AGRICULTURAL AND FOOD SCIENCE IN FINLAND

Vol. 8 (1999): 333–351.

Review

Subsoil compaction due to wheel traffic

Laura Alakukku

Department of Agricultural Engineering and Household Technology, PO Box 27, FIN-00014 University of Helsinki, Finland. Current address: Agricultural Research Centre of Finland, Crops and Soil, FIN-31600 Jokioinen, Finland, e-mail: laura.alakukku@mtt.fi

The article reviews those major soil properties and traffic factors, which together influence subsoil compaction resulting from the passage of agricultural vehicles. Likewise, the effects of subsoil compaction on soil properties, processes and crop growth are discussed on several levels, from methods of measuring to the persistence of compaction effects. The risk of subsoil compaction exists whenever moist soils are loaded with heavy axle load and moderate to high ground contact stress. Subsoil compaction tends to be highly persistent. To avoid the risk of long-term deterioration, limits for the induction of mechanical stresses in the subsoil should be established through international teamwork.

Key words: axle load, ground contact stress, long-term effects, soil physical properties

Introduction

Soil compaction has become a problem of major proportions in agriculture to day (Soane and Ouwerkerk 1994a) causing reduced yield, economic and environmental damage and poorer soil workability. According to Håkansson (1994a), the harmful compaction of arable soils is mainly attributable to wheel traffic where heavy machines are used in unfavourable soil conditions. As mechanization has intensified, machinery power and weight and implement size have increased. As an example, the increase in power and weight of newly sold tractors in Finland during 1976—1996 is shown in Fig. 1. In Germany, the proportion of newly registered tractors larger than 44 kW jumped from 33% in 1976 to 77% in 1992 (Renius 1994). In the United States the average power of new tractors increased from 60 to 85 kW between 1973 and 1986 (Eradat Oskoui and Voorhees 1991), and the gross weight of a 85 kW tractor was 6 Mg. Today in the United States, agricultural tractors commonly have a total weight of 20 Mg. Likewise, in Western Europe, fully loaded combine and sugar beet harvesters may weigh more than 20 and 35 Mg, respectively, and slurry tankers

Manuscript received June 1999

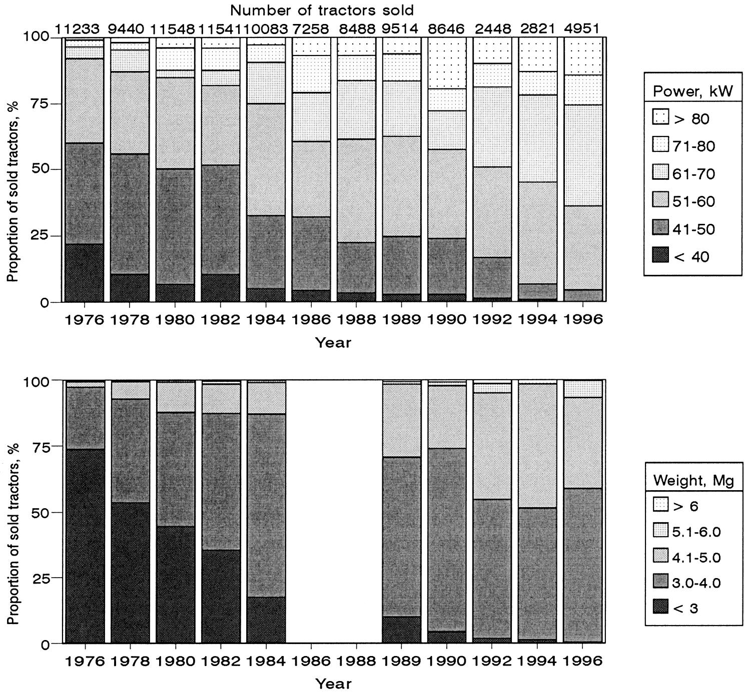


Fig. 1. Tractors of different power and weight as proportion of new tractors sold in Finland in 1976–1996. Calculated from the statistics of annual tractor sales compiled by the Institute of Agricultural Engineering of the Agricultural Research Centre.

may weigh as much as 25 Mg (Håkansson and Petelkau 1994).

The continuous increase in the weight of farm machinery has increased the potential for progressive subsoil damage. In the present paper, subsoil refers to soil below normal primary tillage depth. Although Hadas (1994) argues that subsoil compaction constitutes a problem within the realm of soil compaction in general and should not be a special field of research, some important differences between topsoil and subsoil compaction nevertheless exist. Normal tillage does not loosen the subsoil and the effects of compaction are difficult to correct. Thus, the effects of subsoil compaction often persist for a long time. The present paper reviews, subsoil compaction due to field traffic with the following objectives:

(1) to determine the internal and external parameters that influence the capability of wheel traffic for subsoil compaction
(2) to evaluate existing stress, axle load and farming recommendations for avoiding subsoil compaction
(3) to discuss the long-term effects of subsoil compaction on agriculture

Compaction of subsoils by wheel traffic

According to Koolen and Kuipers (1983), soil compaction in agriculture is usually accompanied by deformation in addition to compression lateral movement. The machinery traffic that causes soil compaction, which may be defined as an increase in bulk density, also causes nonvolumetric changes in soil structure. Factors influencing the compaction capability of wheel traffic include the soil conditions during the traffic, the type and intensity of forces applied, the

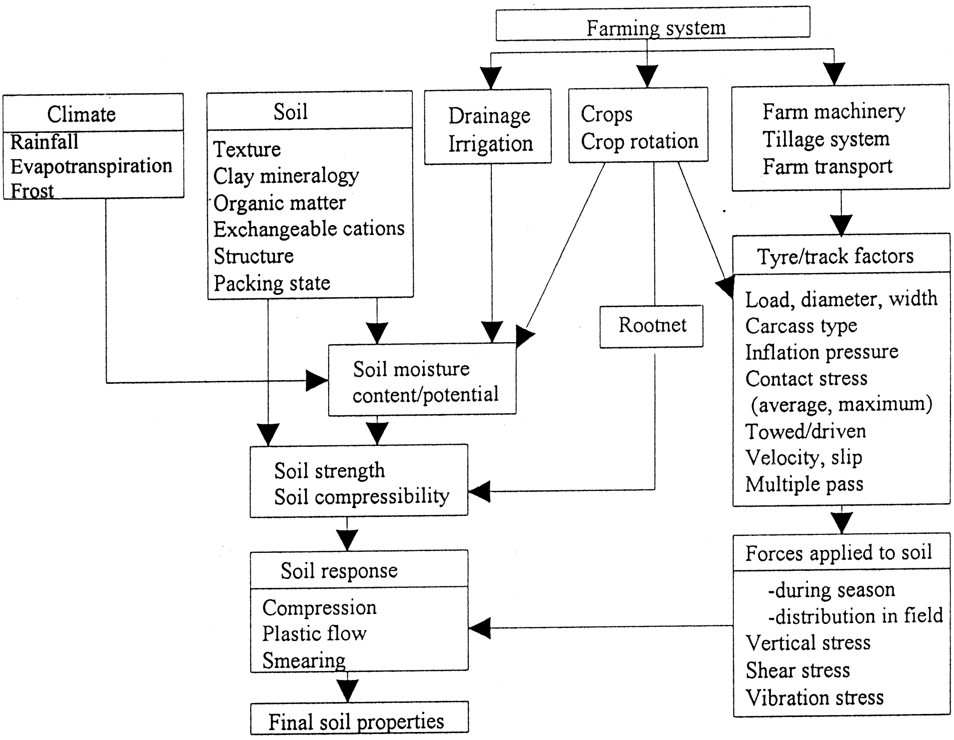


Fig. 2. Field traffic factors and soil properties affecting the soil compaction process (Canarache 1991, Soane and Ouwerkerk 1994b).

number of loading events and the duration of loading (Fig. 2). In this section we look at some of the major soil properties (internal parameters) and traffic factors (external parameters) relevant from an agricultural engineering point of view.

Internal soil strength

Internal topsoil and subsoil strength resists the external stresses induced by wheel traffic. Internal soil strength varies temporally, horizontally and vertically owing to differences in soil texture, content and kind of organic matter, structure, root density and especially moisture content/potential (Fig. 2). The effects of these different parameters on the compressibility and compaction behaviour of soils have been reviewed among others by Horn and Lebert (1994).

Soil moisture content and/or potential is the dominant property affecting soil strength during compaction (Dawidowski and Lerink 1990). As soil moisture content increases, the strength of an unsaturated soil drops rapidly, increasing the risk of soil compaction. Thus, the same stress compacts a subsoil more when it is moist than when it is dry (Salire et al. 1994). Pure sandy soil may be weak when either dry or saturated, however, since soil resists loading best when the capillary cohesion is highest. According to Akram and Kemper (1979), the soil compaction due to a given stress is greatest when the soil is at field capacity ($\psi_m = -10$ kPa). Saturated soil cannot be compacted without the water draining out from the soil. Saturated soil may smear, however, with resultant puddling and subsequent soil compaction when the homogenized soil dries (Guérif 1990).

