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Computed reconstruction of field traffic patterns

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ABSTRACT

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The relationship between the degree of mechanization and the risk of soil compaction on arable farmland was studied, assuming soil conditions did not vary between mechanization systems. An inventory of machine characteristics and all field operations needed to grow the various crops was made on 27 arable farms in The Netherlands. The data obtained were processed so that crop-specific field rut patterns could be reconstructed. An indication of the number of wheel passes, together with information on tyre inflation pressure, wheel load and the soil compaction risk factor, was included.

The wheeled area varies with crop type and farm size, owing to differences in the mechanization. Traffic intensity, or the number of times total coverage of the arable field with ruts occurs, varies between 5.4 ha ha^{-1} $year^{-1}$ for a potato crop (farm sizes <35 ha) and 2.2 ha ha^{-1} $year^{-1}$ for winter wheat (farm sizes between 55 and 80 ha). Considering the average crop rotation occurring on the farms, traffic intensity decreased from 3.9 ha ha^{-1} $year^{-1}$ (farm sizes <35 ha) to 3.2 ha ha^{-1} $year^{-1}$ (farms >80 ha).

The compaction risk factor tends to increase with growing farm sizes. From 80 ha onwards, however, the factor remains constant mainly owing to lower traffic intensity and maximum sizes of tyres, tyre inflation pressure and wheel load. Compaction measurements in normal arable farming practice give way to the assumption that penetration resistance is correlated with farm size, and thus with the degree of mechanization.

INTRODUCTION

During the last 20 years, general field surveys as well as specific complaints have revealed considerable soil degradation, occurring as deterioration of soil structure and an increase in compaction of the subsoil. During the same period, two agricultural developments were observed in The Netherlands: (i) advancing mechanization with increasing wheel loads; (ii) intensification of crop rotation.

To a large extent, crops such as rye and oats have undergone a considerable

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decline, whereas the production of potatoes, sugar beet and fodder maize has increased, yielding a considerably greater mass for harvest later in the year, usually with wetter soil conditions. Mechanization is accompanied by an increase in the working width, weight and power of the equipment. Despite the use of wider tyres, subsoil compaction becomes increasingly more serious and extends to a depth beyond that of the annual main soil tillage, precisely because of the wider tyre sizes (Boels, 1982; Koolen and Kuipers, 1983).

The extent to which a soil will be compacted during field operations depends on the type of field traffic as well as on the prevailing soil conditions. The pressures exerted on the soil by wheel traffic may vary widely depending on tyre properties (dimension, ply rating and inflation pressure) and wheel load. Moreover, when loaded, soils behave differently depending on the wheel load, soil texture, bulk density and especially moisture conditions (Koolen and Kuipers, 1983). However, it is often very difficult to study the effects of all the possible combinations of these factors in the field. Also, the transference of data obtained from experimental fields to other combinations of soil and traffic is often rather difficult. Therefore, in addition to field studies there is a great need for models, using both traffic and soil characteristics as input data, which enable soil compaction under a wide variety of traffic and soil conditions to be described.

Recently attempts have been made to predict soil compaction due to field traffic with computer models using the above-mentioned parameters (Karafiath and Nowatzki, 1978; Raghavan and McKyes, 1978; Blackwell and Soane, 1981; van den Akker and van Wijk, 1987). Applying such models to practical situations requires information concerning wheel loads, tyre sizes, tyre inflation pressure, and traffic intensity and frequency occurring under normal farm conditions when growing various crops. A clear picture of the relationship between these factors and the degree of mechanization on arable farms is not available. Therefore, an investigation consisting of the following three parts was conducted:

(1) An inventory was made of the relationship between mechanization, field traffic intensity and frequency, and soil compaction for different farm sizes and soil types.

(2) Data were processed, enabling crop-specific field traffic patterns to be reconstructed, including an indication of the number of wheel passes, tyre inflation pressure, wheel load and risk of soil compaction.

(3) The amount of wheel traffic occurring on arable land was quantified in order to use computer simulation programs to predict soil compaction due to wheel traffic (van den Akker and van Wijk, 1987).

