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SOIL MECHANICAL PROPERTIES OF A PARTLY-RELOOSENED (SPLIT PLOUGH SYSTEM) AND A CONVENTIONALLY-TILLED OVERCONSOLIDATED GLEYIC LUVISOL DERIVED FROM GLACIAL TILL

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A b s t r a c t. In the Eastern states of Germany, there are many arable soils which have been compacted and overconsolidated as a result of intensive wheeling. These require mechanical loosening in order to improve the structure of the deeper layers of these originally very fertile soils. Repeated wheeling of highly-overconsolidated soils results in a further stress distribution to greater soil depths, because the hard plough pan layer serves as an elastic pressure plate provided that the deeper soil horizons are not strong enough to carry the load applied. Furthermore, the types of stresses induced during wheeling differ depending on the original soil strength and the number of loading events. The slit-ploughed soil volume is subjected to further changes of the pore system and of the soil strength induced by shear stresses, because during wheeling additional soil material is pressed in the weaker slit-ploughed soil volume. The hydraulic properties also change very significantly. In order to preserve the improved soil conditions, two further aspects have to be considered:

1. Wheeling should be carried out only at right angles to the slits which has the benefit of using the adjacent, stronger, unslotted soil to attenuate the stresses applied.

2. Under drier soil conditions, slotted soils can be wheeled.

Wheeling must be avoided if the soil is moist in order to prevent the reloosened soil volume from additional soil compaction due to slip-induced transport of adjacent, previously-undisturbed soil into the slit itself.

K e y w o r d s: soil, mechanical properties, mechanical loosening

INTRODUCTION

Due to the development of heavier agricultural machinery and due to the intensification of soil and plant treatments throughout the year, the most soil-adjusted tillage systems are discussed with respect to reduce the applied stresses to the soil as much as possible [24]. In addition, the compaction status of arable soils has been mentioned as one of the most important world wide phenomena of soil degradation [20]. Soil compaction is always discussed especially because of its effects in reducing crop yield or in preventing root penetration and it is also critically mentioned with respect to increased soil loss by water erosion, reduced filter- and buffer-capacity of the site and the change of physical and chemical site properties [24]. Håkansson *et al.* [8], for example, mentioned the very long-lasting effect of soil compaction on yield reduction as well as on the increased sensivity to draught or to soil wetness due to a single too-intense wheeling event. In the Eastern states of Germany (former German Democratic Republic) the farmers had to use very large and very heavy agricultural machinery in order to finish the different farming operations throughout the year in time. However, because of the use of those machines under unfavourable soil conditions, very severe additional compaction of soil layers even far below the plough pan can usually be found.

In the state of Thuringia, for example, about 40% of the arable soils show significant symptoms of structure damage which may result in yield decreases of up to 30% [26]. As these soil compaction phenomena persist for a long time and are not readily loosened by natural processes, several attempts have been made to improve the ecological soil properties by mechanical means. Attempts at soil amelioration [11] are rather old. With respect to technical and application differences, Schulte-Karring [22] subdivides these techniques in three different types of methods, if soils are loosened mechanically: deep furrow ploughing and sub- ploughing, partial (point) reloosening, complete mixing or non-mixing loosening techniques. However, total soil mixing or reloosening on a large or a small scale induces a very drastic strength reduction, which often results in an even more intensive recompaction than was produced previously by the same machines. If the soil is wet, it will be recompacted even more intensely, especially if wheeled under moist conditions [23].

Because of the problems associated with the low strength of loosened soil during subsequent tillage treatments, Blackwell *et al.* [2] tested a slotter technique successfully. This combines the advantages of an ameliorated soil volume for better plant growth with the strong and non-reloosened side wall soil volume for carrying the load of tractors. However, the shear resistances between the reloosened soil volume and the polished side walls of the slots are very small, and this may result in a very quick resettlement of the soil volume if the slot width is too wide compared with the tyre width or if the slotted soil is wheeled parallel to the slot and/or under wet soil conditions [2]. At the same time, a slit plough was developed in the former GDR in order to ameliorate overconsolidated soils down to 45 cm depth by creating 10 cm wide slits with additional tines (for more technical details see [21]). How far such partly-alleviated soil horizons can be protected between overconsolidated soil segments in spite of consecuted tillage procedures was unknown and is analyzed in this paper with respect to their mechanical and physical properties. The results are also compared with corresponding data from a normally-ploughed gleyic Luvisol derived from glacial till, in order to derive some recommendations for more site-adjusted tillage systems.