Stresses induced by forces applied to subsoil

During field traffic, downwards acting forces due to dynamic wheel load (vertical normal forces), shear forces imposed by wheel slip and vibration forces transmitted from the engine through wheel or track are exerted on the soil. A towed wheel applies mainly vertical normal forces to the soil, while the driven wheel also exerts shear forces. Downwards acting forces have been the main concern in connection with subsoil compaction. Raghavan and McKyes (1977) nevertheless found in laboratory studies that up to 50% of topsoil compaction was attributable to shear stress owing to wheel slip. Likewise, at high slips, smearing damages the soil. According to Koolen et al. (1992), the shear effect vanishes relatively rapidly with depth. However, Kirby (1989) concluded from a model evaluation that shear damage may extend to a depth of 1.5 to 2 times the tyre width in a soil profile of uniform strength. Even though the shear effect may vanish rapidly, it can damage the subsoil markedly, especially during ploughing, owing to furrow wheel slipping. Davies et al. (1973) suggest a slip maximum of 10% to avoid topsoil damage owing to shear. The same limit is probably appropriate for subsoils.

The contribution of vibration effects to the compaction below pneumatic tyres has seldom been documented for arable soils (Soane et al. 1981). Wong and Preston-Thomas (1984) propose that a tracked tractor compacts topsoil more than expected because of the vibration transmitted through the track to the soil. With powerful tracked tractors in increasing used in agriculture, study is needed of the extent of the vibration they transmit to the soil and the possible effects of the vibration on subsoil.

Average ground contact stress

The average ground contact stress (wheel load divided by ground contact area between tyre and soil) estimates the vertical stress exerted on the soil surface by wheel or track. The contact stress is often evaluated from the tyre inflation pressure. The relationship between the average ground contact stress and the inflation pressure of a tyre depends, however, on tyre stiffness and soil conditions. For stiff agricultural tyres, tyre walls carry a considerable proportion of the total load, and on rigid surfaces the contact stress is higher than inflation pressure (Plackett 1984). Burt et al. (1992) found that the dynamic average ground contact stress below an 18.4R–38 tractor tyre on rigid soils was closely approximated by the inflation pressure, whereas on uncompacted soils the contact stress was clearly lower than the inflation pressure. Burt et al. (1992) and Tijink (1994) offer detailed introductions for the determination of contact stress.

The average ground contact stress denotes the calculated average value of the vertical stress in the tyre/track- soil contact area. The stress is not, however, uniformly distributed over the contact area. Stress distribution beneath the wheel is complex because of the tyre lug patterns and because the tyre itself can be deformed. Thus, the maximum ground contact stress under lugs or stiff tyre walls on a firm soil or at the centre of the contact area of a hard tyre on a soft soil may be twice or even four times the estimated average ground stress (Smith 1985, Burt et al. 1992). Likewise, the ground contact stress under a track will concentrate under the roadwheels (Wong 1986). The effect of uneven ground contact stress distribution on soil compaction has been little investigated. It is believed that the effect of the unevenness is limited to the upper part of the soil profile. However, Akker et al. (1994) found that at a depth of 0.35 m the peak stress with a low pressure tyre was about 60% of that with normal tyre even though the inflation pressure of the low pressure tyre (80 kPa) was only 33% that of the normal tyre (240 kPa). They proposed that the ground contact stress was concentrated below the stiff sides of the low pressure tyre.

Extent of stresses

In unsaturated soils, external stresses are transmitted three-dimensionally via solid, liquid and gaseous phases. Most of the analytical models for the propagation and distribution of stresses in the soil profile describe the stress distribution under a point load acting on a homogeneous, isotropic, semi-infinite, ideal elastic medium. The theoretical solution was proposed by Boussinesq (1885, ref. Söhne 1953). Fröhlich (1934) later modified the original solution by introducing a concentration factor (ν) to account for the increase in Young's modulus with soil depth due to overburden stress. Söhne (1953, 1958) and Gupta and Raper (1994) review the equations that describe stresses on a soil element as a result of a point load.

According to the theory, a vertical normal stress (σ_z) under a point load (P) at a given depth (z) can be expressed as

$$\sigma_z = \frac{\nu P}{2\pi R^2}\cos^{\nu}\beta \qquad [1]$$

where R is the radial distance from the point load to the subsoil point under consideration and β is the angle between the vertical line from the loaded point and R (Gupta and Raper 1994).

An analytical solution for the soil vertical normal stress beneath the centre of a uniformly loaded circular ground contact area can be calculated as a function of depth using the equation given by Taylor et al. (1980):

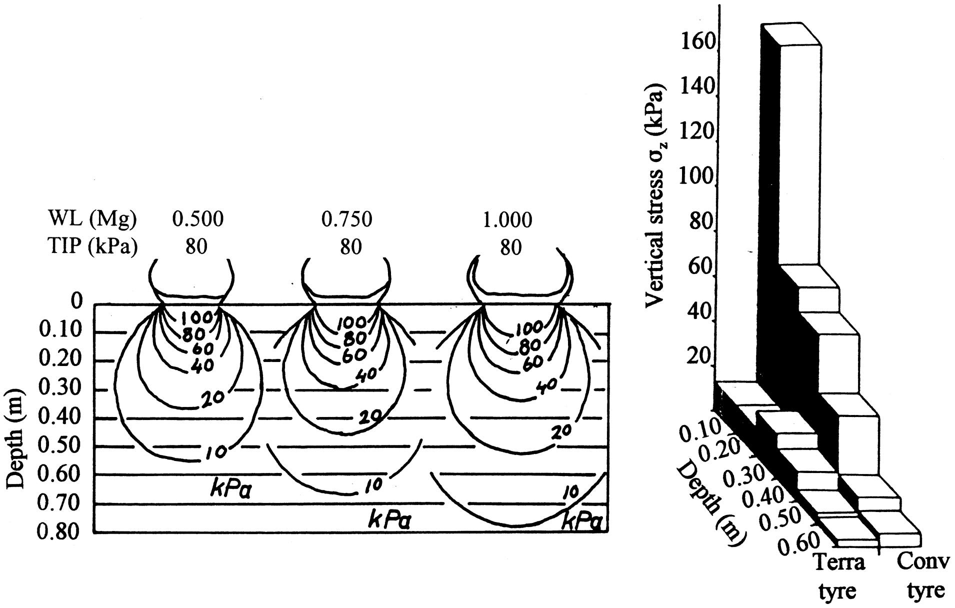
$$\sigma_z = p(1-\cos^{\nu}\alpha) \qquad [2]$$

where p is the average ground contact stress (tyre load/ground contact area) acting on the soil -tyre contact area, and α is the half aperture angle between the point at depth z and the edge of the contact area.

The stress described in the equations corresponds to that in an elastic (Poisson ratio 0.5), isotropic body if the concentration factor n is equal to 3 (Gupta and Raper 1994). Söhne (1953, 1958) assumed the values 4, 5 and 6 for hard, average and soft soil conditions, respectively. Soil firmness he described as a combination of looseness (bulk density) and moistness. Horn et al. (1987) report more fully that the concentration factor depends on the moisture content, density, load history, structure and texture of the soil. According to Horn (1980), ν varies from 1 for strong material to 10 for soft soil, and it is lower in aggregated than in non-aggregated soil (Horn 1986). In summary it can be stated that in strong and/or dry soils with low ν, vertical normal stress is distributed more horizontally, in a shallower soil layer, but in weak and/or wet soils with high ν it is transmitted to deeper depths.

The analytical solution has limitations. Estimation of the concentration factor is problematic and expensive (Gupta and Raper 1994). Furthermore, the soil conditions assumed above are seldom encountered in the field since soil is more a plastic medium than an elastic one, and the conditions vary spatially. Likewise, any nonuniformity in the soil profile tends to distort the stress distribution. Thus, Taylor et al. (1980) found that a plough pan in the soil profile, which is a common situation in agriculture, caused higher stress above the pan and lower stress below it than was the case for a uniform soil profile. Hard-pan tends to act like an elastic bridge, spreading the load over a wider area by reducing the concentration factor (Dexter et al. 1988). Thus, finite-element models are more often used, to take into account the heterogeneity of a soil profile (Kirby 1999). Likewise, the analytical solution described above is based on static stress. Hadas (1994) states that the results may be expected to be different when the stress is dynamic (short duration stress changing during driving). Nor is stress ever uniformly distributed over the ground contact area, as equation [2] assumes (see sect. Average ground contact stress).

