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The effect of compaction of the arable layer in sandy soils on the growth of maize for silage. 1. Critical matric water potentials in relation to soil aeration and mechanical impedance

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Abstract

A new approach in defining the range of soil structure which guarantees optimal maize production is proposed. The effect of different degrees of compaction of ploughed sandy soils on soil aeration and mechanical impedance, root growth and subsequent shoot growth of maize was tested in 5 model field experiments. In this first paper the potential effects on soil aeration and penetration resistance are described. The narrower the range of matric water potentials which allow an unimpeded root growth, the greater the potential risks for plant growth and the greater the need for a controlled supply of water. Soil structures which substantially impede root growth even at the most favourable matric water potential are to be classified as dangerous.

Introduction

In the Netherlands on sandy soils liquid livestock manure is spread during winter and early spring on arable land as well as on grassland. To extend this period, soil tillage in early spring is postponed as long as possible. Ploughing is performed late and sowing of maize follows as soon as possible, sometimes even on the same day. Because the loose soil is not settled sufficiently for proper sowing with a precision drill the soil is compacted artificially to some degree at or directly after ploughing. However, plant establishment and growth sometimes are below expectations. In order to gain knowledge about the range of soil structure which guarantees optimal maize production, the effect of different degrees of compaction of ploughed soil on soil physical aspects, root and subsequent maize growth was tested in 5 model field experiments. In this article potential effects on soil aeration and penetration resistance are described. A new approach towards critical matrix water potentials in relation to both soil physical growth factors is proposed.

Materials and methods

Soils

The experimental fields are located in the eastern part of the Netherlands. Both experiments in Heino (1980 and 1982) are on fine sand, those in Heeten (1981) on loamy fine sand and in Wijhe (1982) on fine sandy loam (de Bakker & Schelling, 1966) (Table 1). The soil in Heino (1982) had been grassland (ley) for three years. Watertable depth at compaction and sowing was 1.2 m, except for Heeten (1981): 1.7 m in Heeten H and 1.45 m in Heeten L.

Treatments

Liquid livestock manure (in 1980: 80 or 230 t ha^{-1}, in 1981 and Heino 1982: 80 t ha^{-1} and in Wijhe 1982: 20 t ha^{-1}) was applied during winter and/or early spring. On 1 May (in 1982 three days earlier) the soil was ploughed to a depth of approximately 0.25 m. Within three days after ploughing the soil was compacted and the seedbed prepared. The different degrees of compaction of the arable layer were designated as follows:

L = loose. Not compacted after ploughing. No separate seedbed preparation.

CL = compacted lightly. Soil compacted with a packer at ploughing (0.7 m diameter, open rings 0.15 m apart). No separate seedbed preparation.

CM = compacted moderately. Compacted by driving once all over the soil after ploughing with a 44 kW tractor on double rear wheels (inflation pressure ca. 150 kPa). Seedbed preparation with spring-tine cultivator (0.05 m).

CS = compacted severely. Compacted by driving three times all over the soil after ploughing with a 44 kW tractor on single rear wheels (inflation pressure ca. 150 kPa). Seedbed preparation with spring-tine cultivator (0.05 m).

On the same day (in Wijhe 1982 six days later) maize was sown with a precision drill at a depth of 0.05 m and a row distance of 0.75 m.

Table 1. Soil characteristics of the arable layer (0-30 cm).

Location	Organic matter (%, w/w)	pH (KCl)	Particle size distribution (% mineral fraction)		
			<2 μm	2-50 μm	50-2000 μm
Heino (1980)	3.3	4.9	2.7	4.2	93.1
Heeten-H (1981)	4.5	.	3.3	29.2	67.5
Heeten-L (1981)	3.3	6.8	3.1	27.5	69.4
Heino (1982)	4.7	5.7	3.0	5.6	91.4
Wijhe (1982)	3.2	4.1	10.1	13.9	76.0

Methods
Rainfall was measured on the site. Water table depths were measured in tubes. Moisture retentivity curves and volume fractions of pores were determined by applying standard techniques to 10 undisturbed core samples of 100 cm^3 from relevant soil layers. Soil matric water potentials (h_m) were measured with tensiometers and a pressure transducer in duplicate in the ploughed layer (0.15 m), at ploughpan depth (0.35 m) and in the subsoil (0.6 m). Gravimetric soil water contents of composite mixed samples were determined at the same time in all treatments at 0.1 m depth intervals.

Oxygen diffusion coefficients were determined at $h_m = -0.3$ or -0.5 m (pF = 1.5 or 1.7) and at $h_m = -1$ m (pF = 2) in 8 undisturbed core samples of 230 cm^3 from the arable layer at a depth of 0.1-0.15 m by a modification of the procedure used by Bakker and Hidding (Boone et al., 1976). Air permeability was measured in the same undisturbed core samples and at the same matric water potentials according to a method proposed by Kmoch (1961) with a hydraulic head of 0.04 m water. Oxygen concentrations of soil air were determined polarographically in five diffusion chambers (1 cm^3) placed at the same depths as the tensiometers.

Penetration resistances were measured (10 replicates) with a recording penetrometer (van Soesbergen & Vos, 1971) during the growing season at various soil water contents. A cone base of 1 cm^2 with a 60° angle was used.

Root diameters of main root axes and first-order laterals (n = 50) were measured with a microscope at small magnification (July 1982).