The combination of wheel loads and inflation pressure with the area covered by ruts per hectare reflects the impact of mechanization on the soil. It is a reasonable assumption that growing a crop is related to specific rut patterns due to fixed wheel spacing distances, implement width and crop row spacing.

A computer program (RUTPAT) was developed to reconstruct such rut patterns from the collected data.

In the RUTPAT program field traffic frequencies and intensities could be visualized in the form of rut patterns with known tyre dimensions, tyre inflation pressures and wheel loads, all in connection with farm size and type of crop. These data coupled with the stress distributions in the soil–tyre contact surface will enable model calculations of the extent of soil compaction in different farm systems to be made. The output of RUTPAT must, therefore, also be seen as input for the soil compaction model SOCOMO (Van den Akker and Van Wijk, 1987; Van den Akker, 1988), as in SOCOMO the effect of field traffic on the density of the subsoil is evaluated according to different conditions of loading and compactability (depending on soil type and moisture conditions).

From the rut patterns obtained, it can be derived how often and how severely a strip of land is subjected to loading. Also, the total area that comes into contact with wheels per hectare of land per year can be obtained. To indicate differences in the risks of soil compaction, a compaction risk factor is calculated for each strip of land. Under given soil conditions, the risk of soil compaction is not simply determined by traffic intensity and frequency, but depends predominantly on machine parameters such as wheel load, wheel dimensions, and tyre inflation pressure. To quantify the risk of soil compaction during various field operations, wheel load is multiplied by inflation pressure and traffic intensity, and is expressed in $kN^2\ ha^{-1}$. The information thus obtained can be used to judge the consequences of advancing mechanization in relation to the risk of soil compaction and its spatial variability in the field.

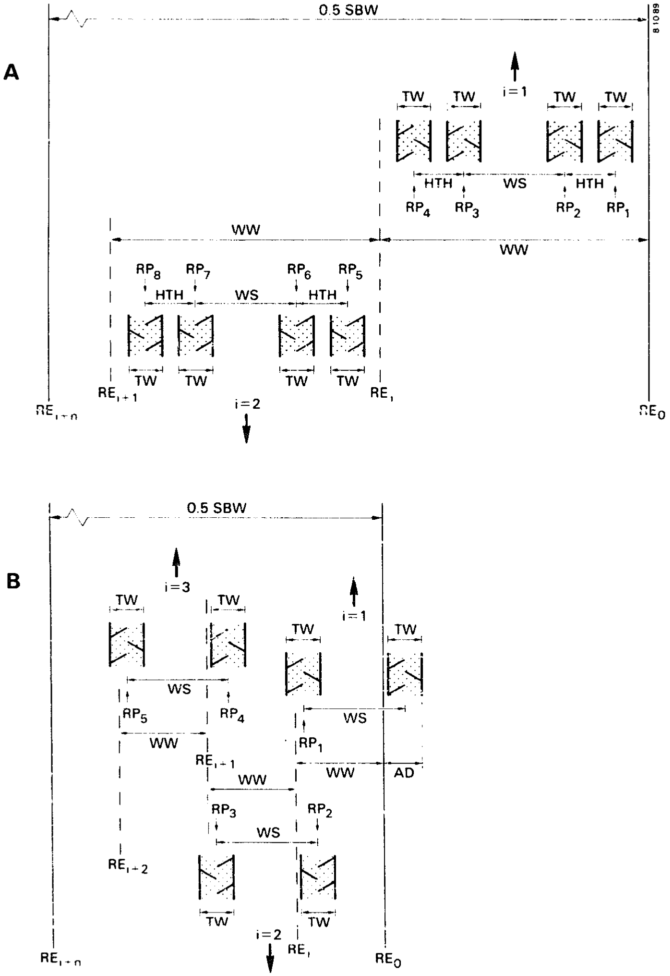
This article explains how specific equipment data can be used to reconstruct field traffic patterns. An example of a computed field traffic map is given and summarized data are computed for traffic intensity and compaction risk for winter wheat, potatoes, sugar beet, and the crop rotations practiced on farms differentiated by size. To characterize the influence of mechanization on soil compaction, penetration resistances have been measured. Results of these measurements are given grouped according to categories made for farm size and texture of the arable layer.

