areas of green (G), yellow (Y) and brown (dieing) peas (B). The final yield in the field was only 2000 kg ha^{-1} compared to a 5-year average for the farm of 4200 kg ha^{-1}. The study comprised 6 sampling sites, each consisting of one G-, one Y- and one B-plot.

In mid August, within each plot, plant height, number of pods per plant, root depth, max. nodulation depth and number of nodules on main and lateral roots were determined (Tab.62). Frame sampling for determination of porosity and degree of compactness in the plough layer was carried out, but data are not yet available. Anyhow, during field work it was observed that soil strength increased from G over Y to B. Determination of the degree of infestation with regard to the root rot complex was undertaken, averagely resulting in indexes of 18 (G), 55 (Y) and 54 (B), respectively, on a 0–100 scale. Values below 30 are considered to be safe for pea cultivation. Values exceeding 51 are considered to be so harmful to the crop, that pea cultivation strictly is discouraged.

Tabs. 60 & 61

Average number of Rhizobium-nodules on the main roots and subjectively assessed occurrence (scale 0–5) of nodules on the lateral roots in G and Y plots

	G[1]	Y[1]	Rel[2]	LSD ($p<0.05$)
Main roots	7.86	3.05	39	2.14
Laterals	3.82	2.09	55	0.80

[1] G=green peas; Y=yellowing peas.
[2] Relative values in Y (G=100).

Dry matter (DM) and plant nutrient content in the aerial parts of plants from G and Y plots at sites 1, 4, 7, 8, and 11

	Concentration				Amount			
	G[1]	Y[1]	Rel.[2]	LSD ($p<0.05$)	G[1]	Y[1]	Rel.[2]	LSD ($p<0.05$)
	% of DM				kg ha^{-1}			
DM					8 780	5 240	60	n.s.
N	2.35	1.12	48	0.44	196	58	30	92
P	0.27	0.16	60	0.10	21.4	8.8	41	9.0
K	2.10	1.17	56	0.43	185	65	35	116
S	0.21	0.19	95	n.s.	17.5	11.1	63	n.s.
Ca	1.31	1.15	87	n.s.	126	63	49	n.s.
Mg	0.20	0.21	106	n.s.	17.1	11.2	66	n.s.
	ppm of DM				g ha^{-1}			
Fe	259	285	110	n.s.	2 200	1 460	66	n.s.
B	19.4	15.0	77	n.s.	176	81	46	n.s.
Mn	27.8	40.0	144	n.s.	250	205	82	n.s.
Zn	35.2	18.8	53	13.8	306	99	32	n.s.
Cu	7.3	5.2	71	1.9	63	28	44	n.s.

[1] G=green peas; Y=yellowing peas.
[2] Relative values in Y (G=100).

(After Grath & Håkansson, 1992)

According to Tab.62, number and frequency of nodules were reduced compared to G and max. nodulation depth was also considerably affected. Nutrient concentrations of N, P and K were all reduced, while the concentration of Fe, Mn and Al all remarkably increased, which partly is in line with earlier observations, especially concerning Mn.

Pea yield losses due to high root rot infestation levels in compact soils was i.a. observed by Burke et al. (1969). Batey and Davies (1971) reported possible additative effects of fungus infection and high bulk density on pea yield losses. Root rot, principally caused by *Fusarium solani* (Mart.) Appel + Wr. f. sp. pisi (F. R. Jones), can reduce yields by up to 57 % (Basu et al. 1976). Root rot has been found to be more prevalent and to have more effect on plants in compacted soils and the organisms can survive in the soil for many years.