MATERIAL AND METHODS

In autumn 1989, an over-compacted, gleyic Luvisol derived from glacial till in Bargeshagen near Rostock was:

1) normally tilled with a conventional mould board plough to 25 cm depth,
2) tilled with a slit plough technique.

The slit plough (developed by Reich *et al.* [21]) consists of 10 cm wide and 20 cm long slightly-bent vertical tines below each mould board. Thus, the compacted plough layer can be partly reloosened to a depth of 45 cm, while the compacted side wall area will be at least partly cracked if during ploughing the soil shows brittle failure (Fig. 1). The distance between the ditches is 20 cm, and the width of the ditch is 10 cm, which results in a reloosened soil volume of 33%. The determination of wheel-induced changes in soil strength and corresponding hydraulic parameters was performed after 1 - 10 consecutive wheeling events carried out during one day, whereby the slit itself was wheeled in a direction at right angles to the slit direction. The wheel loads of the tractor and of an additional slurry tank were 0.8 and 3 Mg respectively, which result in mean values of contact area pressure of 0.13 MPa and 0.65 MPa. In the present paper, only the changes induced by the rear wheels are discussed because these higher stresses are mostly responsible for alterations in soil physical properties. The water content (θ_v) in the normally-ploughed gleyic Luvisol was approximately 0.16 to 0.18 ($m^3 m^{-3}$), while the corresponding values for the slit-ploughed soil were 0.23 in the top 10 cm and decreased to 0.18 ($m^3 m^{-3}$) at 20 - 50 cm depth. The higher values in the top soil were induced by a heavy rain storm of 20 mm just before wheeling. The

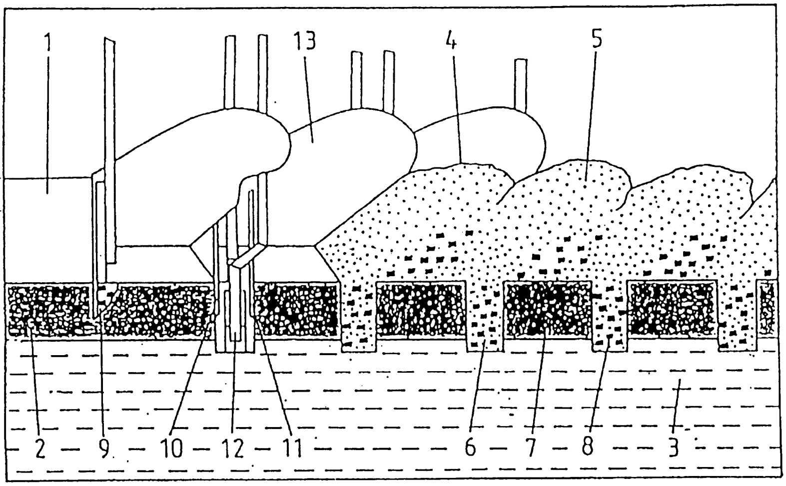

Fig. 1. Schematic diagram of a ditch-ploughed soi: 1 - Ap-horizon, 2 - compacted subsoil, 3 - undisturbed deeper subsoil, 4 -plowed, i.e., reloosened soil volume, 5 - basis of the plowed soil volume, 6 - ditch, 7 - unloosened soil material in between the ditchs, 8 - reloosened subsoil; 9 - 12 show special arrangements of the ditch-plow technique, 13 - slit plough. (Figure taken from Werner *et al.* 1992).

corresponding pore water pressure values ranged between -24 and -11 kPa.

During wheeling, mechanical stresses at various depths in both treatments were measured using stress state transducers (SST) [14], and the 3 principal stresses as well as the octahedral shear stress (OCTSS) and the mean normal stress (MNS) were calculated. In the partly-reloosened slit-ploughed soil, the corresponding stresses were determined both inside the slit and in the unploughed side walls at 35 and 45 cm depths. In total, 8 SST sensors were installed which were distributed as follows: at 20 cm (=seedbed) and in the slotted and unslotted soil volume at 35 cm depth we installed 2 sensors each, while at 48 cm depth only the slotted soil was equipped with two sensors. We expected that the very strong unslotted soil would be not affected by further soil stresses. In case of the unslotted soil, the first three depths were equipped with two sensors each, while at 55 and 65 cm only one sensor per depth was installed. In the present paper only the mean values are shown. The effect of 10 repeated wheeling events in the conventionally-ploughed soil (treatment 1) on hydraulic conductivity was determined and is used to characterize the wheeling effects on ecological site properties. Hydraulic conductivity was measured with a Guelph permeameter at different depths before and after wheeling events [3,6]. The pore size distribution, soil texture and proctor density were determined according to Hartge and Horn [9].