The analytical solution shows that the stress in the soil under a loaded wheel decreases with depth (Fig. 3). From this, a highly simplified conclusion can be drawn: the stress in the topsoil depends on the average ground contact stress, but the stress in the subsoil is determined mostly by the wheel load (Söhne 1958, Carpenter et al. 1985). The same has been found in field and soil bin experiments (Danfors 1974, Taylor et al. 1980, Bolling 1987, Fig. 3). Hadas (1994) and Olsen (1994) criticize the generalization, however. On the basis of analytical calculations, Olsen (1994) concludes that the decrease of in-



	Terra tyre	Conv tyre
WL (rear) (Mg)	1.86	1.86
TIP (kPa)	24	300
A (soil) (m^2)	0.336	0.148
p (soil) (kPa)	54	123

Fig. 3. Calculated isostress lines as a function of wheel load (WL) with constant tyre inflation pressure (TIP) in a homogeneous soil (left, redrawn from Söhne 1953), and measured vertical stress distribution as a function of depth at constant wheel load in a silt soil (right, Lebert et al. 1989). A represents contact area and p represents average ground contact stress. Figures reprinted with kind permission from Institut für Biosystemtechnik, Bundesforschungsanstalt für Landwirtschaft and Kluwer Academic Publishers.

duced vertical normal stress with depth in the upper subsoil (0.10–0.30 m to 1 m depth) depends on both ground contact stress and wheel load, and below 1 m solely on wheel load. The criticism is justified since, based on equation (2), reduction in the average ground contact stress reduces the magnitude of stresses transmitted to the soil. The wheel load determines the normal stress level deep in the soil profile, but the stress level will never exceed the maximum ground contact stress level.

From the analytical solution and experimental results the following conclusion can be drawn on the effects of wheel load and contact stress on the soil stress and compaction. As the wheel load is increased with the same tyre and contact area, the stress at a specific depth increases and a given stress is transmitted deeper (Danfors 1974). When the wheel load is increased, even though the contact stress is kept unchanged by increasing tyre dimensions or the number of tyres (dual, triple), a given isostress is transmitted deeper into the soil and a greater soil volume is stressed (Fig. 3, Hadas 1994). When the number of tyres is increased, the extent of a given isostress may, however, be reduced by spacing the tyres widely apart to avoid any interaction between them (Olsen 1994). Lebert et al. (1989) found in *in situ* stress transmission measurements at the same wheel load but increasing contact area that vertical stresses can be reduced in the topsoil by using larger tyres, but in the subsoil the reductions are less significant (Fig. 3). Likewise, Danfors (1994) reported that a reduction in inflation pressure from 150 to 50 kPa (axle load > 8 Mg) reduced the compaction of moist clay soils only down to a depth of 0.30–0.40m, not in the deeper layers. In summary it can be stated that risk of subsoil compaction exists whenever a moist soil is loaded by a high wheel load and moderate to high ground contact stress.

Number of wheel passes

The number of passes affects the number of loading events and the coverage, intensity and distribution of wheel traffic. In field experiments on mineral soils, an increase in the number of passes in the same track increased subsoil compactness (Gameda et al. 1987, Schjønning and Rasmussen 1994, Alakukku and Elonen 1995a) and the depth of the compacted layer (Sommer and Altemüller 1982, Alakukku 1996a, b). An increase in the number of random passes would normally increase the spatial coverage of traffic in a field. Heavier machines usually reduce the number of passes per unit of land area per operation because of increased working width. Olfe and Schön (1986) report that a doubling in tractor power from 60 to 120 kW clearly reduced the area of soil covered by wheel tracks in cereal cultivation. At the same time, however, the intensity of field traffic increased from 176 to 216 Mg km ha^{-1}. Due to the use of heavier machines. Thus, the risk of subsoil damage may increase, even though the percentage of the field covered by wheel traffic is reduced by increased working width.

Driving speed

When the velocity of a machine is increased, the duration of the loading is reduced. Bolling (1987) measured the effects of velocity on the maximum soil stress below a wheel centre with two wheel loads (0.82 Mg, tyre inflation pressure 160 kPa and 1.5 Mg, 170 kPa) on sandy loam soil and found that an increase in velocity from 2 km h^{-1} to 10 km h^{-1} decreased stress at 0.30 m depth below the wheel centre. The effect of velocity was greater on loose than on dense soil. Similar results were reported by Horn et al. (1989). Earlier, however, Danfors (1974) found that higher velocity caused bouncing, which transmitted high point stresses to the subsoil. An increase in velocity would seen to reduce the stress transmitted to upper subsoil layers. The effects of velocity on the stress in deeper layers and the practical importance of velocity to subsoil compaction have seldom been documented, however. The highest velocity tested has been 8–12 km h^{-1}, which is the normal speed in field operations.

Extent of subsoil compaction

The most serious source of subsoil compaction tends to be tractor wheels running in the open furrow during mouldboard ploughing because the tractor wheels then run directly on the upper part of the subsoil. As summarized in Table 1, field traffic on the soil surface with an axle load higher than 6 Mg and with tyre inflation pressure greater than 50 kPa compacts moist mineral soils to 0.50 m depths or deeper. Under unfavourable soil conditions, an axle load less than 5 Mg also compacts the subsoil. The depth of compaction in organic soils has seldom been investigated because the effects of organic soil compaction have not been considered harmful. An axle load higher than 6 Mg has been found to compact organic soils to 0.40–0.50 m depths (Table 1). In view of the persistence of subsoil compaction (see sect. Long-term effects of compaction in agriculture), Håkansson and Petelkau (1994) regard compaction to depths more than 0.40 m as unacceptable.

Stress, axle load and farming recommendations

With the aim of avoiding subsoil compaction, recommendations have been given for maximum

Table 1. Maximum depth of soil compaction due to field traffic with different axle loads and soil conditions.

Soil Type	 Moisture	Axle load (Mg)	TIP[1] (kPa)	Depth of compaction (m)	 Reference
Coarse sand	At FC[1]	22[2]	220[3]	0.60	Schjønning and Rasmussen (1994)
Sand	Near FC	16[2]	400	0.60	Danfors (1974)
		4	400	0.20	
		6	400	0.40	
Sand	Near FC	16[2]	300	0.50	Håkansson (1985)
Sand	–	6.4	240	0.80	Akker (1988)
Sand	–	2.5	300	0.40	Dumitru et al. (1989)
Loamy sand	60% of FC	1.7	60	0.20–0.40	Lipiec et al. (1990)
Loam	0.22 g g^{-1}	10/20	414/414	0.60	Gameda et al. (1984)
Loam	78% of FC	1.7	60	0.20–0.40	Lipiec et al. (1990)
Silt loam	0.16 g g^{-1}	12.5	220	0.40	Schuler and Lowery (1984)
Silt loam	–14– –60 kPa	13.2	118	0.50	Blackwell et al. (1986)
Silt loam	Near FC	10/20	200/330	0.75	Hammel (1988)
Silt loam	72% of SS[1]	15.2	210	0.40	Wood et al. (1993)
Silty loam	Near FC	12	145	0.35	Stewart and Vyn (1994)
Silt	< 0.3 m FC	11	600	0.50	Alakukku (1997)
Sandy clay	0.23 g g^{-1}	10/20	414/414	0.60	Gameda et al. (1984)
Silty clay loam	–	4.5	250[3]	0.45	Voorhees et al. (1978)
Silty clay	0.20 g g^{-1}	12.5	220	0.40	Schuler and Lowery (1984)
Clay loam	> 0.3 m PW[1]	9/18	150/200[3]	0.30	Voorhees et al. (1986)
	Near FC	9/18	150/200[3]	0.50	
Clay loam	Near FC	8	50/150	0.50	Danfors (1994)
		10[2]	50/150	0.50	
Clay loam	Near FC	5	150/300	0.35	Alakukku and Elonen (1995a)
Clay loam	85–90% of FC	21[2]	800	0.40–0.45	Alakukku (1997)
Clay	Near FC	16[2]	400	0.60	Danfors (1974)
		4	400	0.20	
		6	400	0.40	
Clay	–	40[4]	–	1.00	Eriksson (1976)
Clay	Near FC	3	140	0.20	Aura (1983)
	> FC	3	140	0.40	
Clay	Near FC	16[2]	300	0.50	Håkansson (1985)
Clay	Near FC	19[2]	700	0.50	Alakukku (1996a, b)
Fen	–	6	–	0.50	Schmidt and Rohde (1986)
Mull	> FC	3	120[3]	0.35	Pietola (1995)
Sedge peat[5]	> FC	16[2]	700	0.40–0.50	Alakukku (1996a, b)

[1] TIP = tyre inflation pressure, FC = field capacity, PW = permanent wilting point, SS = saturation

[2] tandem axle

[3] average ground contact stress

[4] total load

[5] sedge peat mixed with clay from 0.20 m to 0.40–0.50 m depths, and underlain by gythia

values of average ground contact stress and stress at 0.50 m depth (Table 2) and for axle loads. For moist soils, it is sometimes recommended that ground contact stress should not exceed 50 kPa (Table 2). Carpenter and Fausey (1983) suggest that the maximum ground contact stress with

Table 2. Recommendations for maximum average ground contact stress and vertical soil stress at 0.50 m depth in different soil conditions to prevent soil compaction.