Results

The volume fraction of pores and gas
Porosity of the arable layer decreases slightly when the ploughed soil (treatment L) is compacted with a packer (treatment CL), clearly when a tractor on double rear wheels is used (treatment CM) and strongly when this tractor on single rear wheels drives 3 times on the surface (treatment CS). Because the same equipment and procedure was used, compaction effects in the various experiments can be compared and related to soil stability and water content. Porosities in treatments L and CL are larger on the fine sand previously in grass and in the fine sandy loam than in the other experiments (Fig. 1). Soil water content at compaction depends on the actual matric water potential and the water retentivity curve of that particular soil. Gravimetric soil water content at field capacity ($h_m \approx -0.8$ m = pF = 1.9) is highest in the loamy fine sand and lowest in the fine sand. The actual matric water potential at compaction depends on rainfall in the previous period, the depth of the water table and the water conductivity-matric water potential relationship. It appears (Table 2) that the smallest porosity in treatment CS is found on the loamy fine sand in the lower part L of the experiment and is associated with the highest water content. The largest porosity is found on the fine sand previously in grass and associated with the smallest water content.

In treatment CS the volume fraction of gas at a high matric water potential (h_m = -0.5 m) is small, especially in the loamy fine sand with values close to 0.05 (Table

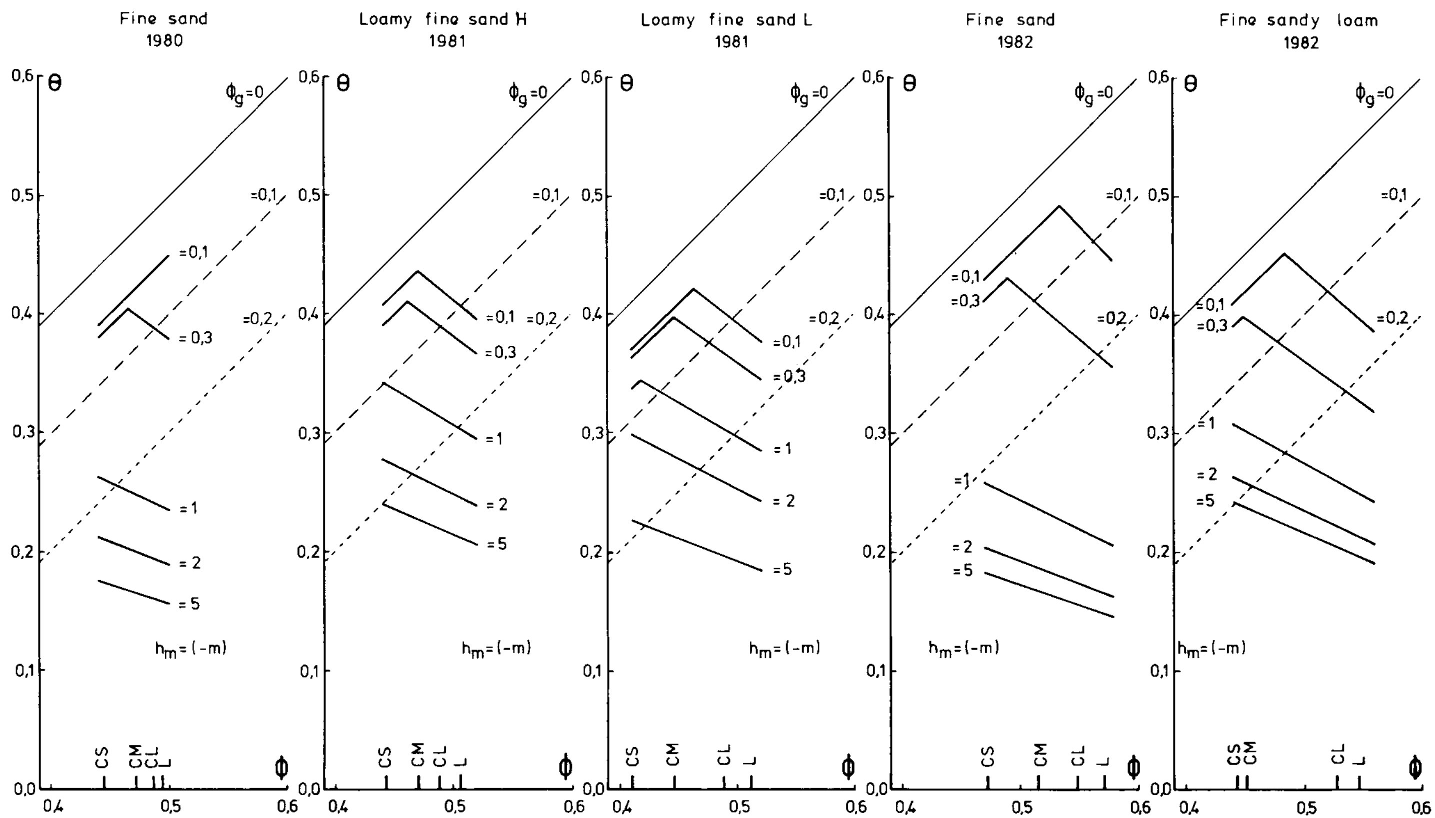

Fig. 1. Relationship between volume fraction of water (θ) at several matric water potentials (h_m) and porosity (ϕ). Volume fractions of gas (ϕ_g), of 0, 0.1 and 0.2 are indicated.

Table 2. Matric water potential h_m (m) and gravimetric water content w (kg kg^{-1}) at compaction and volume fraction of pores ϕ (m^3 m^{-3}) and volume fraction of gas ϕ_g (m^3 m^{-3}) at $h_m = -0.5$ and $h_m = -1$ m after severe compaction (treatment CS).

