EFFECT OF TRAFFIC INTENSITY ON SOIL STRUCTURE AND ROOT DEVELOPMENT IN A FIELD EXPERIMENT ON A SANDY CLAY LOAM SOIL IN THE NETHERLANDS

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INTRODUCTION

In the Netherlands, political and socioeconomic developments have forced farmers to use intensive (narrow) crop rotations with a large proportion of high-yielding, high-profit root crops or silage maize and to strongly increase the degree of mechanization of their farms (stronger tractors, powered implements, wider implements, larger trailers). Consequently, both total load and contact pressures of running gear have increased such that present-day field operations usually are accompanied by harmful soil compaction of the topsoil and, increasingly, of the subsoil. It is now generally believed that soil compaction is one of the most important causes of physical soil degradation.

Compaction and smearing are promoted by wet soil conditions, which usually prevail in autumn when root crops are harvested and transported from the field, and in spring at the time of fertilizer application and seedbed preparation and sowing when, as a rule, the soil is only superficially dry. The damage due to soil compaction and smearing inflicted just prior to or during seedbed preparation is irreparable and may have a direct negative effect on seedbed quality and, thus, on seedling emergence and early crop growth. This may result in an irregular stand and a shortened growing period. Eventually, these effects may result in yield reductions. Deeper-seated compaction may induce denitrification and hamper root proliferation, which may lead to a reduced uptake capacity of the roots (De Willigen and Van Noordwijk, 1987a). This may have a negative effect on crop development in later stages and may induce early senescence. Consequently, harvest operations may be more difficult, biomass production may be decreased and quality of yield components may be unsatisfactory.

After harvest of root crops and silage maize, attempts to repair the damage done to the structure of the topsoil are often only partly successful, as in this season weather conditions are usually not conducive to effective loosening of compacted topsoil by primary tillage operations. Thus, soil compaction induced in autumn often results in unsatisfactory soil structure below the seedbed of spring-sown crops. Alleviation of subsoil compaction is very costly and soil conditions favourable to this operation only occur in unusually dry summers. Whether or not subsoil compaction is always a real threat is probably determined by the physical properties of the subsoil, which may vary considerably in different soil profiles.

Based on previous research and in view of current economical and technical developments, the hypothesis was put forward that, in the Netherlands, the use of low ground-pressure tyres, around the year, would be a manageable, albeit partial solution to the soil compaction problem (Van Ouwerkerk, 1986). During 1984-1989, this hypothesis was tested in a large-scale field experiment in which a working group, consisting of research workers of the Wageningen Agricultural University, four research institutions and one research station, performed specialized investigations into the soil mechanical properties (Lerink, 1990), seedbed quality, soil structure (macro and micro), hydraulic properties and soil water movement, root development, and crop development and yield (Chamen et al., 1990).

METHODS

Layout of the experiment

In the autumn of 1984, an experimental field was laid out on a typical heterogeneous, calcareous sandy clay loam soil (3.4-9.0%,w/w $CaCO_3$; 1.6-2.6%,w/w organic matter; 12.6-32.7%,w/w clay) in the northwest of the Netherlands. The experimental field consisted of 4 blocks (A-D) of 100 x 212 m, each of which carried one crop of a typical four-year, intensive crop rotation consisting of potatoes - winter wheat undersown with rye grass - sugar beet - onions. Each block was split into 4 plots of 50 x 100 m, on which around the year all field traffic was performed with normal "high"-pressure tyres (Treatment H) or with special "low"-pressure tyres (Treatment L), and 2 narrow strips (6 x 100 m), positioned between the large plots, which were allocated to zero-traffic (bed system; Treatment Z). Soil tillage and all other cultural treatments were the same for all three field traffic systems.

Primary tillage for potatoes and sugar beet consisted of ploughing to 25 cm depth with a 3-body mouldboard plough (Treatments H and L) or to 20 cm depth with a 10-body skim plough (Treatment Z). For onions (after sugar beet) and winter wheat (after potatoes), a crankshaft digger was used to 25 cm depth in all three traffic systems. For winter wheat, crankshaft digging was combined with sowing. Seedbed preparation for sugar beet and onions was performed with a reciprocating harrow, and for potatoes a full-width rotary cultivator was used.