MATERIALS AND METHODS

Assuming a relationship between farm size and degree of mechanization, the research was done on arable farms in the southwest region of The Netherlands. Twenty-seven farms were selected on the basis of farm size and texture of the arable layer. The farm sizes were <35, 35–55, 55–80, 80–200 ha, and one farm of 1200 ha, representing a total acreage of approximately 2500 ha.

Degree of mechanization

To characterize the degree of mechanization, an attempt was made to vis-



ualize it by mapping the total field traffic needed for growing a crop in the form of rut patterns (see also Soane et al., 1982; Lumkes, 1984). In close consultation with the farmers, a complete inventory was made of all field operations for the various crops grown on specific fields in the period 1980–1983, and of the implements used to cultivate those crops on each of the selected farms. For each field operation applied in a given crop rotation, data were collected on: (i) date of field operation (ii) soil condition at time of field operation; (iii) implement or combination of equipment used; (iv) driving speed; (v) wheel spacing distances; (vi) tyre sizes and inflation pressures; (vii) wheel loads; (viii) working width and depth.

In the developed program RUTPAT, it is assumed that a strip of land the width of half the boom length of a field sprayer (the implement with the broadest working width) comprises all field operations during cultivation of a crop. In fact, all field operations occur at least once within this strip and thus the strip can be taken to be representative of all that is happening over the entire field.

In the program, all field operations start at the right-hand edge (RE_o) of the strip (Fig. 1). The strip is filled with wheel passes, originating from the consecutive field operations during the crop cultivation period. The program receives information gathered in the field inventory from input files containing data on farm and field code, farm size, crop name, number and type of field operations, plus the following:

SBW = working width (m) of the sprayer;
WS = wheel spacing distance (cm);
HTH = heart to heart distance twin tyres (cm);
TW = tyre width (cm);
TD = tyre diameter (cm);
WW = working width of the implement (cm);
ATO = tyre inflation pressure (kg cm^{-2});
$GRAM$ = wheel load (kg);

Fig. 1. Calculation diagram of the rut pattern for the field operations where the wheels are positioned (a) symmetrically and (b) asymmetrically (a special case; ploughing with one wheel riding in the open furrow) to the working width.
AD = asymmetric distance of working width and wheel spacing;
HTH = heart to heart distance of twin tyres;
LR = left–right option factor; +1 for right wheel, −1 for left wheel;
RE_o = right border of the strip;
RP_i = rut place;
SBW = spray boom width;
TW = tyre width;
WS = wheel spacing;
WW = working width;
i = number of passes within the strip.

VEL = driving speed ($\mathrm{km\,h^{-1}}$).

This is done for all successive cultivation activities from ploughing after the former crop to harvesting the crop under consideration. In this way, all ruts originating from field traffic needed to grow a crop could be located.

To calculate the exact pattern of the ruts, the positioning of wheels (symmetric or asymmetric to the working width) must be distinguished (as illustrated in Fig. 1a and b). Symmetric positioning occurs in most field operations, such as transport, tillage, sowing, spraying and fertilizing. Rut places RP_i can generally be determined using the following formula