Soil	Year	At compaction		After compaction		
		$-h_m$	w	ϕ	ϕ_g	
					$-h_m = 0.5$	$-h_m = 1$
Fine sand	1980	0.8	0.21	0.445	0.088	0.152
Loamy fine sand (H)	1981	1.0	0.21	0.443	0.055	0.080
Loamy fine sand (L)	1981	0.9	0.22	0.411	0.057	0.071
Fine sand	1982	0.9	0.20	0.472	0.089	0.188
Fine sandy loam	1982	0.9	0.21	0.443	0.092	0.131

2). When the soil matric potential decreases from $h_m = -0.5$ to $h_m = -1$ m the volume fraction of gas doubles in the fine sand, clearly increases in the fine sandy loam but increases only slightly in the loamy fine sand. The volume fraction of gas is higher when the soil is compacted moderately. At $h_m = -1$ m the difference in volume fraction of gas between treatments CM and CS is 1.5-1.7 times the difference in porosity and is small in the fine sandy loam and large in the fine sand previously in grass.

Soil aeration

Transport of oxygen from the soil surface to deeper soil layers is determined by diffusion. The diffusion coefficient of oxygen in soils, $D(O_2)$, therefore, is an important index. For the experimental fields different relations are found between $D(O_2)$ and the volume fraction of gas ϕ_g (Fig. 2). In these relations two aspects are to be distinguished: the volume fraction of blocked gas ϕ_{gb} at which $D(O_2)$ approaches zero and the relation between $D(O_2)$ and ϕ_g at a higher air fraction. ϕ_{gb} is 0.08 in the fine sand of 1980 and 0.05 in all other cases. At small gas fractions, $D(O_2)$ is higher in the fine sandy loam and the fine sand previously in grass than in the fine sand of 1980. The loamy fine sand has an intermediate position. At higher gas fractions the relationships converge.

The figures available do not show a distinct influence of ϕ on the $D(O_2)$-ϕ_g relation. The most important effect of compaction on $D(O_2)$, therefore, is the effect on the gas fraction present at a certain matric water potential. By using the appropriate water retentivity curve, the matric water potential at which $D(O_2)$ reaches a critical value is derived.

When in a 0.3 m thick soil layer with a very high oxygen consumption (10^3 mg O_2 m^{-2} h^{-1} = 0.93 mg O_2 m^{-3} s^{-1}) the oxygen concentration should not decrease below 10 %, $D(O_2)$ should equal $3 \cdot 10^{-7}$ m^2 s^{-1} (Bakker & Hidding, 1970). This $D(O_2)$ can be regarded as a safe Upper Critical Aeration Limit (UCAL). Because the diffusion of oxygen in free air at 1 bar and 20 °C, $D_0 = 0.201$, the relative gas diffusion coefficient $D(O_2)/D_0$ at this UCAL is $15 \cdot 10^{-7}$ m^2 s^{-1}. When in the same soil layer the oxygen consumption is 10 times lower (10^2 mg O_2 m^{-2} h^{-1} = 0.093 mg O_2 m^{-3} s^{-1})

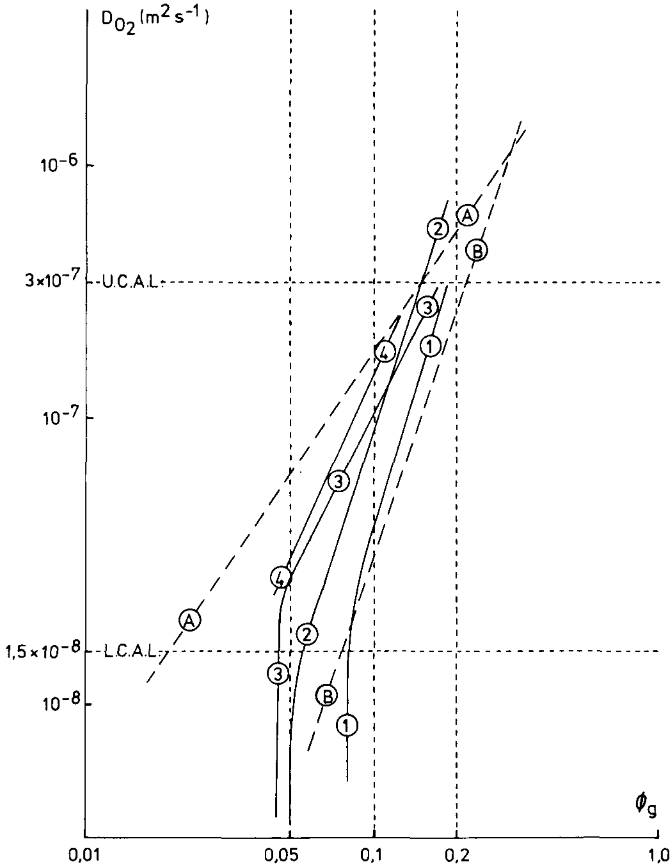

Fig. 2. Relationship between oxygen diffusion coefficient $D(O_2)$ and volume fraction of gas (ϕ_g). The relationship for a single-grain structure and a very well structured loam soil are added (1 = fine sand (1980); 2 = loamy fine sand (1981); 3 = 1 after 3 year grass (1982); 4 = fine sandy loam (1982); A = very well structured loam ($D(O_2) = 0.05\ \phi_g^{1.5}$); B = single-grain structure ($D(O_2) = 0.3\ \phi_g^{3.0}$)).

and the oxygen concentration is allowed to decrease to 1 % a 20 times Lower Critical Aeration Limit (LCAL) of $1.5 \cdot 10^{-8}$ m² s⁻¹ is obtained which equals a relative gas diffusion coefficient of $7.5 \cdot 10^{-8}$ m² s⁻¹. In most conditions this value is fully insufficient. For the various experimental fields these criteria of $D(O_2)$ are translated into critical matric water potentials (Table 3). It appears that the matric water potential at the LCAL is generally high: –0.2 m in treatment CM and –0.3 in treatment CS. In the loamy fine sand, however, the potential is lower: –0.3 m and –0.6 m in the higher part (H), respectively –0.6 m and –0.8 m in the lower part (L) of the field. ϕ_g as this limit is always close to ϕ_{gb}. The matric water potential at the UCAL is much lower than at the LCAL and clearly different for the various experiments and degrees of compaction. In treatment CM values are between –0.6 m (fine sand previously in grass) and –2 m (loamy fine sand L). For treatment CS values are be-

Table 3. Matric water potential h_m (m) and volume fraction of gas ϕ_g ($m^3\ m^{-3}$) at which the relative gas diffusion coefficient $D(O_2)/D_0 = 15 \cdot 10^{-7}\ m^2\ s^{-1}$ (UCAL) and $D(O_2)/D_0 = 7.5 \cdot 10^{-8}\ m^2\ s^{-1}$ (LCAL) for the moderately (CM) and severely (CS) compacted treatments.