In autumn, post-harvest cultivation, primary tillage, and the combined primary tillage + sowing of winter wheat were performed with a John Deere 3140 tractor, fitted with tyres having inflation pressures of 80 or 160 kPa. In spring, at the time of fertilizer application and at the time of seedbed preparation, the same tractor was used, but now low ground-pressure tyres were inflated to 40 kPa and high ground-pressure tyres to 80 kPa. At sowing and planting, and during all other field work in the growing season, the MB-trac 800 tractor was used, with low ground-pressure tyres inflated to 80 kPa and high ground-pressure tyres inflated to 160 kPa. Harvest tractors and transport tractors had 80 or 160 kPa tyre inflation pressure, whereas harvesters and trailers had tyre inflation pressures of 80 or 240 kPa. On the zero-traffic strips, wide-frame tractors and adapted harvesters with a track width of 3.30 m were used.

The Institute of Agricultural Engineering (IMAG) provided the site on its experimental farm "Oostwaardhoeve" (Wieringermeer polder); it carried out all field operations and took care of the required technical adaptations of tractors and trailers, implements and machinery (Vermeulen et al., 1988). The field experiment was terminated in 1989.

Measurements on soil structure

Soil structure was characterized by total pore space, and the moisture and air contents at a matric water potential of -10 kPa. Starting in 1985 on block B, in 1986 on block D, and in 1987 on blocks A and C, total pore space, and the moisture and air contents at -10 kPa were determined each year in the middle of the growing season (May, June) in the 2-7-, 12-17- and 22-27-cm soil layers. In all samplings, on each field, in each layer 10 undisturbed soil cores of 100 cm^3 were taken at random, and results were averaged.

In the early summer of 1989, concurrently with the core sampling, the penetration resistance to 70-cm depth was determined with the Bush recording penetrometer.

Measurements on root distribution

In various years, root distribution of winter wheat, onions and sugar beet was determined in the mature stage of crop development. In a soil pit a 60-cm wide and 80-cm deep vertical profile was prepared perpendicular to the plant rows and the root distribution was mapped on a polythene sheet (Böhm, 1979). Proceeding from the profile pit, the root distribution in one or more horizontal planes was mapped.

The positions of the roots on the maps were digitized and analyzed by means of the nearest-neighbour technique (Van Noordwijk, 1987). First the root intensity, i.e. the number of root intersections per unit area, was calculated. Next, the frequency distribution of nearest-neighbour distances was calculated for root-root distances and for distances from random points to the nearest root. From the difference between these two frequency distributions, a conclusion about the randomness of the root distribution can be derived. The frequency distribution of the distances between random points and the nearest root can be used in the construction of concentric, "equivalent cylinders" around the roots, for which the potential to transport liquids and gases by diffusion can be calculated (De Willigen and Van Noordwijk, 1987b).

A log-normal fit to the frequency distribution of the distances between random points and the nearest root, yields a coefficient of variation σ/μ, which can be regarded as a single value characterizing the degree of homogeneity of the root distribution. Values of σ/μ <1 indicate overdispersed root distributions (with a tendency to regularity), while values >1 indicate underdispersed or clustered root distributions.

RESULTS

Soil texture in the topsoil

In the topsoil, soil texture of the experimental field varied widely among blocks and, on blocks B and D, also within blocks. On blocks A and C, average clay contents were 17.7 and 23.7% (w/w), respectively. On block B, average clay contents ranged from 15.0% (w/w) on plots 1-3 to 22.6% (w/w) on plots 4-6. On block D, average clay contents were 23.0% (w/w) on plots 1-3 and 31.8% (w/w) on plots 4-6.

Due to these differences in soil texture among the four blocks and among the plots within blocks, comparison of the effects of field traffic on soil structure is difficult. This comparison is further complicated by differences in the arrangement of the L and H plots relative to the Z plots. On blocks A, B and C, the L and H plots were situated on both sides of the Z plots, and their texture was similar to that on the Z plots in their midst. Therefore, on these blocks, despite differences in texture within blocks, a direct comparison among treatments is possible. However, on block D, the H treatments were situated on plots 1 and 3, whereas the L treatments were situated on the much heavier soil of plots 4 and 6. Therefore, on this block, only the differences in soil structure between H and Z2 plots, and between L and Z5 plots can be established.