$$RP_i = RE_i + LR * (0.5 * WS + HTH) - 0.5 * WW + AD \tag{1}$$

with

$$RE_{i+1} = RE_i - WW \tag{2}$$

for

$$0 \leq RE_i \leq 0.5 * SBW \tag{3}$$

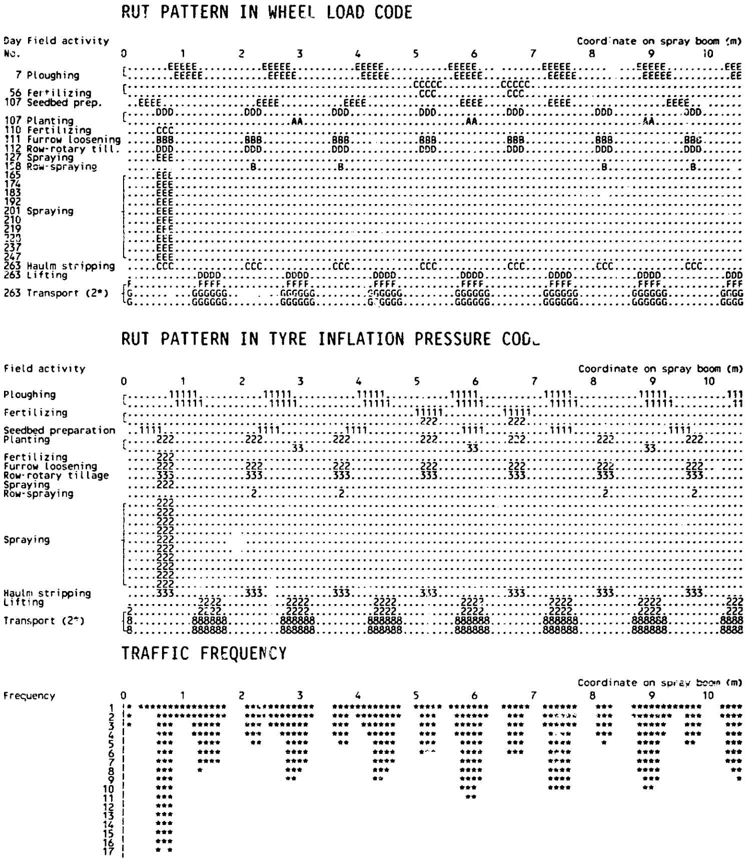
A particular case of asymmetry is formed when ploughing with a working width of <2.0 m (Fig. 1b). It is assumed that in this situation one wheel runs in the plough furrow. This is generally the practice in The Netherlands. The calculation diagram for this case is presented in Fig. 1b and can be derived for the asymmetric distance AD

$$AD = 0.5 * (WW - WS + TW) \ . \tag{4}$$

From the right-hand edge a strip equal to the working width is ploughed. The

Fig. 2. Computed map indicating traffic intensity in terms of wheel load and tyre inflation pressure (upper part) and traffic frequency (lower part) of field activities on a specific date (Julian day no.) on a 10.5-m-wide strip (spray boom width, subdivided into 10-cm-wide strips) needed to grow potatoes on a 150 ha farm in 1982.
Codes used for tyre inflation pressures and wheel loads

Tyre inflation pressure (bar)	Code	Wheel load (kg)	Code
0.5–1.0	0	0– 500	A
1.0–1.5	1	500–1000	B
1.5–2.0	2	1000–1500	C
2.0–2.5	3	1500–2000	D
2.5–3.0	4	2000–2500	E
3.0–3.5	5	2500–3000	F
3.5–4.0	6	3000–3500	G
4.0–4.5	7	3500–4000	H
4.5–5.0	8		



first rut on the surface is found one wheel spacing distance from the right-hand edge minus half a wheel width. The first rut in the furrow is formed at a distance of half a wheel width to the right of the right-hand edge. The right-hand edge is subsequently moved one working width to the left (see eqn. (2)) and the procedure starts again until the whole strip has been worked (see eqn. (3)).

When the location and width of a rut within the strip has been determined in the way indicated above, the program supplies information about wheel load and tyre inflation pressure of the implement to each rut using codes (Fig. 2). In addition to reconstructing the rut pattern, the program computes traffic intensity, traffic frequency and the compaction risk factor.

Traffic intensity is defined as the total area that comes into contact with wheels per hectare of cropped land per year. For each field operation, traffic intensity can be calculated using

$$TI = 100/WW * TW * TF \qquad (5)$$

where TI is the traffic intensity (area coming into contact with wheels in ha ha^{-1}, WW is the working width (cm), TW is the tyre width (cm), and TF is the twin tyre factor (=2, or 4 if twin tyres are used).

To obtain the traffic frequency of the strip (which is subdivided into separate strips of 10 cm), the number of wheel passages over the entire cultivation period of a crop is counted for each 10-cm strip. The severity of field traffic in relation to soil compaction is expressed in the compaction risk factor which can be obtained for each 10-cm strip from

$$CRF = GRAM * ATO * TI * 10^{-4} \qquad (6)$$

where CRF is the compaction risk factor (kN^2 ha^{-1}), $GRAM$ is the wheel load (kg), ATO is the tyre inflation pressure (kg cm^{-2}), and TI is the area covered by ruts (ha ha^{-1}).