Soil	Year	Treat-ment	LCAL		UCAL	
			$-h_m$	ϕ_g	$-h_m$	ϕ_g
Fine sand	1980	CM	0.2	0.07	0.9	0.19
		CS	0.3	0.08	1.6	0.20
Loamy fine sand H	1981	CM	0.3	0.06	1.0	0.15
		CS	0.6	0.07	2.0	0.16
Loamy fine sand L	1981	CM	0.6	0.06	2.0	0.15
		CS	0.8	0.07	3.0	0.16
Fine sand	1982	CM	0.2	0.05	0.6	0.19
		CS	0.3	0.05	0.9	0.18
Fine sandy loam	1982	CM	0.2	0.05	1.0	0.15
		CS	0.3	0.05	1.2	0.15

tween −0.9 m and −3 m. When the soil is compacted severely and the oxygen consumption is high, matric water potential in the fine sand (1980) and especially in the loamy fine sand should be considerably lower than at field capacity. In all experiments limiting ϕ_g is between 0.15 and 0.20.

Another indication of a potential risk for an insufficient soil aeration due to compaction can be derived from the measurement in a steady state of the volume fraction of oxygen when the soil is at field capacity and the oxygen consumption by the crop is still negligible. It appears that in all experiments the measurements at emergence of the maize crop are appropriate in this respect. At that time there is a marked response in oxygen concentrations (Table 4). Concentrations in treatment CS of the fine sand previously in grass drop sharply with depth although $D(O_2)$ is above the UCAL. From the combination of the apparent oxygen diffusion coefficient and the volume fraction of oxygen at a depth of 0.15 m the oxygen consumption α has been calculated (Table 4) assuming that the oxygen consumption is evenly distributed between the surface ($z = 0$) and the lower boundary ($z = L$) of a layer with thickness L, and no oxygen is consumed below this layer.

The flux $f(O_2)$ at depth z ($0 < z < L$) is:

$$f(O_2) = \alpha(L - z) \qquad (1)$$

and according to the first law of Fick:

$$f(O_2) = -D(O_{2)}{}^{d\chi(O2)/dz} \qquad (2)$$

$f(O_2)$ = flux of oxygen ($kg\ m^{-2}\ s^{-1}$)
$D(O_2)$ = oxygen diffusion coefficient in soil ($m^2\ s^{-1}$)
$\chi(O_2)$ = mass concentration of oxygen in the air phase ($kg\ m^{-3}$)
α = oxygen consumption ($kg\ m^{-3}\ s^{-1}$)
(1) + (2) yields:

Table 4. Volume fraction of gas ϕ_g ($m^3\ m^{-3}$), oxygen diffusion coefficient $D(O_2)$ ($10^{-7}\ m^2\ s^{-1}$), volume fraction of oxygen O_2 ($m^3\ m^{-3}$ gas) at 0.15 m depth, and oxygen consumption α (10^{-1} mg $O_2\ m^3\ s^{-1}$) at emergence.

Soil	Year	Treatment	ϕ_g	O_2	$D(O_2)$	α
Fine sand	1980	CL	0.208	0.198	4.3	2.2
		CM	0.188	0.184	3.0	3.2
		CS	0.146	0.144	1.5	4.1
Loamy fine sand (H)	1981	CL	0.249	0.199	8.0	3.6
		CM	0.192	0.182	4.8	5.6
		CS	0.138	0.122	2.2	7.8
Loamy fine sand (L)	1981	CL	0.236	0.197	7.0	3.8
		CM	0.170	.	3.6	.
		CS	0.141	0.130	2.4	7.8
Fine sand	1982	CL	0.313	0.194	20.0	13.3
		CM	0.261	0.168	8.0	14.0
		CS	0.196	0.062	3.6	22.1
Fine sandy loam	1982	CL	0.275	0.203	12.0	3.5
		CM	0.181	0.184	4.5	4.9
		CS	0.166	0.166	3.8	7.0

$$d\chi(O_2) = [\alpha/D(O_2)](L-z)dz$$

$$= [\alpha/D(O_2)] \int d(Lz - z^2/2) \quad (3)$$

When the change in oxygen concentration between the soil surface to depth z = $\Delta\chi(O_2)$:

$$\alpha = -[D(O_2)\cdot\Delta\chi(O_2)]/(Lz - z^2/2) \quad (4)$$

In the calculation the arable layer L is 0.3 m and $D(O_2)$ is constant with depth. Because the diffusion coefficient is higher in than beneath the seedbed, it is calculated that α is underestimated by 25 % at maximum. Soil respiration at emergence has been very high in the 1982 experiment on fine sand previously in grass. Although the same amount of liquid livestock manure is applied soil respiration of the loamy fine sand is only one third. The oxygen consumption in the 1980 experiment on fine sand is smallest although 4 times as much manure is applied. This coincided with a lower temperature: mean ambient air temperature at emergence in the second decade of May was 12.7 instead of 14.2 °C. The calculations show also a marked influence of the degree of compaction on the oxygen consumption. Severe compaction nearly doubled the consumption on volume basis. Only 8-18 % of this increase is explained by difference in porosities between treatments CL and CS.