Soil structure in the topsoil

Pore space, and moisture and air contents at -10 kPa

Average differences in soil structure among L, H and Z plots are presented in Tables 1 and 2. The results for the 12-17-cm layer are of special interest, as this layer was tilled in all treatments each year. On average, in this layer, within blocks A, B and C, L plots had a slightly larger pore space and a slightly lower moisture content at -10 kPa. Therefore, the air content at -10 kPa was slightly higher on L plots (+1.6%, v/v) than that on H plots. Z plots had a clearly larger pore space (+2.0%, v/v), a moisture content at -10 kPa similar to those on L and H plots and, therefore, a clearly higher air content at -10 kPa (+3.4%, v/v) than that on L and H plots. On L and H plots the average air content at -10 kPa was near the critical value for satisfactory plant growth (12%, v/v), but on Z plots it was clearly above that level.

In the 12-17-cm layer of block D, pore space on plots 1,2,3 was similar to the pore space on blocks A, B and C. However, the differences in pore space and air content at -10 kPa between plots H1,H3 and plot Z2 were clearly larger (+3.3 and +7.0%, v/v, respectively) than those between H and Z plots on blocks A, B and C. In the much heavier soil of plots 4,5,6, pore space was clearly larger but, due to the higher moisture content at -10 kPa, the air content at -10 kPa was lower than that on plots 1,2,3. However, the differences in pore space and air content at -10 kPa between L and Z5 plots were similar to those on plots 1,2,3 (+3.0 and +5.0%, v/v, respectively). Contrary to blocks A, B and C, on L and H plots of block D the average air content at -10 kPa was far below the critical value of 12% (v/v). On the Z2 plot the average air content at -10 kPa (14.4%, v/v) was clearly above the critical value, but on the heavier soil of the Z5 plot the average air content at -10 kPa (11.8%, v/v) was slightly below this level.

With increasing depth, on blocks A, B and C, average pore space gradually decreased and the moisture content at -10 kPa gradually increased (Table 1). Therefore, in all treatments, but especially in the H treatment, the air content at -10 kPa clearly decreased with increasing depth. In the 2-7-cm layer, pore space tended to be larger in the H than in the L treatments, probably because of the smaller area trafficked in the H treatment. At greater depths, pore spaces in the H and L treatments were similar. The differences in pore space and air content at -10 kPa between Z and L,H plots were similar in all 3 layers investigated, on average +1.9 and +3.4 % (v/v), respectively. On block D, the differences in pore space and air content at -10 kPa between Z2 and H1,H3 plots and between Z5 and L4,L6 plots were clearly larger in the 12-17-cm layer than those in the 2-7 and 20-25-cm depth (Table 2). This is in accordance with the well-known fact that the strongest compaction is usually found in the centre of the tilled layer.

On average, the differences between the pore space and the air content at -10 kPa in the 2-7-cm layer and in the 20-25-cm layer were much larger in the heavier soil of block D than those on the much lighter soil of blocks A, B and C. On block D, the largest differences were found on Z plots where, apart from possible compacting effects of secondary tillage, only natural short-term consolidation played a role. Probably this may be explained by the fact that the effect of natural short-term consolidation on pore space is greater the looser and the heavier the soil is. On L and H plots, natural consolidation hardly played a role as its possible effect was overruled by field traffic, which resulted in a smaller pore space and a lower air content at -10 kPa throughout the tilled layer than on non-trafficked plots, especially on heavy soil. The differences in the depth of primary tillage among years and, in each year, between Z and L,H treatments (not shown), did not have a consistent effect on the average pore space in the 20-25-cm layer.