Tab. 62 *Mean plant height, number of pods per plant, root depth, maximum nodule depth, number of nodules in the upper 10 cm of the root system, contents of dry matter and plant nutrients in the aerial parts of the plants, and root rot index in G, Y and B in 6 sites in one field in 1991.*

	G	Y	B	Y rel[1]	B rel[1]	LSD
Plant height, cm	139	80	10	58	7	66
Number of pods per plant	6.3	2.1	0	33	0	0.9
Root depth, cm	56	-	17	-	30	19
Max. nodulation depth, cm	31	9	0	30	0	16
Number of nodules on main roots	15.8	15.1	0	96	0	4.9
Number of nodules on lateral roots	9.6	5.2	0	54	0	5.1
Dry matter, kg ha^{-1}	7571	4185	744	55	10	3588
N, %	2.67	1.51	2.09	56	78	0.65
kg ha^{-1}	204	65	16	32	8	111
P, %	0.28	0.20	0.22	70	77	n.s.
kg ha^{-1}	21	9	2	40	8	12
K, %	1.84	1.21	1.05	66	57	0.22
kg ha^{-1}	141	51	8	36	5	73
Fe, ppm	156	161	709	103	454	183
Mn, ppm	18	15	49	83	276	21
Al, ppm	78	96	430	124	554	104
Root rot index	22	55	54	245	242	14

[1] Relative values in Y or B; G = 100

(After Grath & Håkansson, 1992)

In north eastern part of the US– the most widespread canning pea district in the world– pea root rot caused by *Aphanomyces* is regarded to be the most important disease. The average yearly loss due to *Aphanomyces* is estimated to 10 % (Stamps, 1978).

In Sweden, pea root rot caused by *Aphanomyces*, was first observed in canning and freezing pea areas. Fig.74 describes areas of actual known infestations.

At the time of infestation the fungus invades the cortex which becomes discoulored (Engqvist, 1985). Root hairs and finer roots become rotten as well as root necks (Figs.75,76). The inability for the damaged root to supply the plant with water and nutrients results in a depressed growth and the crop prematures. The root rot makes the plants sensitive to drought and the fungus also inhibits the establishment of the nodule bacteria, and at high levels of infestation even nodules are destroyed. This leads, among other things, to a lowered protein content of the seed (Engqvist, 1985).

High soil water content is important for the development of *Aphanomyces* and this in combination with soil compaction fortifies the damage situation (Burke et al., 1969). It appears that root rot increases in compacted soils, because the roots are unable to penetrate the infested upper layer and grow down into deeper areas of the soil (Miller & Burke, 1974). It has been found that even if infestation levels are high, the plants are not as severely affected in less compact soil as they are in a denser soil (Burke & Kraft, 1974). This could be attributed to two things; either the level of infestation in the deeper soils is much lower or the plants are more able to compensate for the root damage because their root surface area is increased (Miller & Burke, 1974).

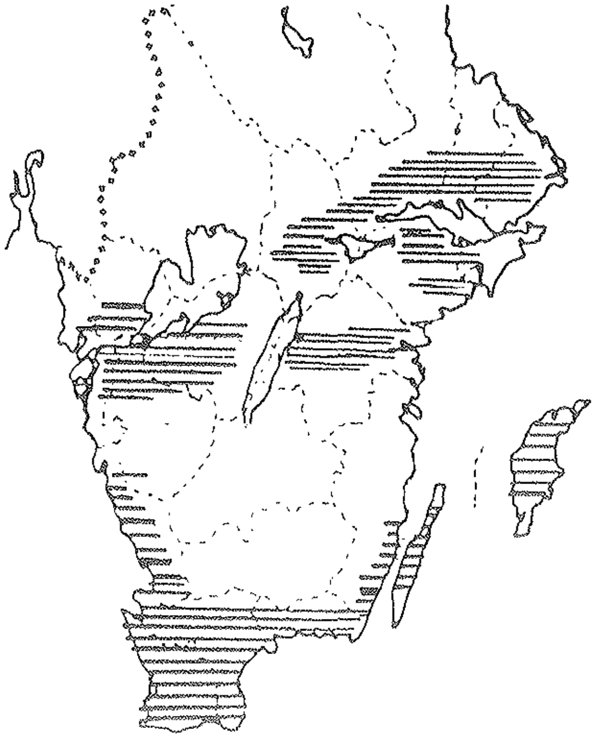


Fig. 74 Känd förekomst av svampen **Aphanomyces euteiches.**
(After Engqvist, 1985)

Yield losses of 50 % or more are observed in heavyly infesteted fields in Sweden. Soil structure damages and oxygen deficiency are in most cases reported as causes, but the importance of the fungus has been neglected (Eckerbom, 1985).