Mechanical resistance

The mechanical restriction roots encounter is a function of the dimensions and continuity of the system of macropores, the diameters of individual roots and the energy necessary to widen pore necks and pores smaller than individual roots.

The air permeability and gas diffusion coefficient give information about the dimensions and continuity of the macropores. The flux of oxygen per cross-sectional area with n straight, parallel cylindrical pores of one size perpendicular to the diffusion is:

$$f(O_2) = n\pi r^2 D_c^{d\chi(O2)/ds} \tag{5}$$

with D_c = oxygen diffusion coefficient in a capillary tube ($m^2\ s^{-1}$) with radius r (m). In pores with $r > 1.5\ \mu m$ ($h_m = -10$ m) the friction of the pore walls is negligible compared to the internal friction in the gas. In moist soils we therefore can use the diffusion coefficient of oxygen in free gas D_0. If the pores are of various sizes and n_i is the number of pores in the ith pore size class with radius r_i divided by the total cross sectional area, than the total flux yields:

$$f(O_2) = -\Sigma n_i \pi r_i^2 D_0^{d\chi(O2)/ds} \tag{6}$$

In an isotropical soil the total area of soil pores $\Sigma\ n_i\ \pi\ r_i^2$ per unit cross-sectional area equals $\Sigma\Delta(\phi_g)_i = \phi_g$. Soil pores normally are not parallel and therefore a geometrical reduction factor τ (<1) is introduced:

$$f(O_2) = -\tau\,\phi_g D_0^{d\chi(O2)/ds} = -D(O_2)[d\chi(O_2)/ds] \tag{7}$$

Mass flow of air per cross-sectional area in a soil with n straight, parallel cylindrical pores with radius r perpendicular to the flow is according to Poiseuilles' law:

$$f_a = -(n\pi r^4/8\eta)(dp/ds) \tag{8}$$

with f_a = flux density of air ($m^3\ m^{-2}\ s^{-1} = m\ s^{-1}$)
η = viscosity of air (at 1 bar and 20 °C $\approx 20\ \mu$Pa s)
dp/ds = air pressure gradient (Pa m^{-1})

If the pores are of various sizes and n_i is the number of pores in the ith pore size class with radius r_i than the flux is:

$$f_a = 1/(8\eta)\Sigma n_i \pi r_i^4 (dp/ds) \tag{9}$$

In an isotropical soil with non-parallel pores the geometrical reduction factor τ has to be introduced as was done for diffusion:

$$f_a = \tau/8\eta\,\phi_g r_i^2 (dp/ds) = -K_a (dp/ds) \tag{10}$$

with K_a = air conductivity (m^2). Air conductivity in contrast to gas diffusion (Eq. 7),

Table 5. Volume fraction of gas ϕ_g, intrinsic air permeability K_{ia} and relative gas diffusion coefficient $D(O_2)/D_0$ per volume percent of gas and the ratio $K_{ia}/[D(O_2)/D_0]$ of treatment CS at a matric water potential $h_m = -0.3$ m and the increase between $h_m = -0.3$ m and $h_m = -1$ m, respectively.

Soil	Year	$h_m = -0.3$ m				$\Delta((h_m = -1\text{ m}) - (h_m = -0.3\text{ m}))$			
		ϕ_g ($m^3\,m^{-3}$)	$\frac{K_{ia}}{\phi_g}$ ($10^{-12}\,m^2$)	$\frac{D(O_2)}{\phi_g D_0}$ ($10^{-7}\,m^2\,s^{-1}$)	$\frac{K_{ia}D_0}{D(O_2)}$ (10^{-5} s)	$\Delta\phi_g$ ($m^3\,m^{-3}$)	$\Delta\frac{K_{ia}}{\phi_g}$ ($10^{-12}\,m^2$)	$\Delta\frac{D(O_2)}{\phi_g D_0}$ ($10^{-7}\,m^2\,s^{-1}$)	$\Delta\frac{K_{ia}D_0}{D(O_2)}$ (10^{-5} s)
Fine sand	(1980)	0.084	6.4	8	0.8	0.066	65.0	105	0.62
Loamy fine sand (H)	(1981)	0.046	0.5	2	0.25	0.033	5.8	70	0.08
Fine sand	(1982)	0.044	13.0	20	0.65	0.144	21.0	110	0.20
Fine sandy loam	(1982)	0.043	13.0	29	0.45	0.088	45.0	125	0.36

therefore, is strongly dependent on the radii of the largest air-filled pores. Macropores with diameters equal or larger than individual roots are of special interest because they largely determine soil rootability. These pores are created by soil tillage but when a tilled soil is compacted, especially the largest pores disappear (Boone et al., 1985). Soil tillage and soil compaction therefore influence air permeability measured at high matric water potentials more than the gas diffusion coefficient.

In the present experiments ϕ_g at $h_m = -0.3$ m, at which pores equivalent with a diameter of $\geqslant 100\,\mu$m are gas-filled, is close to ϕ_{gb}. Therefore both the intrinsic air permeability $K_{ia} = \eta\, K_a$ and the relative gas diffusion coefficient $D(O_2)/D_0$ is small (Table 5). The fine sand previously in grass and the fine sandy loam compare relatively favourable, the loamy fine sand relatively unfavourable. When K_a and $D(O_2)$ are determined at the same matric water potential then τ is identical. The ratio $K_{ia}D_0/D(O_2)$ then yields information about $\Sigma\, r_i^2$ and at high matric water potentials therefore about the largest pores. It appears at $h_m = -0.3$ m the loamy fine sand has the smallest and the fine sand of 1980 has the largest ratio. Between $h_m =$ -0.3 and $h_m = -1$ m, equivalent with pores of 100-30 μm, K_{ia} and $D(O_2)$ indices increase relatively strongest on both soils with the smallest indices at $h_m = -0.3$ m. Especially in these soils part of the ineffective pores become effective and contribute

Table 6. Diameter of main root axes and first-order laterals of maize (sampling depth 10-20 cm; $n = 50$).