Penetration resistance

Table 3 shows that, in the topsoil, on blocks A (sugar beet) and C (onions), the levels of penetration resistance were similar and not high, because the moisture content (%,w/w) was about 95%, relative to the moisture

TABLE 1

Pore space, and moisture and air[1] contents at -10 kPa on blocks A, B and C in May/June, averaged for all crops

Depth (cm)	Pore space (%,v/v)			Moisture content at -10 kPa (%,w/w)			Air content at -10 kPa (%,v/v)		
	L	H	Z	L	H	Z	L	H	Z
2- 7	48.0	49.1	50.1	24.3	25.5	24.5	14.7	15.1	18.0
12-17	47.6	47.2	49.4	24.8	25.4	25.1	13.4	11.8	16.0
20-25	46.5	46.5	48.5	25.6	26.7	26.0	10.5	9.1	13.3
Average	47.3	47.5	49.3	24.9	25.9	25.2	12.7	11.8	15.6

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[1] 2-7 cm: 7 crop years; 12-17 cm: 10 crop years; 20-25 cm: 9 crop years.

TABLE 2

Pore space, and moisture and air contents at -10 kPa on block D in May/June (1986-1989), averaged for all crops

	Depth (cm)	L4,L6	Z5	Diff.	H1,H3	Z2	Diff.
Pore space (%,v/v)	2- 7	52.0	54.5	2.5	49.7	52.1	2.4
	12-17	49.4	52.4	3.0	46.2	49.5	3.3
	20-25	49.4	51.0	1.6	47.1	49.2	2.1
	Mean	50.2	52.6	2.4	47.5	50.2	2.7
Moisture content at -10 kPa (%,w/w)	2- 7	29.9	30.1	-0.2	26.7	25.1	-1.6
	12-17	32.0	32.0	0.0	27.4	26.5	-0.9
	20-25	33.2	33.8	0.6	29.8	28.8	-1.0
	Mean	31.7	32.0	0.3	27.9	26.8	-1.1
Air content at -10 kPa (%,v/v)	2- 7	14.2	18.4	4.2	14.3	20.4	6.1
	12-17	6.8	11.8	5.0	7.4	14.4	7.0
	20-25	5.0	7.4	2.4	6.0	11.0	5.0
	Mean	8.5	12.5	4.0	9.0	15.2	6.2

content at -10 kPa (%,w/w). The differences between L and H treatments were only small and not systematic. On Z plots, the penetration resistance was always smaller, on average by ~0.2 MPa (~20%).

On block B (winter wheat), the moisture content at sampling was much lower than that on blocks A and C (65%, relative to the moisture content at

TABLE 3

Penetration resistance (MPa) in the early summer of 1989

Block	Crop	Depth (cm)	Plots 1-3				Plots 4-6			
			L	H	Z	H,L-Z	L	H	Z	H,L-Z
A	Sugar beet	5.0	1.1	1.1	0.9	0.2	1.1	1.2	1.0	0.1
		15.0	0.9	0.9	0.8	0.1	1.3	1.1	0.7	0.5
		22.5	0.9	0.9	0.7	0.2	1.1	1.0	0.9	0.1
B	Winter wheat	5.0	2.0	2.1	1.6	0.5	1.7	1.6	2.0	-0.4
		15.0	2.4	2.8	1.5	1.1	2.1	2.6	1.9	0.4
		22.5	2.1	2.5	1.8	0.5	2.1	2.3	1.9	0.3
C	Onions	5.0	1.1	1.1	1.0	0.1	1.0	1.3	1.0	0.2
		15.0	0.8	0.9	0.8	0.1	1.2	0.8	0.9	0.1
		22.5	0.9	0.9	0.7	0.2	0.9	1.1	0.9	0.1
D	Potatoes	5.0	-	-	-	-	-	-	-	-
		15.0	-	1.8[1]	1.0	0.8	1.2[2]	-	1.2	0.0
		22.5	-	1.7[1]	1.3	0.4	1.4[2]	-	1.4	0.0

[1] Average of plots 1 (H) and 3 (H).
[2] Average of plots 4 (L) and 6 (L).

-10 kPa (%,w/w)) and, therefore, the level of penetration resistance was -100% higher than that on blocks A and C. On block B, in the 12-17- and 20-25-cm layers, the penetration resistance was -15% higher on H plots than on L plots. In these layers, the difference in penetration resistance between Z and L,H plots amounted to -20%, as on blocks A and C.