	Ground contact stress (kPa)		Stress at 0.50 m depth (kPa)		
Soil	Spring	Summer/ autumn	Spring	Summer/ autumn	Reference
Sand	50	80[1)]			Petelkau (1984)
Loam	80	150[1)]			
Clay	150	200[1)]			
Arable land	50	100			Vermeulen et al. (1988)
Clay					Rusanov (1994)
MC > 90% of FC[2)]	80	100	25	30	
MC 70–90% of FC	100	120	25	30	
MC 60–70% of FC	120	140	30	35	
MC 50–60% of FC	150	180	35	45	
MC < 50% of FC	180	210	35	50	
Sand, Sandy loam					
MC > 90% of FC	95	120	25	30	
MC 70–90% of FC	120	145	25	30	
MC 60–70% of FC	145	170	30	35	
MC 50–60% of FC	180	215	35	45	
MC < 50% of FC	215	250	35	50	
Silts, 14–27% clay					Salire et al. (1994)
ψ_m –30 kPa[2)]			64–271[3)]		
ψ_m –100 kPa			119–356		
Mineral soils					Bondarev et al. (1988)[4)]
MC ≥ FC	40–50				

[1)] moisture content < 70% of field capacity

[2)] moisture content (MC) of field capacity (FC), ψ_m is matric potential

[3)] the stress at which irreversible deformation occurs at 0.45 m depth
Soil with high bulk density has higher value than soil with low bulk density

[4)] cited by Lipiec and Simota (1994)

high wheel loads should not exceed the stress allowed in the subsoil. Few data exist, however, to allow assessment of the maximum allowable subsoil stress in different conditions, and this area should be addressed in future studies.

From a practical point of view it is relevant that the recommendations for ground contact stress are close to the recommendations for the maximum tyre inflation pressures given by Dwyer (1983, 50 kPa for moist soil, 100 kPa for dry soil) and Perdok and Tijink (1990, 50 kPa for moist soil, 250 kPa for dry soil). When the contact stress is to be minimized, the technical solution will depend on the demands of the operation in which a machine is used. The tyre inflation pressure should, however, always be the lowest allowable in the prevailing situation (tyre loading capacity, velocity, traction), and the tyre -soil contact should be uniform. For a detailed discussion of tyre factors see, among others, Tijink (1994); for track factors see Erbach (1994).

To avoid soil compaction below normal primary tillage depth (0.2–0.3 m), single axle loads not exceeding 4 to 6 Mg have been recommended for moist mineral soils (Danfors 1974, 1994, Voorhees and Lindstrom 1983, Petelkau 1984) even when the tyre inflation pressure is 50 kPa (Danfors 1994). For tandem axle loads on moist soils Danfors (1974, 1994) proposes a limit of 8–10 Mg. On dry soil, the axle load may be high without causing subsoil compaction (Table 1). Farmers cannot, however, easily estimate moisture conditions in the subsoil. Moreover, heavy field traffic on moist fields often cannot be avoided owing to the time constraints of given field operations. Thus, recommendations need to be set with a view to the wettest conditions prevailing during the normal use of a machine.

While stress and axle load limits may be considered to be the engineering tools for the control of soil compaction, it should be remembered that the farming system, and the way of using machinery as part of that system, will markedly influence the effects of the field traffic on soils and crops. For instance, if the drainage does not work, a larger tractor or larger tyres will not essentially reduce the workability or trafficability problem and may even intensify the compaction problem. Moreover, spring application of slurry manure before seedbed preparation is recommended as the most effective way of conserving plant nutrients. Yet slurry tankers exert substantial axle loads on soils which are usually wet, and may induce significant compaction. Thus, Håkansson and Danfors (1988) calculated that the compaction cost of spreading liquid manure on wet soil may exceed the economic value of the nutrients supplied by the manure. Furthermore, the area covered by wheel traffic can be reduced without increasing working width by using combined implements or linked operations or by concentrating field traffic to the same tracks. An example is combined seedbed preparation, fertilization and sowing. Likewise, the transport traffic on moist soil should be concentrated to as few tramlines as possible, with these located perpendicular to the subsurface drains or to headland roadways.

Long-term effects of compaction in agriculture

Compaction induced by field traffic has both short- and long-term effects on soil and crop production. Short-term (1–5 years) effects are mainly associated with topsoil (0–0.30 m) compaction, which is largely controlled by tillage operations, field traffic and the way in which these operations are adapted to soil conditions. The topsoil compaction is alleviated by tillage and natural processes of freezing/thawing, wetting/drying and bioactivity. Aura (1983) found that the compaction of clay soils within the plough layer due to traffic with an axle load of 3 Mg in spring was alleviated by ploughing and frost by the following spring. When the plough layer is severely compacted, the recovery of heavy clays may take three (Alakukku 1996b) or even five years (Arvidsson and Håkansson 1996) despite annual ploughing and frost. This section discusses the effects of wheel traffic on subsoil properties and on crop production in field conditions.

Subsoil properties and behaviour

Many studies have found that compaction modifies the pore size distribution of mineral subsoils mainly by reducing the macroporosity (> 30 µm) (Eriksson 1976, Ehlers 1982, Blackwell et al. 1986, Alakukku 1996a, 1997). Besides the volume and number of macropores, compaction may also affect their continuity. Modifications in soil macroporosity are very important since they affect other soil properties and soil behaviour.

Subsoil compaction has been found to have harmful effects on many soil properties relevant to soil workability, drainage, crop growth and environment. Subsoil compaction due to heavy field traffic increased the dry bulk density, vane shear resistance and penetrometer resistance of subsoils with clay content 0.06–0.85 g g^{-1} (Table 3). Compacted subsoils had a more massive

Table 3. Change in dry bulk density (BD), total porosity (TP), penetrometer resistance (PR), vane shear resistance (VR), macroporosity (MP), saturated hydraulic conductivity (K_{sat}) and number of cylindrical pores (NB) in the subsoil of mineral soils after compacting treatments. Results are expressed relative to the control.

		Change in soil properties due to loading (%)							
Soil	Loading	BD	TP	PR	VR	MP	K_{sat}	NB	Reference
Sandy loam	6 years earlier by tractor	10		200					Pollard and Webster (1978)
Sandy loam	4 passes 38 Mg sugar beet harvester	3					–64		Arvidsson (1998)
Loam	9 years earlier, 4 passes 16 Mg tandem axle load					–33	–67	–32	Alakukku (1996b)
Loam	4 passes 38 Mg sugar beet harvester	4					–84		Arvidsson (1998)
Silt loam	1 pass 13.2 Mg axle load		–7	12	63	–15			Blackwell et al. (1986)
Silty clay loam	Traffic during one season	20		400					Voorhees et al. (1978)
Silt	3 passes 10 Mg single axle load	5				–45	–80	–17	Alakukku (1997)
Clay loam	9 years earlier, 4 passes, 750 kPa contact stress			15			–78		Blake et al. (1976)
Clay loam	7 years earlier, 4 passes 18 Mg axle load	11					–90		Logsdon et al. (1992)
Clay loam	3 passes 20 Mg tandem axle load	3		–1		–8	57	–7	Alakukku (1997)
Clay loam	4 passes 18 Mg axle load	4		25					Voorhees et al. (1986)
Silty clay	4 passes 12.5 Mg axle load	2		23			13		Lowery and Schuler (1994)
Clay	9 years earlier, 4 passes 16 Mg tandem axle load			18		–14	–48	–67	Alakukku (1996b)
Heavy clay	Several years 40 Mg	6	–8		12	–42	–14	–38	Eriksson (1976)

and coarse structure (Pollard and Webster 1978, Alakukku 1997). Likewise, compaction reduced the saturated hydraulic conductivity (Table 3), CO_2 and O_2 exchange (Simojoki et al. 1991) and air permeability (Horn et al. 1995) of subsoils.

The likelihood of drainage problems increases when compaction reduces the permeability of the subsoil and may lead to waterlogging problems in rainy years. Poorly drained soil may also dry slowly, reducing the number of days available for field operations. Furthermore compaction may increase surface runoff and topsoil erosion by impeding water infiltration (Fullen 1985). Likewise, the reduction in drainage rate attributed to subsoil compaction can be expected to increase the emission of green house gases from the soil, for instance, by increasing denitrification. The environmental consequences of soil compaction have been reviewed by Soane and Ouwerkerk (1995). However, there is little information as yet on the implications of machinery induced subsoil compaction for the hydraulic processes in the soil profile and the quality of the environment. These subjects are in need of further study.

Normal tillage does not loosen the subsoil (below about 0.30 m). The effects of subsoil compaction may persist for a very long time. For example, in spite of cropping and deep frost, the effects of subsoil compaction due to high axle load traffic were measurable in soils with clay contents of 0.06–0.85 g g^{-1} three to 11 years after application of heavy loading (Table 3, Gaultney et al. 1982, Voorhees et al. 1986, Gameda et al. 1987, Etana and Håkansson 1994, Lowery and Schuler 1994, Wu et al. 1997). Subsoil compaction still persisted six years after the traffic in a cropped sandy loam (Pollard and Webster 1978)

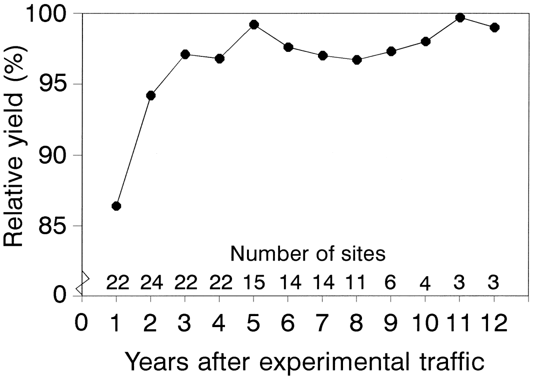


Fig. 4. Crop yields relative to control treatment (=100%) for 12 successive years (1–12) after loading with four passes by vehicles having a single axle load of 10 Mg or tandem axle load of 16 Mg and tyre inflation pressure > 200 kPa. Mean values from field experiments in seven countries in Europe and North America. Data for the last four years (Alakukku 1999) are included in the figure, which is redrawn from Håkansson and Reeder (1994).

and ten years after the traffic in a cropped clay (Duval et al. 1989). In all these investigations, the effects of compaction persisted for the duration of the experiment. Håkansson and Petelkau (1994) concluded that subsoil compaction tends to be highly persistent, and in non-swelling sandy soils and tropical areas it may be permanent immediately below the tillage depth.