Because soil moisture conditions are dealt with in the soil compaction model SOCOMO (Van den Akker, 1988) it has not been introduced again in the compaction risk factor (*CRF*) defined in RUTPAT. Velocity was omitted from the *CRF* because of the small differences in speed at which field operations occurred (0.5–1.5 m s^{-1}).

Mechanization and soil compaction

To investigate the influence of mechanization on soil compaction, three fields were selected on each farm. For each field, distinctions were made with respect to the texture of the arable layer: 10–15%, 15–25%, 25–35%, 35–45% and >45% of soil particles smaller than 16 μm. The penetration resistance was measured up to a depth of 70 cm with a penetrograph (conus: top apex 60°, base 1 cm^2). The measurements were carried out ten times at an oblique angle (45°) to the direction of field operations, at four places in each field.

In addition to the penetrometer readings, bulk density was measured six times in four layers of 10 cm directly below the arable layer. For each farm size category, two fields were cored, one in the texture category of 15–25% and the other in the category of 25–35% particles < 16 μm.

RESULTS AND DISCUSSION

An output of the computer program RUTPAT is shown in Fig. 2. It concerns a computerized map giving the field traffic intensity in terms of wheel loads and tyre inflation pressure (upper part) and frequency of field traffic on a 10.5-m-wide strip needed to grow potatoes on a 150 ha farm. Some strips come into contact with wheels very frequently and others are never subjected to traffic when cropping potatoes. The ruts formed by the field sprayer coincide with ruts from other field operations. The strip of land under consideration came into contact with wheels up to 17 times. Strips where ruts from ploughing and harvesting are situated were subjected to wheel traffic less frequently but at higher wheel loads and inflation pressures.

Degree of mechanization

The traffic intensity and *CRF* on all farms involved in this investigation for the crops potatoes, sugar beet and winter wheat and for the crop rotation carried out on these farms is presented in Fig. 3. In the case of the potato crop, the difference in traffic intensity between the farm size category < 35 and the farm size categories 35–55, 55–80 ha and the 1200 ha farm is significant (Table 1) ($P \leq 0.10$, test = least significant difference (LSD)).

Field operations that contribute excessively to traffic intensity are ploughing, potato-lifting and transport. With the increasing size of farms, the working width of ploughs increases and the potato harvesters used change from one-row to two-row lifters. The transport trailers change from 5 t one-axle and small bi-axle ones on farms < 55 ha to larger tandems with up to 16 t loading capacity with greater tyre sizes on the larger farms (Table 2).

In the case of sugar beet a less clear relationship between traffic intensity and farm size is found (Fig. 3). This is mainly due to the great variation in machinery used for harvesting. On the smaller farms both one-row (working width 0.50 m) and six-row (working width 3.00 m) lifters are applied. The latter category is used mainly by contractors and are self-propelled. The traffic intensity on the 1200 ha farm is significantly ($P \leq 0.10$, test = LSD) lower than on all other farm sizes (Table 1).

The traffic intensities found for winter wheat are significantly lower ($P \leq 0.01$, test = LSD) than for potatoes and sugar beet (Table 1). Also, for winter wheat a decrease in traffic intensity with increasing farm size is observed, mainly owing to the use of wider implements for ploughing and seedbed preparation (Fig. 3). The 1200 ha farm has a traffic intensity greater than the 55–80 and 80–200 ha farms, owing to the more extensive practice of post-harvest tillage.