RESULTS

Soil physical properties of the sites

Table 1 shows some main soil physical properties of the conventionally-tilled (NP) and the slit-ploughed (SP) soil. The gleyic Luvisol is derived from glacial till and sandy outwash material consists of sandy loam to loamy sand. The clay content in the slit itself was a bit higher than in the corresponding unslotted soil volume due to the mixing process. The pore volume data of the conventionally-ploughed site show smallest values in the plough pan layer with only a few coarse pores (derived from the smallest (α-values). The slit-ploughed site, however, is less compacted inside the slotted soil volume, possibly because of previous soil compaction, while the unloosened side walls are dense and have only a few macro pores. The amount of plant-available water exeeds 20% throughout the total profiles, if calculated using the parameters of the van Genuchten equation. The plasticity index of the soil material was 0.15 and the activity value was 0.83 (according to Skempton,

Table 1. Soil physical properties of the conventionally (NP) and the ditch ploughed (SP) soil for gleyic Luvisol derived from glacial till. Location: Bargeshagen near Rostock (*nd. - not determined)

Depth (cm)	Horizon	Particle size distribution							Degree of compactness (d60/d10)	Org. matter (g/100g)	Proctor density (Mg/m^3)
		clay	fine silt	medium silt	coarse silt (%)	fine sand	medium sand	coarse sand			
					Conventionally ploughed (NP)						
0-30	Ap	7.5	5.4	7.4	15.3	41.5	19.2	3.3	33	1.48	
30-40	AlBv	3.1	6.0	7.0	13.5	42.1	21.8	3.7	21	0.81	1.84
40-50	Bv	7.9	3.2	6.4	16.0	39.6	21.2	5.1	29	0.40	1.84
50-60	Btg	11.1	5.2	8.7	11.9	36.7	18.6	4.2	n.d.*	0.29	
					Slit ploughed (SP)						
0-30	Ap	7.7	5.0	6.4	17.3	41.2	19.2	2.8	35	1.61	
30-50	R.AlBv	6.2	5.0	8.3	16.1	41.0	18.5	4.5	26	0.80	1.84
50-60	Btg	16.6	5.9	6.5	13.5	35.3	16.7	4.2	n.d.*	0.33	1.84

T a b l e 1. Continuation

Depth (cm)	Water content θv (m^3 m^{-3}) at pore water pressure (kPa)							Proctor density (Mg/m^3)	Bulk density (Mg/m^3)	Plasticity (g/g)	Activity according to Skempton
	0	-1	-3	-6	-15	-30	-90				
					Conventionally ploughed (NP)						
0-30	0.454								1.42		
10-20	0.442	0.497	0.427	0.400	0.318	0.240	0.177	1.84	1.45		
20-30	0.396	0.384	0.367	0.331	0.266	0.210	0.164		1.59		
30-40	0.389	0.384	0.372	0.340	0.257	0.190	0.140		1.62		
40-50	0.411	0.405	0.396	0.355	0.267	0.210	0.172	1.90	1.68	0.15	0.83
50-60	0.415								1.66		
					Slit ploughed (SP)						
0-10	0.427							1.84	1.49		
10-20	0.408								1.84		
20-30	0.423								1.53		
30-40	0.408								1.57		

cited in Kretschmer [18]. These values can be explained by the grain size distribution and the clay mineralogy of illite as the most dominant clay mineral. The unwheeled soil aggregates were small (5 - 10 mm) subangular blocks in the top soil, while in the plough pan and in the deeper soil horizons coarser and especially in the plough layer platy aggregates were found. In the slit-ploughed soil, anthropogenic aggregate fragmentation resulted in blocky structures (not shown). During wheeling, the top soil became completely kneaded resulting in more or less plastic deformation. In the deeper layers (40 -50cm) of the slit-ploughed soil, it was not possible to differentiate between the normal or the slotted soil volume. However, the anthropogenically-formed aggregates inside the slit volume were coarser and sharper-edged and had no inter-aggregate pores.