On block D (potatoes), the level of penetration resistance was higher than that on blocks A and C, due to the heavier soil, a lower moisture content (87%, relative to the moisture content at -10 kPa (%,w/w)), and, as a result of the intensive seedbed preparation, a relatively small pore space. The penetration resistance was clearly higher on H1,H3 plots than on the Z2 plot, especially in the 12-17-cm layer. On L4,L6 plots, the penetration resistance was similar to that on the Z5 plot.

In the subsoil, differences in penetration resistance among treatments were small and erratic. The results (not shown) do not allow a conclusion with respect to differences in subsoil compaction among traffic systems.

Root development of spring wheat, onions and sugar beet

The analysis of all root maps made in the course of the experiment has as yet not been concluded. Therefore, only some preliminary results will be presented here. Figure 1 shows a root map for onions; the track was used for spraying operations during the growing season. It is clear that zero-traffic led to the most homogeneous root distribution throughout the topsoil and to the deepest root development. In the H and L treatments root distribution and development were similar. Underneath wheel tracks no roots were observed at all. Root maps for winter wheat and sugar beet show similar but less pronounced differences.

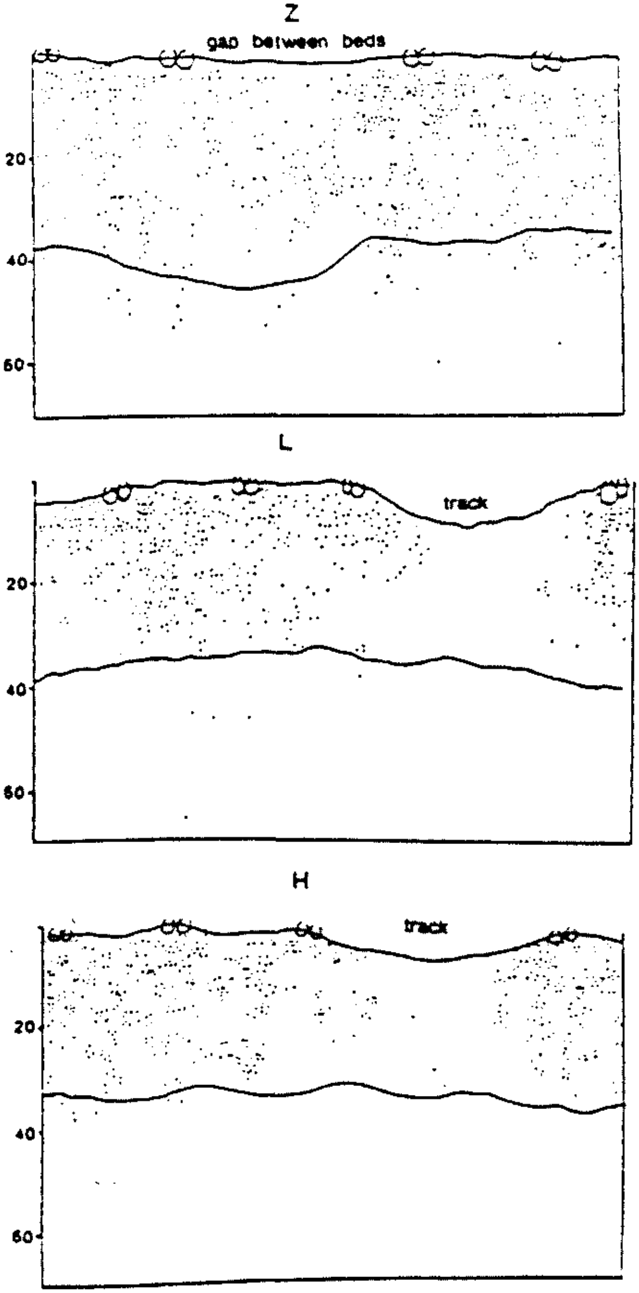

Fig. 1. Root maps in the vertical plane for onions on Z, L and H plots, 28 August 1987.