In an experiment by Raghavan et al. (1982) a study was designated to the effects of measured levels of compaction on the growth and yield of green peas grown in a field with a known history of root rot. At the same time, a companion experiment in a field where peas had never been grown was performed. The two sites selected for field trials were a clay loam soil with a history of pea root rot and a clay soil. No peas had ever been grown at the latter site.

In both fields, plots were set up as a randomized complete block design and were subjected to measured cumulative ground contact pressures ranging from 0 to 690 kPa, using tractors exerting ground contact pressures per pass of 34, 41 and 46 kPa.

The overall percentage emergence of peas was low at both locations (Tab.63). The clay loam field had a maximum percentage of seedlings emerged of 59 % observed in the 1R (34–kPa) treatment. The minimum of 26 % seedlings emerged was in the 15Q (690–kPa) treatment. The clay soil had even lower rates with 23 % and 29 % seedling emergence, respectively, in compacted and uncompacted plots.

The root rot index, calculated according to Basu et al. (1976), was highest in the heavily compacted plots of both soils. Vine length generally decreased with increasing compaction level (Tab.63). The longest vines in both soils were in uncompacted plots.

Ärter odlade i jordprov från icke infekterat fält (till vänster) och från ett fält med stark infektion av svampen Aphanomyces euteiches (till höger).

Figs. 75 & 76
(After Engqvist, 1985)

Frisk planta längst till vänster och därefter plantor med ökande angrepp av ärtrotröta.

Yield results showed the most dramatic decreases. On the clay loam, contact pressures of 46 kPa, with passes of greater than one, and 34 kPa with passes greater than five resulted in virtual elimination of pea yield. The yields in the clay soil were all very low. Fig.77 shows the profiles of soil bulk density for all treatments. Most of the effect of compaction was in the top 0.075 m for both soils.

Tabs. 63 & 64 AVERAGE VALUES FOR PERCENTAGE SEEDLING EMERGENCE, ROOT ROT INDEX, VINE LENGTH AND DRY YIELD

Treatment	Cumulative contact Pr. (kPa)	% plants emerged	Root rot index	Vine length, (m)	Dry yield (kg/ha)
			Clay-loam soil		
000	0	54 *a*	72 *ab*	0.462 *a*	560 *a*
1†Q‡	46	54 *a*	72 *ab*	0.321 *b*	342 *b*
1R	34	59 *a*	60 *b*	0.316 *b*	328 *b*
5Q	230	44 *ab*	82 *a*	0.214 *cd*	0 *c*
5R	170	36 *bc*	76 *ab*	0.270 *bc*	40 *c*
10Q	460	30 *bc*	84 *a*	0.194 *d*	0 *c*
10R	340	27 *c*	89 *a*	0.195 *d*	0 *c*
15Q	690	26 *c*	84 *a*	0.184 *d*	0 *c*
15R	510	31 *bc*	89 *a*	0.215 *cd*	0 *c*
			Clay soil		
000	0	29 *a*	52 *a*	0.666 *a*	185 *a*
5Y	206	23 *a*	48 *a*	0.561 *ab*	161 *a*
15Y	618	23 *a*	.52 *a*	0.444 *b*	79 *a*

†Number of passes.

‡Contact pressure: Q = 46 kPa; R = 34 kPa; Y = 41 kPa.

a-d Letters denote significance at 5% level using Duncan's new multiple range test. Means with the same letter are not significantly different.