As shown above, subsoil compaction can be quantified by measuring many different soil properties. A common approach is to determine the changes in bulk density. Bulk density is also included in most models predicting subsoil strain due to external stresses (Smith 1985). The usefulness of bulk density determinations for agricultural purposes is limited, however, since the bulk density does not take into account the non-volumetric changes of subsoil strcture due to the loading and it does not determine the behaviour of subsoils. Horn et al. (1996) demonstrated under idealized sandy loam soil bin conditions that up to 60% of soil deformation can be determined as a volumetric compression and up to 40% has to be defined as volume-constant deformation. Changes in soil behaviour properties, such as mechanical behaviour, water retention and water and air flow, better express the effects of compaction on soil than does bulk density (Gupta et al. 1989, Carter 1990).

Crop response

The harmful effects of subsoil compaction are reflected not only in soil properties but in crop growth and yield. Soil compaction to depths of 0.50 m or more by axle load traffic greater than 9 Mg decreased the yield of grain (Håkansson et al. 1987, Fig. 4) and nitrogen uptake (Alakukku and Elonen 1995b), and delayed (Gaultney et al. 1982, Gameda et al. 1987) or accelerated (Alakukku and Elonen 1995b) the ripening of crops up to several years after the loading. The greatest decrease in yield occurred in the first three years after the compaction (Fig. 4), probably mainly owing to plough layer compaction (Håkansson and Reeder 1994). By degrees, annual ploughing and freezing alleviated the plough layer compaction, and after the first few years the reduction in yield became less (Fig. 4).

It may be that the subsoil compaction is not alleviated, however, and its long-term effect on the crop growth and yield will then depend on the climatic conditions of the growing season. Voorhees (1992) found that subsoil compaction resulting from loading with an 18 Mg axle load decreased maize yield significantly on clay loam in relatively dry and rainy years but not in years with normal precipitation. Lowery and Schuler (1994) reported that the subsoil compaction due to traffic with a 12.5-Mg axle load reduced maize yield considerably only in a rainy year. Likewise, Alakukku and Elonen (1995b) found that, when the beginning of the growing season was dry, subsoil compaction in clay soil had little effect on the grain and nitrogen yields of annual crops whereas in rainy years the yields were clearly reduced. They also observed that extended drought reduced the yields in all plots. Furthermore, subsoil compaction may have little effect on crop yield if the crop does not need to extract water from the subsoil. Montaga et al. (1998) reported that the root growth of vegetable crops in the subsoil was reduced by compaction, but there was no direct effect on crop shoot growth or yield when water and nutrients were adequately supplied to the soil.

A common approach in examinins the effects of subsoil compaction is to determine the quantitative changes in yields. Yield quantity alone does not, however, always show how harmful the influence of soil compaction on crops may be. Interestingly, nitrogen yield has been found to be a more sensitive measure of the influence of topsoil and subsoil compaction than the grain yield. Douglas et al. (1995) found that the average dry matter yield and nitrogen uptake of grass silage over a period of four years were 13 and 18% lower, respectively, in conventional traffic plots than in zero traffic plots. Likewise, taken as a mean of the first nine years after a clay soil was compacted to 0.50 m depth by a single heavy loading, the grain yield of annual crops in compacted plots was reduced by 3% but the nitrogen yield harvested in grain yield by 7% (Alakukku and Elonen 1995b). The long-term effects of subsoil compaction on crop quality and nutrient uptake have seldom been studied, however.

The reasons for yield reduction are not always well quantified. Yet in any attempt to monitor the consequences of compaction it is important to quantify the effects on the subsoil/plant/weather system. Likewise, mainly annual grain crops were grown in field experiments. Yet crop sensitivity to topsoil compaction varies with plant species (Brereton et al. 1986) and even variety. In summary it should be emphasized that field experiments on the effects of subsoil compaction on crop production in different crop rotations need to be carried out over a sufficiently long period of time to account for iteractions between variations in weather conditions and crop response. Moreover, to better quantify subsoil/plant/weather interactions, measurements of plant development, water and nutrient uptake, root growth and soil and weather conditions need to be made during the growing season.

Cumulation of subsoil compaction

Since the alleviation of a severe subsoil compaction takes many years, if it occurs at all, a heavy loading repeated in the same place each year may increase soil compactness and yield losses year by year. The area of compacted soil may also increase if the heavy field traffic is not concentrated annually in the same tracks. Soil compaction may thus become more harmful as time goes on, even though the effect of a single pass by a heavy vehicle tends to be rather small (Håkansson 1994a). Arvidsson and Håkansson (1996) report that repeated loading of 350 Mg km ha^{-1} on wet clay soils before ploughing increased the yield losses of spring cereals annually during the first four years. After that, the yields levelled out. They evaluated, however, that the effects of compaction were mainly caused by compaction in the topsoil. Gameda et al. (1987) did not observe cumulative yield losses with maize even though heavy field traffic with axle loads 10–20 Mg increased the maximum soil density each year during the first three years. Repeated field traffic does not always increase soil compaction cumulatively. Alblas et al. (1994) loaded sandy soils with an axle load of 10 Mg twice a year for four years but did not find any cumulative subsoil compaction or cumulative losses in silage maize yield.

In separate studies, Håkansson et al. (1996) and Fenner (1997) quantified the cumulative compaction effects on the subsoil in farmers fields induced by machinery traffic in recent decades. Håkansson et al. (1996) found that soil penetration resistance at 0.40 m depth was an average 40% higher in 17 fields (subsoil clay content 0.01–0.58 g g^{-1}) with intensive potato and sugar beet production and where large quantities of slurry were spread than in the control fields under permanent grass without field traffic in the past 35 years. In eight fields (subsoil clay content 0.35–0.60 g g^{-1}) in a cereal production region with less intensive machinery traffic, the corresponding increase in penetration resistance was 10%. Håkansson et al. (1996) estimated persistent crop yield reductions caused by subsoil compaction in the 17 and eight fields to be 6% and 1.5%, respectively. According to these two studies the state of compactness of arable subsoils and soil productivity are dependent on the intensity of heavy field traffic. Fenner (1997) reported similar results for penetration resistance on loess soil in two neighbouring fields with maximum axle loads of 4 Mg and 8.9 Mg during the past 20 years.

General discussion and conclusions

Results reviewed in the present paper show that heavy machinery traffic increases the risk of long lasting soil physical degradation and crop yield losses, particularly in temperate, moist zones. Threats to soil productivity need to be minimized in future. As world population is forecasted to grow 8 billion and the demand for food to increase by 64% during the next 25 years (Worldwatch Institute 1996), world food production must necessarily be increased. Yet little additional arable land is available. In general, this means that food production per unit area will have to be increased rather than be allowed to decrease. Furthermore, the impact of agriculture on the environment must be diminished. Likewise, in developing countries, improved and modern farming systems are needed to enhance crop production. Thus, it is necessary to continue developing technical solutions to avoid detrimental topsoil and subsoil compaction induced by field traffic and to find methods to improve already compacted subsoils.

The risk of subsoil compaction is high when moist soils are loaded with high axle load traffic with moderate to high ground contact stress. Håkansson (1994b) notes that the gradually increasing weight of agricultural machinery raises concern about a possible permanent deterioration of the subsoil. With the aim of avoiding subsoil compaction, some recommendations have been given for axle loads and for maximum permissible ground contact stress and stress at 0.50 m depth. To avoid long-lasting soil physical degradation below normal tillage depth, international limits should be established for mechanical stresses in the subsoil. Håkansson and Reeder (1994) suggest that these could be simple maximum axle load limits, or combined axle load -ground contact stress limits. Since agricultural machinery and farming practices are similar world-wide, the recommendations for maximum mechanical stress limits should be arrived at through international teamwork. Our understanding of the subsoil compaction process is incomplete, however, and our modelling of compaction in soil/machine/plant systems imperfect. Thus, before appropriate stress limits can be set, areas such as the bearing capacity of subsoils under different conditions should be investigated.