Figure 2 shows an example of the vertical distribution of the root intensity for spring wheat (sown after winter wheat failed), onions and sugar beet. Obviously, zero-tillage plots differ from high and low ground-pressure plots where root intensities were similar. In onions, root ensitintensity on Z plots was similar to the root intensity on H and L plots in the topsoil, but higher at 40 cm depth. In spring wheat and sugar beet, on Z plots, much higher root intensities than on H and L plots were found in the topsoil but not in the subsoil.

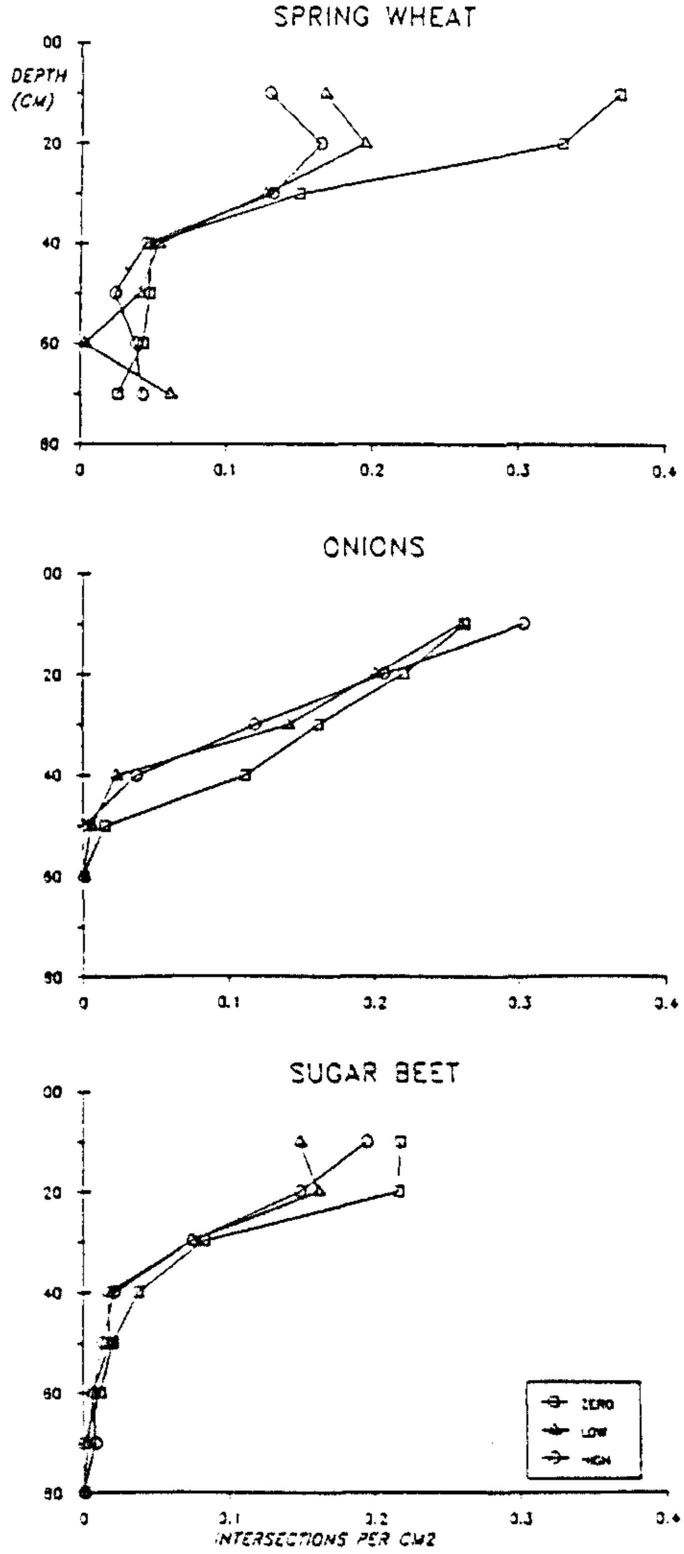

Fig. 2. Vertical distribution of root intensity for spring wheat (1988), onions (1988) and sugar beet (1989) on Z, L and H plots.