YIELD LOSSES RESULTING FROM INCREASES IN SOIL BULK DENSITY AND ROOT ROT INDEX

Dry density (Mg/m^3)	Yield (kg/ha) ($R_D=0$)	Yield loss due to $\Delta\gamma$ (%)†	Yield (kg/ha) ($R_D=50$)	Yield loss from total potential (%)‡	Yield loss due to root rot (%)	Yield ($R_D=90$)	Yield loss from total potential (%)‡	Yield loss due to root rot
				Clay-loam soil				
1.20	1340	29	965	49	20	666	65	36
1.30	1108	42	733	61	20	434	77	36
1.40	885	53	510	73	20	211	89	36
1.50	676	64	301	84	20	2	100	36
1.60	480	75	105	95	20	0	100	25
1.70	296	84	0	100	16	0	100	16
				Clay soil				
1.00	221	0						
1.10	165	25						
1.20	113	49						
1.30	66	70						

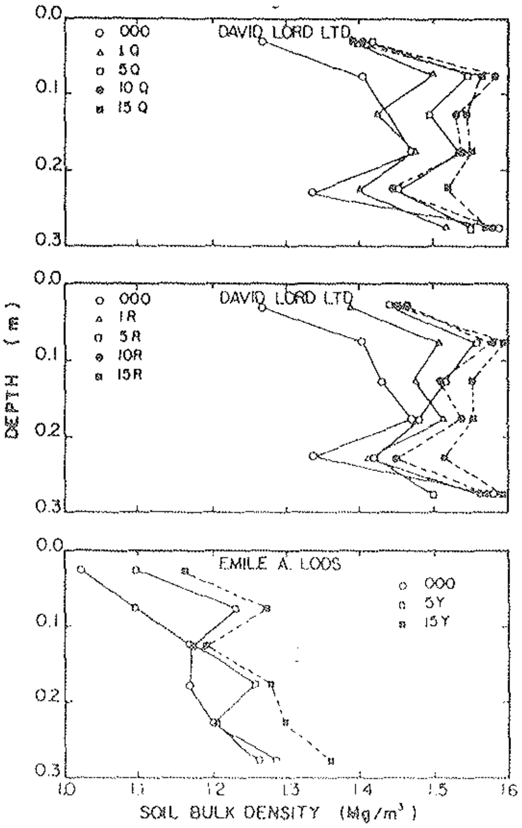
†No yield loss expected at $\gamma = 1.0$ Mg/m^3 and potential yield → 1899 kg/ha for David Lord Ltd., and 221 kg/ha for Emile A. Lods.

‡Net effect for both γ and root rot

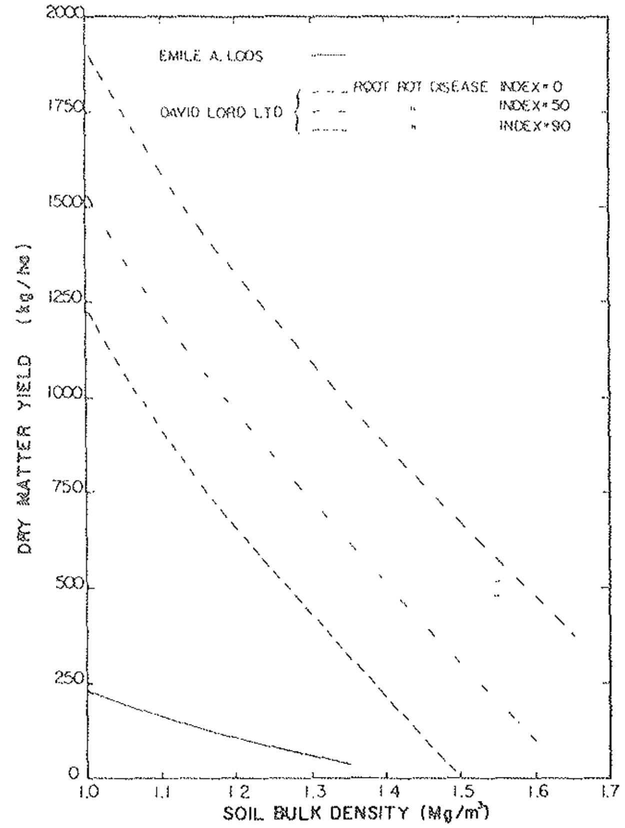
(After Raghavan et al., 1982)