Treatment	Main root axes		First-order laterals	
	$\bar{X}$ (μm)	$s_{\bar{x}}$ (μm)	$\bar{X}$ (μm)	$s_{\bar{x}}$ (μm)
L	1037	22	314	10
CL	1607	28	442	16
CM	1911	38	533	18
CS	2208	62	640	24

to the transport of gas. The ratios again indicate that the pores in the fine sand are relatively large and those in the loamy fine sand are relatively small.

In treatment L of the fine sand previously in grass, main root axes and first-order laterals of maize have diameters of about 1000 and 300 μm respectively (Table 6). The clearly thicker roots in treatment CL indicate that in this soil pores with a size equal or larger than main root axes are lost easily by compaction. This process proceeds at further compaction.

Penetration resistance at field capacity is small in treatment L, slightly higher in treatment CM and values are still moderate in treatment CS. A highest value of 1.5 MPa is found in the loamy fine sand with the smallest porosity (Table 7). Penetration resistance increases when soil water content decreases and distinctly more at small than at a large porosity. Root growth decreases when roots are mechanically impeded. At 3 MPa growth is a fraction of the growth without impedance or completely stops in a homogeneous soil (Taylor & Gardner, 1963; Boone & Veen, 1982). This penetration resistance can be regarded as an Upper Critical Mechanical Limit (UCML). As a Lower Critical Mechanical Limit (LCML) the penetration re-

Table 7. Mean cone resistance (MPa) between 0.1 and 0.15 m depth at field capacity (h_m = –0.8 m).

Soil	Year	Treatment			
		L	CL	CM	CS
Fine sand	1980	0.6	0.5	0.7	1.1
Loamy fine sand (H)	1981	0.6	0.8	1.0	1.3
Loamy fine sand (L)	1981	0.6	0.6	1.0	1.5
Fine sand	1982	0.6	0.6	0.8	1.1
Fine sandy loam	1982	0.6	0.6	1.0	1.3

Table 8. Matric water potential (h_m) at a cone resistance of 1.5 (LCML) and 3.0 MPa (UCML) and corresponding decrease in volumetric fraction of water ($\Delta\theta$) between field capacity (h_m = –0.8 m) and this matric water potential, respectively.

Soil	Year	Treatment	LCML		UCML	
			$-h_m$ (m)	$\Delta\theta$ ($m^3 m^{-3}$)	$-h_m$ (m)	$\Delta\theta$ ($m^3 m^{-3}$)
Fine sand	1980	CM	5.0	0.109	.	.
		CS	1.6	0.029	10.0	0.143
Loamy fine sand H	1981	CM	5.0	0.082	.	.
		CS	1.6	0.008	16.0	0.136
Loamy fine sand L	1981	CM	3.0	0.088	.	.
		CS	0.9	0.000	5.0	0.146
Fine sand	1982	CM	10.0	0.111	.	.
		CS	2.5	0.053	>160.0	0.217
Fine sandy loam	1982	CL	160.0	0.135	.	.
		CM	1.6	0.028	30.0	0.114
		CS	1.3	0.015	5.0	0.073

sistance which causes a decrease in root growth rate of 50 % may be assumed. In a rather homogeneous soil structure this corresponds with a penetration resistance of about 1.5 MPa for maize (Boone & Veen, 1982).

With the penetration resistances measured at various soil water contents and the appropriate water retentivity curves, for treatments CM and CS the soil water content and soil water potential at both critical penetration resistances was estimated (Table 8).

A penetration resistance of 1.5 MPa is reached in treatment CS at a matric water potential at or slightly lower than field capacity. In treatment CM soil water content and potential should decrease clearly whereas in treatment CL this value, except for the fine sandy loam, is not reached. A value of 3 MPa is already obtained at h_m = −5 m in treatment CS of the fine sandy loam and the loamy fine sand with the smallest porosity. Matric water potentials are smaller in the less compacted loamy fine sand and in fine sand, especially after grass. The smaller the difference between field capacity and the water content and potential at which a penetration resistance of 3 MPa is reached, the higher the risks a suboptimal crop water supply. It may be concluded that in the fine sandy loam and the loamy fine sand with a small porosity a risky situation may develop easily whereas in the fine sand previously in grass this will happen only in extreme cases.

Potentials and restrictions of soil structures for root growth in relation to matric water potential

The combination of the aspects discussed in the previous sections enables the estimation of potential root growth as affected by soil compaction and matric water potential. The following assumptions are made.

1. Soil aeration is fully inhibitive for root growth at the LCAL and non-restrictive at the UCAL for oxygen diffusion. The actual oxygen consumption by the soil serves as a minimum.
2. Mechanical impedance is fully inhibitive for root growth at the UCML and partly restrictive at the LCML in soils with a homogeneous structure. In heterogeneous soil structures limits should be increased.
3. The more the matric water potential at which soil aeration becomes insufficient is above field capacity ($h_m \approx -1$ m) and the closer the matric water potential at which mechanical impedance strongly restricts root growth is to the permanent wilting point ($h_m \approx -160$ m) the higher the potential for root growth is.

Moderate compaction of the fine sand is not or weakly restrictive unless the soil is excessive wet or dry (Fig. 3). Severe compaction is weak to moderate restrictive: a soil water potential a little above $h_m = -0.9$ m or below $h_m = -10$ m are potential risky. The mechanical restriction may be overestimated because some large pores are present. Potential risks are smaller when grass instead of maize is a previous crop, unless the oxygen consumption remains as high as measured at crop emergence.