The differences in mean traffic intensity for potatoes, sugar beet, and win-

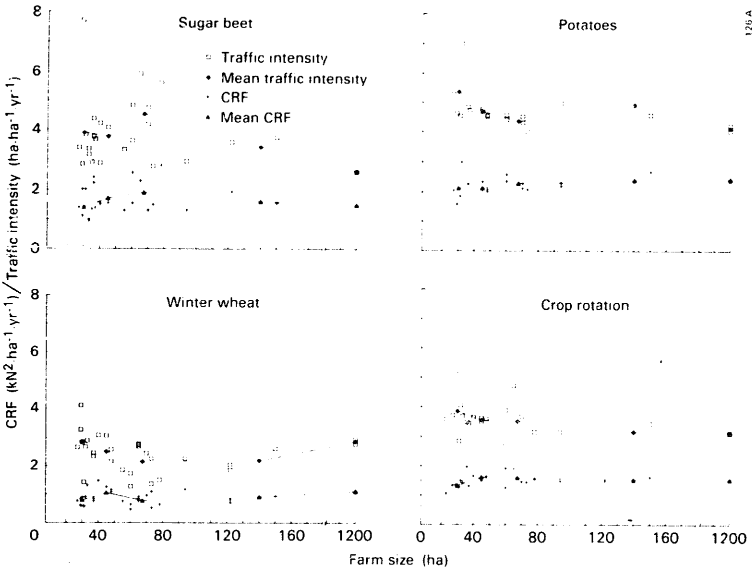


Fig. 3. Relationship between traffic intensity (ha ha^{-1} year^{-1}), compaction risk factor (kN^2 ha^{-1} year^{-1}) and farm size (ha) for the crops sugar beet, potatoes and winter wheat and the crop rotations practiced on farms of different sizes.

TABLE 1

Traffic intensity for potato, sugar beet and winter wheat crops and for the crop rotations practised on farms of different sizes

	Traffic intensity (ha ha^{-1} year^{-1})					
	< 35 ha	35–55 ha	55–80 ha	80–200 ha	1200 ha	Mean
Potato	5.37(a)	4.69(b)	4.37(b)	4.93(a,b)	4.13(b)	4.73(x)
Sugar beet	3.90(c,d)	3.77(c,d)	4.54(d,b)	3.44(c,d)	2.62(c)	3.94(y)
Winter wheat	2.88(c,e)	2.52(e,f)	2.16(f)	2.21(f)	2.89(c,e)	2.52(z)
Crop rotation	3.86(g)	3.56(g,h)	3.52(g,h)	3.17(g,h)	3.13(h)	3.56
Mean 3 crops	3.65(i)	3.61(i)	3.42(i)	3.39(i)	3.33(i)	3.52

Superscripts a–f denote pairs of groups significantly different at the 0.10 level, test = LSD; g–i denote pairs of groups significantly different within the rows only at the 0.10 level, test = LSD; x–z denote pairs of groups significantly different within the mean column at the 0.01 level, test = LSD.

TABLE 2

Mean tyre width and mean wheel load of tractors used for ploughing and trailers used for harvest field transport for different farm size categories in The Netherlands

Farm size (ha)	N[1]	Tractors		Trailers	
		Tyre width (cm)	Wheel load (kg)	Tyre width (cm)	Wheel load (kg)
<35	22	35.0±2.5	1630±475	35.5±4.0	2300±200
35–55	20	38.0±4.0	1690±345	39.0±8.0	2750±450
55–80	22	40.0±5.0	2010±340	43.5±5.0	2875±300
80–200	10	47.0±0.5	2325± 50	41.0±1.4	2675±375
1200	5	58.0±0.5	1800± 50	38.0±0.5	2550± 50

[1] Number of observations

TABLE 3

Compaction risk factor for potato, sugar beet and winter wheat crops and for the crop rotation practiced on farms of different sizes

	Compaction risk factor (kN^2 ha^{-1} year^{-1})					
	<35 ha	35–55 ha	55–80 ha	80–200	1200 ha	Mean
Potato	2.14(a)	2.14(a)	2.30(a)	2.41(a)	2.43(a)	2.25(x)
Sugar beet	1.42(b)	1.72(b,c)	1.92(a,c)	1.62(b,c)	1.51(b,c)	1.68(y)
Winter wheat	0.80(d)	1.06(e)	0.78(d)	0.92(d,e)	1.12(e)	0.88(z)
Crop rotation	1.34(g)	1.62(h)	1.60(h)	1.54(g,h)	1.54(g,h)	1.52
Mean 3 crops	1.24(i)	1.61(j)	1.49(i,j)	1.58(i,j)	1.72(j)	1.48

Superscripts a–e denote pairs of groups significantly different at the 0.10 level, test=LSD; g–j denote pairs of groups significantly different within the rows only at the 0.10 level, test=LSD; x–z denote pairs of groups significantly different within the mean column at the 0.01 level, test=LSD.

ter wheat (4.73, 3.94 and 2.52 ha ha^{-1} year^{-1}, respectively) are statistically significantly ($P \leq 0.01$, test=LSD).