TABLE 4

Coefficients of variation (σ/μ) of the frequency distribution of "equivalent cylinders", reflecting the degree of homogeneity of the root distribution of spring wheat (1987), onions (1987) and sugar beet (1989)

Plane position	Depth (cm)	Spring wheat			Onions			Sugar beet		
		L	H	Z	L	H	Z	L	H	Z
Vertical	0-30	0.44	0.50	0.52	0.44	0.47	0.48	0.39	0.40	0.42
	30-70	0.34	0.34	0.34	0.33	0.32	0.34	0.32	0.32	0.33
Horizontal	5	-	-	-	-	-	-	0.36	0.37	0.36
	10	-	-	-	0.41	0.38	0.39	-	-	-
	15	0.38	0.77	1.43	-	-	-	0.39	0.40	0.39
	20	-	-	-	0.37	0.36	0.36	-	-	-
	25	0.36	0.38	0.36	-	-	-	-	-	-
	30	-	-	-	-	-	-	0.33	0.34	0.38

The example of Table 4 shows that, in the vertical plane, all three crops had a fairly regular root distribution, both in the topsoil (0-30-cm depth) and in the subsoil (30-70-cm depth). In the horizontal planes, about the same degree of homogeneity was found as in the vertical plane in the subsoil. Differences between treatments were generally small. For spring wheat, the differences between treatments found in the horizontal plane at 15 cm depth, are not in agreement with the absence of differences in the horizontal plane at 25 cm depth.

According to available transport theory, differences in root distribution may have important consequences for the nutrient uptake by the crop (De Willigen and Van Noordwijk, 1987b). Mathematical models to predict the uptake capacity of root systems, based on the coefficient of variation of "equivalent cylinders", are in preparation. Alternatively, given the root distribution pattern and average root length density, such models may serve to establish the required P and K fertility status of the soil.

CONCLUSIONS

(1) In the topsoil (0-25 cm depth) of coarse- to medium-textured soils (blocks A, B and C), on L and H treatments, pore space, and the moisture and air contents at -10 kPa, averaged for all crops, were similar. On Z plots, pore space and air content at -10 kPa were clearly larger, on average by +1.9 and +3.4% (v/v), respectively, than on L and H plots.

(2) On fine-textured soil (block D), the differences in soil structure between L and Z plots and between H and Z plots were similar, and clearly larger than on coarse- to medium-textured soil. On average, on Z plots, pore space was 2.5% (v/v) larger and air content at -10 kPa was 5.1% (v/v) higher than in the tilled layer (0-25 cm depth) of L and H plots.

(3) On coarse- to medium-textured soil (blocks A, B and C), soil structure on L and H plots was acceptable, the average air content at -10 kPa being slightly above or only just below the critical value for satisfactory plant development (12%,v/v).

(4) On fine-textured soil (block D), the air content at -10 kPa in the 2-7-cm layer was satisfactory and similar to the average on blocks A, B and C. However, below 7 cm depth, on L and H plots the average air content at -10 kPa was far below the critical value. On Z plots air content at -10 kPa was satisfactory to 17 cm depth but deeper down it was below the critical level, especially on the plot with the heaviest soil (Z5).

(5) The effects of natural short-term consolidation and of field traffic on soil structure increased with increasing clay content.

(6) Under dry conditions and on heavy soil, the low ground-pressure system (L) may result in a clearly lower penetration resistance in the lower part of the tilled layer than the high ground-pressure system (H). The zero-traffic system (Z) always showed a lower penetration resistance throughout the tilled layer than the low ground-pressure system, except for very heavy soil.

(7) The zero-traffic system ensured a satisfactory soil structure, except for the heaviest soil. The low ground-pressure traffic system did not result in a clearly better soil structure than the high ground-pressure traffic system.

(8) Roots were found to be clustered in cracks between soil aggregates. Therefore, root distribution was much more regular on non-trafficked than on trafficked plots. According to available transport theory, these differences may have important consequences for nutrient uptake by the crop. Plants grown on ruts, made and covered up by loose soil during seedbed preparation, had a clearly different root development than plants grown between ruts.

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