Moderate compaction of the loamy fine sand at a matric water potential of h_m = −1 m is not or weakly restrictive, but at $h_m = -0.9$ m clearly restrictive. In this last case aeration may be sub-optimal at field capacity. Mechanical restrictions are less clear. Severe compaction, especially at a matric water potential above −0.9 m is po-

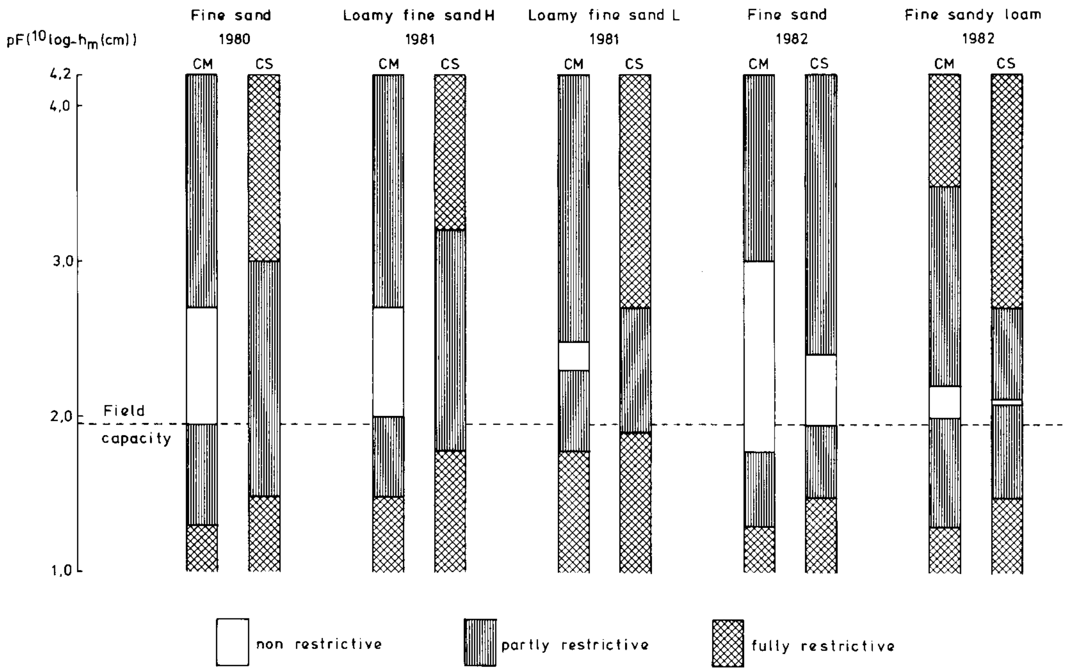

Fig. 3. Range of non-restrictive and restrictive matric water potentials of treatments CM and CS based on gas diffusion coefficients and penetration resistances.

tentially dangerous: the range of matric water potentials without some restriction is very small or absent. Pore size distribution is unfavourable.

Moderate compaction of the fine sandy loam is weakly, severe compaction moderately restrictive when matric water potential is clearly above field capacity or smaller than $h_m = -5$ m. A clay content of 10 % indicates some capacity for shrinkage upon drying and therefore mechanical restriction will be not absolute.

Discussion

There is a growing demand for knowledge about the range of optimal soil structure for specific conditions and crops. The technical possibilities for the realisation of specific soil structures during crop growth are increasing. New tillage systems such as wide, permanent bed systems create a number of options. The second reason for this growing demand is opposite to the first: optimalization of present farming systems imposes technical limitations to part of the system. The enormous extension of spreading liquid livestock manure minimized and delayed the time available for soil tillage and therefore necessitates some degree of artificial compaction before sowing maize. However, the heavy equipment used for spreading the manure substantially increases the risks of compaction of the soil below the usual ploughing depth.

In developing criteria for soil structure an analytical approach, by studying specific aspects, or an integral approach by pure empirical field research may be followed. Both approaches have their own limitations. In this study a combination of both procedures is proposed.

When the range of optimal soil structure is represented by a series of soil porosities, limitations arise at the dense as well as at the loose side of this range. To reduce the complexity, emphasis is laid on the dense part of the range. In a dense soil, root growth and activity may be limited in (very) wet and (very) dry soil conditions: by soil aeration and mechanical impedance, respectively.

Although soil aeration acts also indirectly by biochemical factors (e.g. (de)nitrification), attention is concentrated to the availability of oxygen in gas-filled pores at different depths in the soil. This macrotransport is the boundary condition for the microtransport from the nearest gas-filled pore through the solid particle-air-water complex to the root surface. The smaller the area of the root surface in direct contact with the continuous system of gas-filled pores is, the higher the oxygen concentration in these pores should be (de Willigen & van Noordwijk, 1984; van Noordwijk & de Willigen, 1984). This aspect is included arbitrarily in the earlier defined lower and upper critical limits of the oxygen diffusion coefficient $D(O_2)$ by limiting oxygen concentrations of 1 and 10 %, respectively. More realistic limits will be known if data become available on root-soil contact in relation to soil structure.