Fig.78 shows relationships assuming root rot indices of 0, 50 and 90. Soil bulk density actually had more effect on yield in both fields than did the degree of root rot. In the clay loam, the effect of the root rot increased slightly with increasing soil bulk density. Tab.64 shows the yield losses resulting from increases in bulk density and root rot index. As the soil bulk density increased from 1.0 to 1.7 in the clay loam soil the yield fell from a potential of 1899 kg ha^{-1} to 0 kg ha^{-1}, meaning a 100 % reduction, but with a root rot index of 90, the maximum loss in yield was only 36 %.

The results of this study showed that peas are a sensitive crop, susceptible to increases in soil bulk density and to root rot.



Profiles of mean soil bulk density with depth for the treatments studied.



Figs. 77 & 78 Plot of yield of peas vs. soil bulk density for increasing levels of root rot index.

(After Raghavan, 1982)

SUMMARY AND PERSONAL COMMENTS

This report is aimed to describe effects of soil compaction and anaerobiosis on physical, chemical and biological soil properties and crop production. A comprehensive literature search has been undertaken in order to cover research done during the last twenty years or so. The report deals with fields of research directed towards the function of soil and root, mechanical impedence and penetration by roots, effects of anaerobic soil conditions, losses of soluble compounds, response of plants to anaerobic conditions and effects of compaction on nutrient uptake in mono- and dicots.

Soil compaction is a serious problem in modern agriculture caused by several practices, primarely through use of heavy machinery and also by continuous cropping, inorganic fertilizer application and a reduction in use of green and animal manures (Raghavan et al., 1979). The latter results from the replacement of mixed farming by large-scale cash crop farming and consequently, soil organic matter continues to be depleted, soil texture and moisture holding capacity degraded and soil compaction increased (Tu & Tan, 1991). Increased soil compaction is associated with increased bulk density and soil strength, and decreased aeration, porosity and water retention capacity (Sills & Carrow, 1982).

Compaction of soil has been shown to reduce growth of many plant species (Trouse, 1971). It reduces bean and pea biomass and yield and also increases root rot incidence and severity (Tu & Tan, 1988; Grath & Håkansson, 1992). Burke et al. (1972) showed that working the soil to reduce compaction could reduce bean root rot. Apparently, soil compaction predisposes roots to infection by soil pathogens and also limits root generation and replacement (Voorhees et al., 1971). Soil compaction has also been shown to reduce photosynthesis in plants (Tu & Tan, 1988), as well as nodulation and nodule efficiency in legumes (Tu & Buttery, 1988; Grath & Håkansson, 1992). These phenomena are expected because compaction can effectively reduce aeration (Grobbelaar et al., 1971), soil moisture and soil temperature (Sprent, 1971). All these factors affect the normal physiology of a plant. There is evidence that compaction can reduce N utulization by 10–31 % as compared to uncompacted soil (Sills & Carrow, 1982).

One method to consider how the soil environment is able to affect crop development can be described by Fig.79 (Håkansson, 1992). The diagram tries to explain how a soil air content of 10 % (v/v), which is frequently mentioned as a lower limit for adequate aeration, and a penetration resistance of 2.5 MPa, usually regarded as critical limits with respect to plant growth are related to the degree of compactness and matric water tension of the top soil.