While large and heavy machinery is often blamed for soil compaction problems, it should be noticed as well that the farming system is not usually changed when the machinery size increases. Larger machines, often equipped with large, low-pressure and/or dual tyres, are used in the same soil conditions (macroporosity, drainage) and in the same tillage and other working practices as smaller ones. Added to this, increased engine power and/or enlarged tyre constructions make it possible to work in worse conditions. Large machines do not, however, compensate for the poor drainage or other mismanagement of soil structure. Thus, in examining the possible ways to avoid subsoil compaction due to field traffic, the whole farming system needs to be considered, not just the machinery.

Soil compaction affects virtually all physical, chemical and biological soil properties and processes by modifying soil macroporosity. Yet the effects of heavy loading on subsoils and the effects of subsoil compaction on drainage, crop growth and environment are typically investigated with a limited number of soil, crop and environmental parameters. When these effects are being evaluated, it is relevant to take the economics into account as well. Voorhees (1991) has pointed out that even though a given machinery system decreases crop yield a little, it still may make economic sense to use it. Eradat Oskoui et al. (1994) reviewed the economics of modifying machinery to minimize soil compaction. The effects of subsoil compaction on the farm economy have seldom been documented, however. Further studies will be needed to obtain sufficient information on the long-term and cumulative effects of machinery induced subsoil compaction on soil hydrology, crop productivity, farm economics and environment. The risks of subsoil compaction should be analysed on the basis of the findings of these studies, and the probabilities of harmful consequences of subsoil compaction in different situations should be evaluated.

Subsoil compaction has been documented to be long-lasting and difficult to correct. Deep loosening is expensive and will seldom ameliorate the compacted structure completely. Moreover, the loosened soil is often recompacted within two or three years, with even worse physical properties (Kooistra and Boersma 1994). Thus, it is better to avoid subsoil compaction in the first place than to rely on alleviating the compacted structure afterwards. The alleviation of soil compaction through biological tillage by earthworms and plant roots is in need of further study. Whalley and Dexter (1994) note that biopores are more stable than the macropores produced by mechanical tillage.

Acknowledgements. This writing of this paper was financially supported by the Commission of the European Communities, Agriculture and Fisheries (FAIR) specifiec RTD programme, FAI5–CT97–3589, "Experiences with the impact of subsoil compaction on soil, crop growth and environment and ways to prevent subsoil compaction". In principle the presented data do not necessarily reflect its views and in no way anticipates the Commission's future policy in this area.

References

Akker, J.H.H. van den 1988. Model computation of subsoil stress distribution and compaction due to field traffic. *Proceedings 11th International Conference of ISTRO*, 11–15th July, Edinburgh, Scotland 1: 403–408.

– , Arts, W.B.M., Koolen, A.J. & Stuiver, H.J. 1994. Comparison of stresses, compaction and increase of penetration resistance caused by a low ground pressure tyre and a normal tyre. *Soil & Tillage Research* 29: 125–134.

Akram, M. & Kemper, W.D. 1979. Infiltration of soils as affected by the pressure and water content at the time of compaction. *Soil Science Society of America Journal* 43: 1080–1086.

Alakukku, L. 1996a. Persistence of soil compaction due to high axle load traffic. I. Short-term effects on the properties of clay and organic soils. *Soil & Tillage Research* 37: 211–222.

– 1996b. Persistence of soil compaction due to high axle load traffic. II. Long-term effects on the properties of fine-textured and organic soils. *Soil & Tillage Research* 37: 223–238.

– 1997. Properties of fine-textured subsoils as affected by high axle load traffic. *Acta Agriculturae Scandinavica. Section B. Soil and Plant Science* 47: 81–88.

– 1999. Response of annual crops to subsoil compaction in a field experiment on clay soil lasting 17 years. *International Conference on Subsoil Compaction.* Christian-Albrechts-Universität zu Kiel, Kiel, Germany 24.–26.03.1999. Abstracts. p. 13–15.

– & Elonen, P. 1995a. Cumulative compaction of a clay loam soil by annually repeated field traffic in autumn. *Agricultural Science in Finland* 4: 445–461.

– & Elonen, P. 1995b. Long-term effects of a single compaction by heavy field traffic on yield and nitrogen uptake of annual crops. *Soil & Tillage Research* 36: 141–152.

Alblas, J., Wanink, F., Akker, J. van den & Werf, H.M.G. van der 1994. Impact of traffic-induced compaction of sandy soils on the yield of silage maize in The Netherlands. *Soil & Tillage Research* 29: 157–165.

Arvidsson, J. 1998. Soil compaction caused by heavy sugar beet harvesters measurements with traditional and new techniques. In: Märländer, B. et al. (eds.). Soil compaction and compression in relation to sugar beet production. *Advances in Sugar Beet Research* 1: 35–42.

– & Håkansson, I. 1996. Do effects of soil compaction persist after ploughing? Results from 21 long-term field experiments in Sweden. *Soil & Tillage Research* 39: 175–197.

Aura, E. 1983. Soil compaction by the tractor in spring and its effect on soil porosity. *Journal of the Scientif-*

ic Agricultural Society of Finland 55: 91–107.

Blackwell, P.S., Graham, J.P., Armstrong, J.V., Ward, M.A., Howse, K.R., Dawson, C.J. & Butler, A.R. 1986. Compaction of a silt loam soil by wheeled agricultural vehicles. I. Effects upon soil conditions. *Soil & Tillage Research* 7: 97–116.

Blake, G.R., Nelson, W.W. & Allmaras, R.R. 1976. Persistence of subsoil compaction in a Mollisol. *Soil Science Society of America Journal* 40: 943–948.

Bolling, I. 1987. Bodenverdichtung und Triebraftverhalten bei Reifen-Neue Mess- und Rechenmethode. *Forschungsbericht Agrartechnik Arbeitskreises Forschung und Lehre Max-Eyth-Gesellschaft (MEG)* 133: 1–274.

Bondarev, A.G., Sapozhnikov, P.M., Utkaieva, V.F. & Shepotiev, V.N. 1988. Izmeneniye fizicheskykh svoystv I plodorodya pochv pri ikh uplotnieny dvizhytelamy sielskokhazyaystvennoy tyekhniki. (Changes in soil physical properties and productivity as related to compaction by agricultural vehicles, in Russian.) *Sbornik Nauchnykh Trudov, VIM, Moscow, U.S.S.R.* 188: 46–57.

Boussinesq, J. 1885. *Application des potentials à l'etude de l'equilibre et du mouvement des solides elastiques.* Gauthier-Villais, Paris, France. 30 p.

Brereton, J.C., McGowan, M. & Dawkins, T.C.K. 1986. The relative sensitivity of spring barley, spring field beans and sugar beet crops to soil compaction. *Field Crops Research* 13: 223–237.

Burt, E.C., Wood, R.K. & Bailey, A.C. 1992. Some comparison of average to peak soil-tire contact pressures. *Transaction of American Society of Agricultural Engineers* 35: 401–404.

Canarache, A. 1991. Factors and indices regarding excessive compactness of agricultural soils. *Soil & Tillage Research* 19: 145–164.

Carpenter, T.G. & Fausey, N.R. 1983. Tire sizing for minimizing subsoil compaction. *American Society of Agricultural Engineers. Paper* no. 83/1058. 23 p.

– , Fausey, N.R. & Reeder, R.C. 1985. Theoretical effect of wheel loads on subsoil stresses. *Soil & Tillage Research* 6: 179–192.

Carter, M.R. 1990. Relative measures of soil bulk density to characterize compaction in tillage studies of fine sandy loams. *Canadian Journal of Soil Science* 70: 425–433.

Danfors, B. 1974. Packning i alven. Summary: Compaction in the subsoil. *Swedish Institute of Agricultural Engineering. Special report* S24: 1–91.

– 1994. Changes in subsoil porosity caused by heavy vehicles. *Soil & Tillage Research* 29: 135–144.

Dawidowski, J.B. & Lerink, P. 1990. Laboratory simulation of the effects of traffic during seedbed preparation on soil physical properties using quick uni-axial compression test. *Soil & Tillage Research* 17: 31–45.

Davies, D.B., Finney, J.B. & Richardson, S.J. 1973. Relative effects of tractor weight and wheelslip in causing soil compaction. *Journal of Soil Science* 24: 399–409.

Dexter, A.R., Horn, R., Hollaway, R. & Jakobsen, B.F. 1988. Pressure transmission beneath wheels in soils on the Eyre Peninsula of south Australia. *Journal of Terramechanics* 25: 135–147.

Douglas, J.T., Crawford, C.E. & Campbell, D.J. 1995. Traffic systems and soil aerator effects on grassland for silage production. *Journal of Agricultural Engineering Research* 60: 261–270.

Dumitru, E., Colibas, I., Ludusan, V., Nicolae, H., Niculescu, R., Ion, P., Seitan, L. & Canarache, A. 1989. Effects of wheel traffic under drought conditions on soil and yield in Romania. *International Conference in Soil Compaction, 5–9 June, Lublin, Poland.* Abstracts. p. 63–64.

Duval, J., Raghavan, G.S., Mehuys, G.R. & Gameda, S. 1989. Residual effects of compaction and tillage on the soil profile characteristics of a clay-textured soil. *Canadian Journal of Soil Science* 69: 417–423.