For the various sandy soils distinct differences are observed in the oxygen diffusion-volume fraction of gas ($D(O_2)$-ϕ_g) relationship. The relationship for the fine sand is similar to the relationship for single grain structures (Bakker et al., 1986). When this soil was in grass the relationship is more favourable and resembles a fairly well structured soil. Obviously the grass root system provided continuous gas-filled pores for diffusion. A similar result is obtained for the fine sandy loam but the loamy fine sand scored less. Because no distinct influence of total pore space on the $D(O_2)$-ϕ_g relationship is obtained the effect of compaction is the reduction in ϕ_g present at any matric water potential. This simplifies the establishment of predictive aeration indices for sandy soils. The prediction however, is complicated by a reliable calculation of the oxygen consumption. Because the consumption by the soil and the root system of a growing crop are of a similar magnitude (Brown & Fountaine, 1965), the consumption by the soil is an absolute minimum. The dynamic properties of the processes indicate that only measurements under strictly standardized conditions (e.g. soil water and temperature) of large undisturbed soil samples taken at the proper time will give valuable results which can be compared. Soil oxygen concentrations obtained around crop emergence may provide empirical information at the start of the growing season. These figures will gain when information is available about soil temperature, amount, distribution, turnover rate and date of application of freshly applied organic substances and applied soil tillage. Amendments with a high turnover rate have a large flux during a rather limited time (Bakker, 1982). The same is known for soil loosening by tillage (Brown & Fountaine, 1965). In the present experiments the consumption appears to be increased by soil compaction so it may be concluded that every mechanical disturbance of the soil has an impact on the consumption of oxygen.

When soil water content decreases the soil matrix becomes more rigid and therefore the mechanical aspect of root growth gains importance in compacted soils. By compaction the force needed to widen pores increases and the number of pores with a diameter equal or larger than the growing root tips decreases. For the first aspect penetration resistances are indicative. As a lower critical limit of mechanical impedance (LCML), the soil conditions which cause a decrease in root growth rate of 50 % may be assumed. In a rather homogeneous soil structure this corresponds with a penetration resistance of about 1.5 MPa for maize (Boone & Veen, 1982). As an upper critical limit (UCML) soil conditions may be considered which allow a root growth which is only a fraction of the growth without mechanical impedance or completely stops root growth. A value of 3 MPa is appropriate in a homogeneous soil structure without pores equal or larger than the growing root tips (e.g. Taylor & Gardner, 1963). This limit has to be regarded as a safe limit. In less homogeneous soils the mean critical value will be higher because mean values obscure the rootability of the weaker spots (Groenevelt, 1984). This points to the real problem: how to quantify the number and continuity of macropores with dimensions which accommodate roots. For maize roots with a mean diameter of main root axes of 1000 μm requirements are higher than, for instance, for ryegrass with root diameters of 100-200 μm (Boone, 1976).

Present methods characterizing the system of large pores are not well suited to evaluate the mechanical aspect of soil rootability. Most limitations are related to the pore size range or pore geometry. The highest matric water potential applicable is $h_m = -0.1$ m and represents all pores with a diameter >300 μm. Only thin sections, which are not (yet) adapted for routine purposes, may provide more essential information about the system of these large pores. Measurements of air and saturated water permeability provide information about pathways which are not necessarily similar to the paths taken by growing roots. A method specially designed to simulate root growth in beds of aggregates in dependance of mechanical forces was proposed by Dexter (1976). For (very) compact soils with a limited number of large pores the analysis of thin sections is still required. The determination at a high matric water potential of the ratio between the intrinsic air permeability and the relative oxygen diffusion coefficient may provide some additional information. If it is assumed that all gas-filled pores have a diameter of the main root axes it is possible to calculate the maximum number of these pores. This may aggrevate the 3 MPa mechanical impedance boundary or relieve it to a higher limiting value. A similar indication may be derived from the potential shrinkage and swelling characteristics of a soil. In untilled loess soil with large biopores (Ehlers, 1982) and in untilled marine loam soil (Boone et al., 1984) root growth of cereals was observed until penetration resistances reached a value of 5 and 4 MPa, respectively.

Soil structures which guarantee a maximum crop yield under a wide range of environmental circumstances are preferable above those with a small range, unless the environment can be controlled adequately. In the proposed concept root growth which allows optimal crop growth is supposed to be possible between the critical limits of soil aeration and mechanical impedance and therefore have been related to the matric water potentials. The lower the matric water potential at which aeration becomes sufficient the greater the chance of a hampered root growth in wet conditions. Especially situations with a sufficient aeration only at matric water potentials lower than field capacity are potentially limiting. The lower the matric water potential at which root growth is unimpede the smaller the risk of insufficient root growth in dry situations. In the Netherlands in years with a dry period after sowing, matric water potential at the rooting front in the arable layer is generally $h_m = -2$ to -5 m, the last figure therefore may be taken as a minimum value. The narrower the range of matric water potentials without both limitations the greater the risks. When root growth is limited even at the best possible situation a real dangerous situation is to be expected. This situation occurs in the lower part (L) of treatment CS on loamy fine sand.

Conclusions

1. Soil porosities obtained by compaction of sandy soils were affected by soil composition, soil conditions and cropping history. A slightly wetter soil gave a smaller and three-year grass instead of maize as a previous crop, a larger porosity.
2. For the fine sand the relationship between the oxygen diffusion coefficient and the volume fraction of gas was similar to the relation for a single grain structure. A more favourable relationship was found when grass instead of maize had been the previous crop or when a significant amount of clay was present in the soil. The porosity did not have a specific influence on the relationship. The primary effect of compaction on oxygen diffusion therefore is the reduction in the volume fraction of gas.
3. Soil compaction shortly before sowing markedly increased the oxygen consumption of the soil at emergence.
4. The combination of several aspects of soil aeration and mechanical impedance in relation to matric water potential enables the evaluation of soil structure in relation to root growth.
5. The narrower the range of matric water potential which allow an unimpeded root growth, the greater the potential risks for plant growth and the greater the need for a controlled supply of water. Soil structures which substantially impede root growth even at the most favourable matric water potential are to be classified as dangerous. This situation was encountered in the lower part of the experiment on loamy fine sand severely compacted at field capacity.

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