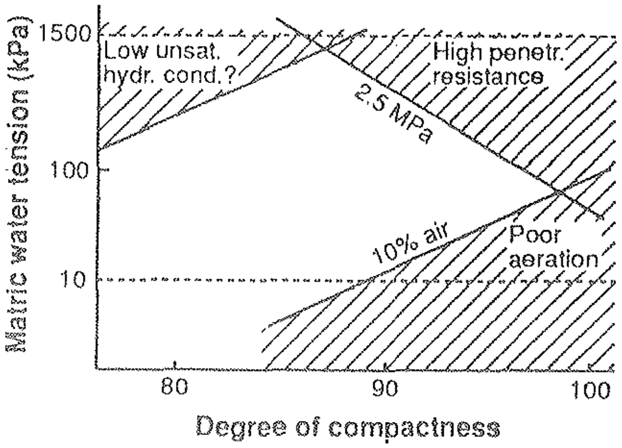
At a water matric tension of 10 kPa (field capacity) the soil contains more than 10 % air if the degree of compactness (D) is lower than 87, and less than 10 % if D is higher. The higher the D-value the higher is the water tension and concequently, the lower the water content at which aeration becomes critical. At 1500 kPa (wilting percentage), the penetration resistance exceeds the critical value of 2.5 MPa when D exceeds about 85, and the higher the D-value the higher is the water content at which penetration resistance becomes critical. Only when D is about 85, neither soil aeration nor penetrability becomes critical within the 10–1500 kPa tension range. Important conclusions which can be drawn from the figure are:

1. In a moisture situation represented by the unshaded area in the diagram, crop growth is possible even if D is high.

2. At a low matric tension in combination with increasing D–value, the crop will suffer from anaerobiosis (shaded area in the lower right corner). For leguminous crops like peas another problem now arises, namely the proliferation of root rot fungi, which aggravates and complicates the situation.

3. At high D–values in combination with high matric tension, root growth is restricted due to high penetration resistance (upper right corner). Root penetration depth will here be depending on the ability of the crop to force compacted layers, which can differ between different species.

4. During very loose soil conditions and if the growing season is dry the crop will be affected by a too low unsaturated hydraulic conductivity and/or poor root–to–soil contact causing too slow uptake of water and nutrients. This situation is represented in the upper left corner.



Schematic diagram showing how a soil air content of 10 % (v/v) and a penetration resistance of 2.5 MPa, usually regarded as critical limits with respect to plant growth, are related to the degree of compactness and matric water tension of the plough layer.

Fig. 79
(After Håkansson, 1992)

While most studies reported plant shoot and root growth as influenced by water potential, soil strength or aeration, very few investigators have been concerned with plant nutrient uptake in compacted soils. This is especially noticeable with regard to dicots. Only one report was found directed to leguminous crops except works in progress by Grath & Håkansson (Grath & Håkansson, 1992; T. Grath & I. Håkansson, 1993, unpublished results).

Cultural practices such as crop rotation, tillage in growing crops, incorporation of residue, mulching and cover cropping could prevent and alleviate soil compaction (Lal, 1984).

The area of pea cultivation in Sweden has been drastically reduced during the last two years This is partly due to the uncertainty to grow this crop as demonstrated by low yields in 1991 and 1992, originating from high precipitation at sensitive plant development stages. This in combination with soil compaction and root rot lead to prematured, stunted crops and concequently low yields.

It would be attractive to grow more peas, because of the many advantages this crop yields. The high protein content of the seed makes it possible to reduce the import of soybean and the value of the pea crop as a preceding crop especially in grain dominated districts is well documented due to its ability to fix nitrogen, which partly can be utulized by the subsequent crop. The coarse and deep growing root system also affects the soil structure in a favourable manner.

More research of multidiciplinary character directed to interaction effects between soil compaction, root rot diseases and nutrient uptake would be appreciated in order to try to overcome present obstacles in the cultivation of peas. A breeding programme in order to find resistant genes against pea root rot would be of value. Such research has given positive results abroud as mentioned above. A joint venture between scientists specialized in soil science, plant nutrition, plant pathology, genetics, microbiology and physiology should probably give rise to fruit-bearing results, which could be used in the practical advisory service to pea growing farmers.

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