Dwyer, M.J. 1983. Soil dynamics and the problems of traction and compaction. *Agricultural Engineering* 38: 62–68.

Ehlers, W. 1982. Die Bedeutung des Bodengefüges für das Pflanzenwachstum bei moderner Landbewirtschaftung. *Mitteilungen Deutsche Bodenkundliche Gesellschaft* 34: 115–128.

Eradat Oskoui, K, Campbell, D.J., Soane, B.D. & McGregor, M.J. 1994. Economics of modifying conventional vehicles and running gear to minimize soil compaction. In: Soane, B.D. & Ouwerkerk, C. van (eds.). Soil compaction in crop production. *Developments in Agricultural Engineers* 11. Elsevier Science B.V., The Netherland. p. 539–567.

– & Voorhees, W.B. 1991. Economic consequences of soil compaction. *Transaction of American Society of Agricultural Engineers* 34: 2317–2323.

Erbach, D.C. 1994. Benefits of tracked vehicles in crop production. In: Soane, B.D. & Ouwerkerk, C. van (eds.). Soil compaction in crop production. *Developments in Agricultural Engineering* 11. Elsevier Science B.V., The Netherlands. p. 501–520.

Eriksson, J. 1976. Influence of extremely heavy traffic on clay soil. *Grundförbättring* 27: 33–51.

Etana, A. & Håkansson, I. 1994. Swedish experiments on the persistence of subsoil compaction caused by vehicles with high axle load. *Soil & Tillage Research* 29: 167–172.

Fenner, S. 1997. Langjährige Verdictungswirkung durch unterschiedliche Achslasten auf einem Löß-Ackerstandort. *Zeitschrift für Pflanzenernährung und Bodenkunde* 160: 157–164.

Fröhlich, O.K. 1934. *Druckverteilung im Baugrunde.* Verlag von Julius Springer, Wien, Austria. 178 p.

Fullen, M.A. 1985. Compaction, hydrological processes and soil erosion on loamy sands in east Shropshire, England. *Soil & Tillage Research* 6: 17–29.

Gameda, S., Raghavan, G.S.V., McKyes, E. & Theriault, R. 1984. Soil and crop response to the high axle load subsoil compaction – Recovery and accumulation. *American Society of Agricultural Engineers. Paper* no. 84/1542. 24 p.

– , Raghavan, G.S.V., McKyes, E. & Theriault, R. 1987. Subsoil compaction in a clay soil. I. Cumulative effects. *Soil & Tillage Research* 10: 113–122.

Gaultney, L., Krutz, G.W., Steinhardt, G.C. & Liljedahl, J.B. 1982. Effects of subsoil compaction on corn yields. *Transaction of American Society of Agricultural Engineers* 25: 563–569, 575.

Guérif, J. 1990. Factors influencing compaction-induced increases in soil strength. *Soil & Tillage Research* 16: 167–178.

Gupta, S.C. & Raper, R.L. 1994. Prediction of soil compaction under vehicles. In: Soane, B.D. & Ouwerkerk, C. van (eds.). Soil compaction in crop production. *Developments in Agricultural Engineering* 11. Elsevier Science B.V., The Netherlands. p. 71–90.

– , Sharma, P.P. & DeFranchi, S.A. 1989. Compaction effects on soil structure. *Advances in Agronomy* 42: 311–338.

Hadas, A. 1994. Soil compaction caused by high axle loads-review of concepts and experimental data. *Soil & Tillage Research* 29: 253–276.

Håkansson, I. 1985. Swedish experiments on subsoil compaction by vehicles with high axle load. *Soil Use Management* 1: 113–116.

– 1994a. Soil tillage for crop production and for protection of soil and environmental quality: a Scandinavian viewpoint. *Soil & Tillage Research* 30: 109–124.

– 1994b. Subsoil compaction caused by heavy vehicles-a long-term threat to soil productivity. *Soil & Tillage Research* 29: 105–110.

– & Danfors, B. 1988.The economic consequences of soil compaction by heavy vehicles when spreading manure and municipal waste. *Swedish Institute of Agricultural Engineering. Report* 96(13): 1–10.

– , Grath, T. & Olsen, H.J. 1996. Influence of machinery traffic in Swedish farm fields on penetration resistance in the subsoil. *Swedish Journal of Agricultural Research* 26: 181–187.

– & Petelkau, H. 1994. Benefits of limited axle load. In: Soane, B.D. & Ouwerkerk, C. van (eds.). Soil compaction in crop production. *Developments in Agricultural Engineering* 11. Elsevier Science B.V., The Netherlands. p. 479–500.

– & Reeder, R.C. 1994. Subsoil compaction by vehicles with high axle load – extent, persistence and crop response. *Soil & Tillage Research* 29: 277–304.

– , Voorhees, W.B., Elonen, P., Raghavan, G.S.V., Lowery, B., Wijk, A.L.M. van, Rasmussen, K. & Riley, H. 1987. Effect of high axle load traffic on subsoil compaction and crop yield in humid regions with annual freezing. *Soil & Tillage Research* 10: 259–268.

Hammel, J.E. 1988. Influence of high axle loads on subsoil physical properties and crop yields in the Pacific northwest, USA. *Proceedings 11th International Conference of ISTRO*, 11–15th July, Edinburgh, Scotland. 1: 275–280.

Horn, R. 1980. Die Ermittlung der vertikalen Druckfortpflanzung im Boden mit Hilfe von Dehnungsmessstreifen. *Zeitschrift für Kulturtechnik und Flurbereitung* 21: 343–349.

– 1986. Auswirkung unterschiedlicher Bodenbearbeitung auf die mechanische Belastbarkeit von Ackerböden. *Zeitschrift für Pflanzenernährung und Bodenkunde* 149: 9–18.

– , Blackwell, P.S. & White, R. 1989. The effect of speed of wheeling on soil stresses, rut depth and soil physical properties in an ameliorated transitional red-brown earth. *Soil & Tillage Research* 13: 353–364.

– , Burger, N., Lebert, M. & Badewitz, G. 1987. Druck fortpflanzung in Böden unter fahrenden Traktoren. *Zeitschrift für Kulturtechnik und Flurbereitung* 28: 94–102.

– , Domzal, H., Slowinska-Jurkiewicz, A. & Ouwerkerk, C. van 1995. Soil compaction processes and their effects on the structure of arable soils and the environment. *Soil & Tillage Research* 35: 23–36.

– , Gräsle, W. & Kühner, S. 1996. Einige theoretische Überlegungen zur Spannungs-und Deformationsmessung in Böden und ihre meβtechnishe Realisierung. *Zeitschrift für Pflanzenernährung und Bodenkunde* 159: 137–142.

– & Lebert, M. 1994. Soil compactability and compressibility. In: Soane, B.D. and Ouwerkerk, C. van (eds.). Soil compaction in crop production. *Developments in Agricultural Engineering* 11. Elsevier Science B.V., The Netherlands. p. 45–70.

Kirby. J.M. 1989. Shear damage beneath agricultural tyres: a theoretical study. *Journal of Agricultural Engineering Research* 44: 217–230.

– 1999. Soil stress measurement: Part I. Transducer in a uniform stress field. *Journal of Agricultural Engineering Research* 72: 151–160.

Kooistra, M.J. & Boersma, O.H. 1994. Subsoil compaction in Dutch marine sandy loams: loosening practices and effects. *Soil & Tillage Research* 29: 237–247.

Koolen, A.J. & Kuipers, H. 1983. Agricultural soil mechanics. *Advanced Series in Agricultural Science* 13. Springer-Verlag, Berlin Heidelberg, Germany. 241 p.

– , Lerink, P., Kurstjens, D.A.G., Akker, J.J.H. van den & Arts, W.B.M. 1992. Prediction of aspects of soil-wheel systems. *Soil & Tillage Research* 24: 381–396.

Lebert, M., Burger, N. & Horn, R. 1989. Effects of dynamic and static loading on compaction of structured soils. *NATO Advanced Science Institutes Series. Series E: Applied Science* 172: 73–80.

Lipiec, J., Kania, W. & Tarkiewicz, S. 1990. Effect of wheeling on physical characteristics of soils and rooting of some cereals. *Zeszyty Problemowe Postepow Nauk Rolniczych* 385: 105–114.

– & Simota, C. 1994. Role of soil and climate factors in influencing crop responses to soil compaction in central and eastern Europe. In: Soane, B.D. & Ouwerkerk, C. van (eds.). Soil compaction in crop production. *Developments in Agricultural Engineering* 11. Elsevier Science B.V., The Netherlands. p. 365–390.

Logsdon, S., Allmaras, R.R., Nelson, W.W. & Voorhees, W.B. 1992. Persistence of subsoil compaction from heavy axle loads. *Soil & Tillage Research* 23: 95–110.

Lowery, B. & Schuler, R.T. 1994. Duration and effects of compaction on soil and plant growth in Wisconsin. *Soil & Tillage Research* 29: 205–210.

Montaga, K.D., Conroy, J.P. & Francis, G.S. 1998. Root and shoot response of field-grown lettuce and broccoli to a compact subsoil. *Australian Journal of Agricultural Research* 49: 89–97.