For the crop rotations carried out on the farms, only the traffic intensities of the small farms (<35 ha) and the large farm (1200 ha) are statistically significantly different ($P \leq 0.10$, test=LSD).

The relationship between compaction risk and farm size for different crops and for the crop rotation practiced is given in Fig. 3 and in Table 3. In the case of potatoes and winter wheat cropping, the risk of compaction tends to increase with increasing farm sizes despite decreasing traffic intensity (Fig. 3). For sugar beet, the farms in the size category of 55–80 ha are mechanized in such a way that the risk of soil compaction is greater than on smaller or larger farms.

From Table 3 one may draw the conclusion that the replacement of cereals by root crops is related to an increase in the risk of soil compaction. Root crops require more soil tillage and are generally harvested using equipment with a relatively small working width. Therefore, the soil is almost completely covered by wheel tracks owing to root crop harvesting. Moreover, 40–60 t of potatoes or sugar beet need to be transported from the field later in the growing season, usually under soil moisture conditions ideal for compaction. The differences in the mean compaction risk factor for potatoes, sugar beet and winter wheat (2.25, 1.68 and 0.88 kN^2 ha^{-1} $year^{-1}$, respectively) are statistically significant ($P\leq 0.01$, test=LSD).

For the crop rotations carried out on the investigated farms the compaction risk factor in the farm size category <35 ha is significantly lower (Table 3) than for farms in the farm size categories 35–55 and 55–80 ha ($P\leq 0.10$, test=LSD).

Mechanization and soil compaction

Figure 4 shows the penetrometer readings on the field for which Fig. 2 was computed. Spatial variability of penetration resistance with depth distribution is large; even at each sampling point, variability is large. At each sampling point, penetrometer readings showed patterns in the penetration resistance distribution which resembled the rut pattern distribution as demonstrated in Fig. 2.

To characterize the influence of mechanization degree on soil compaction, the penetrometer readings were grouped according to the categories made for farm size and texture of the arable layer. Figure 5 summarizes these measurements. The curves represent minimum and maximum distributions with depth enclosing the 95% confidence interval. When the penetration resistance exceeds a value of 2.5–3.0 MPa, soil density seriously impedes root penetration. Considering Fig. 5, this will be the case on many of the fields investigated. Of

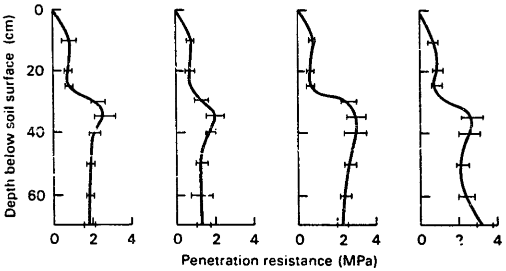


Fig. 4. Place and distribution of penetration resistance (mean plus 95% confidence intervals) with depth for four sampling locations on a field needed to grow potatoes on a 150 ha farm (example of a field with arable layer in texture class 15–25% particles < 16 μm).