Olfe, G. & Schön, H. 1986. Bodenbelastung durch Schlepper- und Maschineneinsatz in der Landwirtschaft. *KTBL-Schrift* 308: 35–47.

Olsen, H.J. 1994. Calculation of subsoil stresses. *Soil & Tillage Research* 29: 111–123.

Perdok, U.D. & Tijink, F.G.J. 1990. Developments in IMAG research on mechanization in soil tillage and field traffic. *Soil & Tillage Research* 16: 121–141.

Petelkau, H. 1984. Auswirkungen von Schadverdichtungen auf Bodeneigenschaften und Pflanzenertrag sowie Massnahmen zu ihrer Minderung. *Tag.-Ber. Akad. Landwirtsch. – Wiss. DDR, Berlin, Tagungsber.* 227: 25–34.

Pietola, L. 1995. Effect of soil compactness on the growth and quality of carrot. *Agricultural Science in Finland* 4: 139–237.

Plackett, C.W. 1984. The ground pressure of some agricultural tyres at low load and with zero sinkage. *Journal of Agricultural Engineering Research* 29: 159–166.

Pollard, F. & Webster, R. 1978. The persistence of the effects of simulated tractor wheeling on sandy loam subsoil. *Journal of Agricultural Engineering Research* 28: 217–220.

Raghavan, G.S.V. & McKyes, E. 1977. Laboratory study to determine the effect of slip-generated shear on soil compaction. *Canadian Agricultural Engineering* 19: 40–42.

Renius, K.Th. 1994. Trends in tractor design with particular reference to Europe. *Journal of Agricultural Engineering Research* 57: 3–22.

Rusanov, V.A. 1994. USSR standards for agricultural mobile machinery: permissible influences on soils and methods to estimate contact pressure and stress at a depth of 0.5 m. *Soil & Tillage Research* 29: 249–252.

Salire, E.V., Hammel, J.E. & Hardcastle, J.H. 1994. Compression of intact subsoils under short-duration loading. *Soil & Tillage Research* 31: 235–248.

Schjønning, P. & Rasmussen, K. 1994. Danish experiments on subsoil compaction by vehicles with high axle load. *Soil & Tillage Research* 29: 215–227.

Schmidt, W. & Rohde, S. 1986. Untersuchungen zur wirkung von Raddruck auf die Lagerungsdichte von Niedermoorboden. *Archiv Acker- und Pflanzenbau und Bodenkunde* 30: 37–44.

Schuler, R.T. & Lowery, B. 1984. Subsoil compaction effect on corn production with two soil types. *American Society of Agricultural Engineers. Paper* 84/1032. 13 p.

Simojoki, A., Jaakkola, A. & Alakukku, L. 1991. Effect of compaction on soil air in a pot experiment and in the field. *Soil & Tillage Research* 19: 175–186.

Smith, D.L.O. 1985. Compaction by wheels: a numerical model for agricultural soils. *Journal of Soil Science* 36: 621–632.

Soane, D.B., Blackwell, P.S., Dickson, J.W. & Painter, D.J. 1981. Compaction by agricultural vehicles: A review. II. Compaction under tyres and other running gear. *Soil & Tillage Research* 1: 373–400.

– & Ouwerkerk, C. van 1994a. Soil compaction in crop production. *Developments in Agricultural Engineering* 11. Elsevier Science B.V., The Netherlands. 662 p.

– & Ouwerkerk, C. van 1994b. Soil compaction problems in world agriculture. In: Soane, B.D. & Ouwerkerk, C. van (eds.). Soil compaction in crop production. *Developments in Agricultural Engineering* 11. Elsevier Science B.V., The Netherlands. p. 1–21.

– & Ouwerkerk, C. van 1995. Implications of soil compaction in crop production for the quality of the environment. *Soil & Tillage Research* 35: 5–22.

Söhne, W. 1953. Druckverteilung im Boden und Bodenverformung unter Schlepper Reifen. *Grundlagen der Landtechnik* 5: 49–63.

– 1958. Fundamentals of pressure distribution and soil compaction under tractor tires. *American Engineering* 39: 276–281, 290.

Sommer, C. & Altemüller, H.J. 1982. Direkt- und Nachwirkungen starker verdichtungen auf das Bodengefüge und den Pflanzenertrag. *Mitteilungen Deutsche Bodenkundliche Gesellschaft* 34: 187–192.

Stewart, G.A. & Vyn, T.J. 1994. Influence of high axle loads and tillage systems on soil properties and grain corn yield. *Soil & Tillage Research* 29: 229–235.

Taylor, J.H., Burt, E.C. & Bailey, A.C. 1980. Effect of total load on subsurface soil compaction. *Transaction of American Society of Agricultural Engineers* 23: 568–570.

Tijink, F.G.J. 1994. Quantification of vehicle running gear. In: Soane, B.D. & Ouwerkerk, C. van (eds.). Soil compaction in crop production. *Developments in Agricultural Engineering* 11. Elsevier Science B.V., The Netherlands. p. 391–416.

Vermeulen, G.D., Arts, W.B.M. & Klooster, J.J. 1988. Perspective of reducing soil compaction by using a low ground pressure farming system; selection of wheel equipment. *Proceedings 11th International Conference of ISTRO*, 11–15th July, Edinburgh, Scotland 1: 329–334.

Voorhees, W.B. 1991. Compaction effects on yield – are they significant? *Transaction of American Society of Agricultural Engineers* 34: 1667–1672.

– 1992. Wheel-induced soil physical limitations to root growth. *Advances in Soil Science* 19: 73–95.

– & Lindstrom, M.J. 1983. Soil compaction constraints on conservation tillage in the northern corn belt. *Journal of Soil Water Conservation* 38: 307–311.

– , Nelson, W.W. & Randall, G.W. 1986. Extent and persistence of subsoil compaction caused by heavy axle loads. *Soil Science Society of America Journal* 50: 428–433.

– , Senst, C.G. & Nelson, W.W. 1978. Compaction and soil structure modification by wheel traffic in the northern corn belt. *Soil Science Society of America Journal* 42: 344–349.

Whalley, W.R. & Dexter, A.R.1994. Root development and earthworm movement in relation to soil strength and structure. *Archiv für Acker- und Pflanzenbau und Bodenkunde* 38: 1–40.

Wong, J.Y. 1986. Computer aided analysis of the effects of design parameters on the performance of tracked vehicles. *Journal of Terramechanics* 23: 95–124.

– & Preston-Thomas, J. 1984. A comparison between a conventional method and an improved method for predicting tracked vehicle performance. *Proceedings 8th International Conference of International Society for Terrain-vehicles Systems,* 5–11th August, Cambridge, England. p. 361–380.

Wood, R.K., Reeder, R.C., Morgan, M.T. & Holmes, R.G. 1993. Soil physical properties as affected by grain cart traffic. *Transaction of American Society of Agricultural Engineers* 36: 11–13.

Worldwatch Institute 1996. *State of the World.* Worldwatch Institute, Washington D.C., USA. 209 p.

Wu, L., Allmaras, R.R., Gimenez, D. & Huggins, D.M. 1997. Shrinkage and water retention characteristic in a fine-textured mollisol compacted under different axle loads. *Soil & Tillage Research* 44: 179–194.

SELOSTUS

Raskaan peltoliikenteen aiheuttama pitkäaikainen maan tiivistyminen

Laura Alakukku

Maatalouden tutkimuskeskus

Maataloudessa käytettävien koneiden tehot ja painot ovat kasvanut viime vuosikymmenien aikana jatkuvasti. Tämä on lisännyt pohjamaan tiivistymisriskiä. Tässä kirjoituksessa tarkastellaan, miten maan ominaisuudet ja peltoajoon liittyvät tekijät vaikuttavat pohjamaan tiivistymiseen. Lisäksi selvitetään, miten pohjamaan tiivistymisen vaikuttaa maahan, peltoviljelyyn, satoon ja ympäristöön.

Pohjamaan tiivistymisriski on suuri, kun kostealla pellolla ajetaan raskaalla kalustolla, jonka pintapaine on kohtalainen tai suuri. Tiivistymisen ehkäisemiseksi on annettu yksittäisiä suosituksia akselipainon, pintapaineen ja maassa 0,50 metriin ulottuvan jännityksen ylärajaksi. Tekniset suoditukset pitkäaikaisten tiivistymishaittojen ehkäisemiseksi tulisi kuitenkin laatia kansainvälisenä yhteistyönä. Ennen suositusten laatimista on tutkittava mm. pohjamaiden kuormituksen kestävyyttä vaihtelevissa olosuhteissa.

Pohjamaan tiivistyminen vaikuttaa lähes kaikkiin maan fysikaalisiin, kemiallisiin ja biologisiin ominaisuuksiin ja prosesseihin. Se on todettu pienentävän myös kasvien satoa ja typenottoa. Tutkimusten mukaan pohjamaan tiivistymisen vaikutukset säilyvät pitkään. Karkeissa maissa ne voivat olla jopa pysyviä.