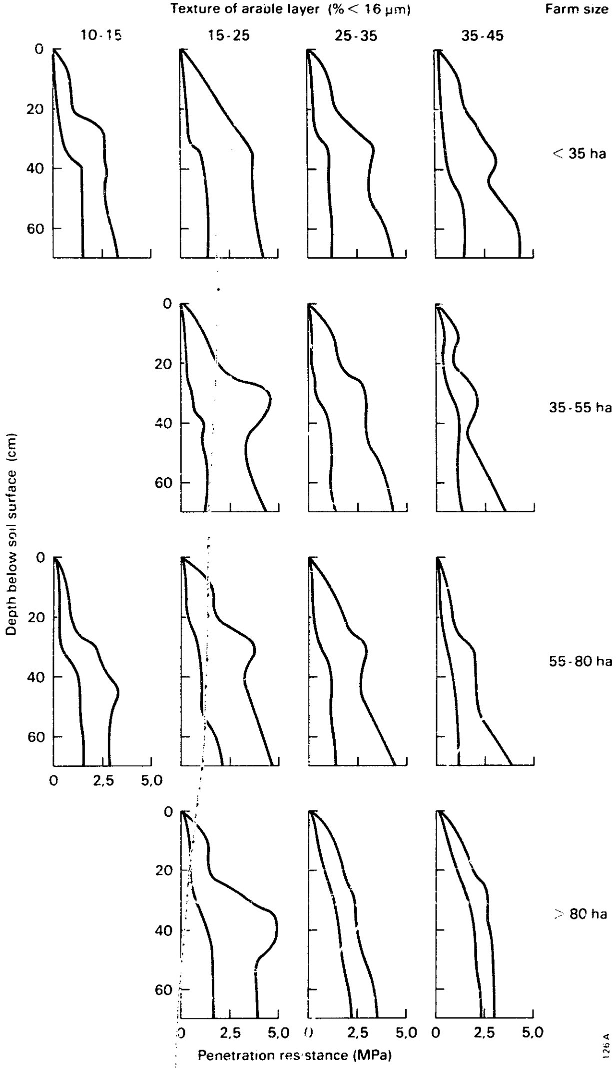


Fig. 5. Distribution of minimum and maximum 95% confidence intervals of penetration resistance (MPa) with depth for different categories of soil texture (% arable layer < 16 μm) and farm sizes (ha).

note are the sometimes extremely high compaction levels found immediately below the arable layer, especially for the texture class of 15–25% particles $< 16\ \mu m$. At heavier textures compaction below the arable layer is less pronounced. High densities in the subsoil below a depth of about 50 cm cannot be ascribed to mechanization but more probably to sedimentary deposition. The influence of farm size may be detected from the size of the intervals between minimum and maximum curves, which become more narrow in cases of larger farm sizes, mainly because of a shift of minimum penetration resistances to higher values.

From bulk density and pore volume readings measured on a number of fields from where the penetrometer readings also originated, the same tendencies emerged as found from the penetrometer readings. The layer from about 25 up to 50 cm below surface generally showed the highest density. Moreover, the compaction tends to extend to greater depths on farms larger than 55 ha. The latter may be connected with wider tyres applied on larger farms. The mean tyre width of tractors used on farms <35 ha amounts to 35 cm and on farms >80 ha, mean tyre width is 47 cm. The ground pressure exerted depends on the combination of wheel load, tyre inflation pressure and tyre dimensions. Increasing tyre width enlarges the contact surface and reduces the ground pressure, but that pressure is propagated to a greater depth. Soils normally withstand without compaction a mean ground pressure of about 1 bar corresponding to a tyre inflation pressure of about 0.6–1 bar. However, most tractors have tyre inflation pressures varying between 1 and 2.5 bar and those of transport trailers, 3–5 bar (see also Fig. 2).

In conclusion, this development can only lead to more soil compaction, the reversal of which will be even more difficult because of the increasing depth of occurrence.

CONCLUSIONS

Mean seasonal traffic intensity varies between 2.2 ha ha^{-1} $year^{-1}$ for winter wheat (farm size 55–80 ha) and 5.4 ha ha^{-1} $year^{-1}$ for a potato crop (farm size <35 ha). Traffic intensity for average crop rotations, as practiced on the investigated farms, decreases from 3.9 ha ha^{-1} $year^{-1}$ for farm sizes <35 ha to 3.2 ha ha^{-1} $year^{-1}$ for farm sizes between 80 and 200 ha.

The compaction risk factor tends to increase with growing farm sizes, although levelling off occurs from 80 ha onwards owing to maximum sizes of tyres, tyre inflation pressure, and wheel load. On the investigated farms, the differences between mean traffic intensity and mean compaction risk factor are statistically significant for potato, sugar beet, and winter wheat crops.

The foregoing illustrates the applicability of the program to a comparison of mechanization levels and their consequences for the rate of trafficking agricultural land. The area of land subjected to different levels of ground pres-

sure and distribution of loading over the land can be easily determined with the program. Places incurring the greatest risk of soil compaction and those field operations which are the most harmful can be indicated. Measured penetrometer readings indicate that a minimum penetration resistance grows with increasing farm size. Mean penetration resistance tends to extend to greater depths for larger farms.

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