Soil mechanical properties

The effect of repeated wheeling on mechanical stress distribution in conventionally-ploughed agricultural soils is shown in Fig. 2. It can be seen that during the first wheeling at constant speed most of the stresses are attenuated in the top soil. During repeated wheeling, however, the deeper soil layers (up to 45 cm) became more stressed, resulting in higher normal stress values. Therefore, the soil at these depths became more and more overconsolidated. Additionally the delay of the stress increasing steps due to repeated wheeling events can be explained by the time-dependent stress attenuation processes. If changes in the mean normal stresses and octahedral shear stresses are calculated from the measurements from the SST-sensors, the following can be seen (Fig. 3).

In the top soil (i.e., 20 cm) the mean normal stress values first increase and later decrease again. The corresponding data for the unslotted soil volume at 35 cm depth show only a slight negative trend after 10 wheeling events. Inside the slotted soil volume, a steady decrease in the mean normal stresses occurred with increasing number of wheeling events. The octahedral shear stress always decreased with the number of wheeling events, but especially during the first part, a very high value was obtained at 20 cm depth, compared with that at 35 cm. In the slotted soil volume at 35 cm depth, greater values were detected, especially during the first pass, in comparison with the adjacent unslotted soil. The possible soil deformation at a given normal stress can be shown by the shear stresses created during wheeling which can be calculated from the single stress components (principal stresses, σ_1 and σ_3). The greater the value,

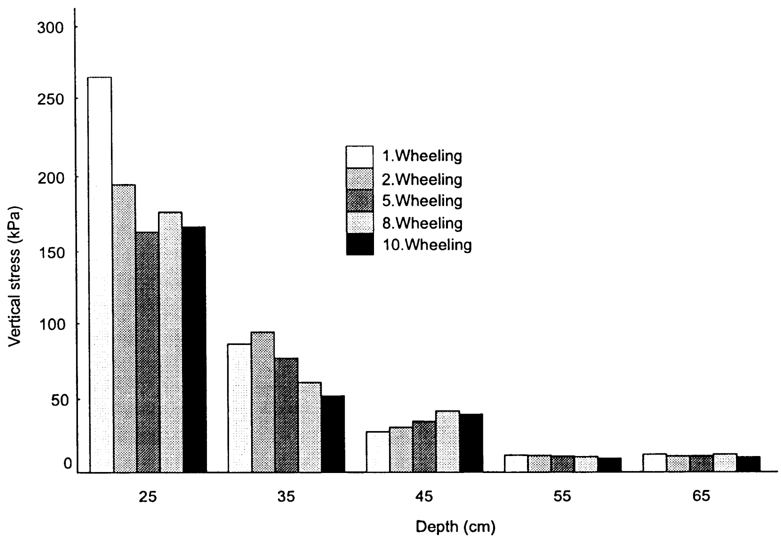

Fig. 2. The effect of number of wheeling events on vertical stresses (kPa) in the conventionally-ploughed gleyic luvisol derived from glacial till (the ploughing depth was 30 cm).

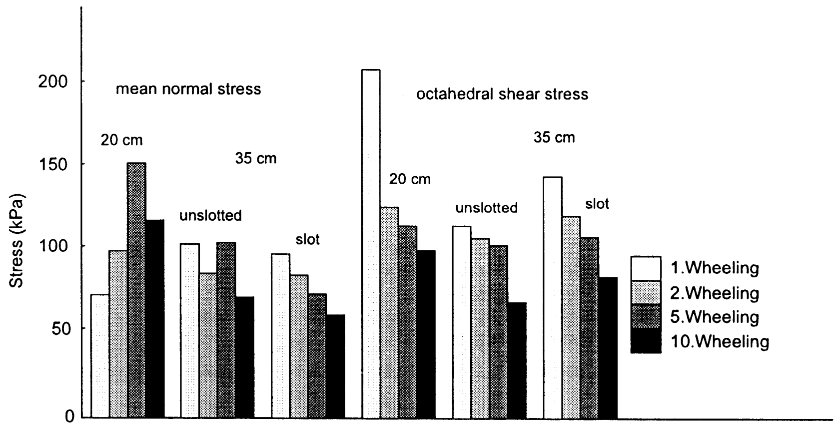

Fig. 3. Mean values of normal and octohedral shear stresses induced by repeated wheeling in the undisturbed and in the ploughed top and slotted soil volume as a function of number of wheeling events.

the more likely is an internal soil deformation by shearing. As can be seen in Fig. 4, shear stresses are especially high at 20 cm depth, and in the slot itself during the first wheeling event. In contrast, subsequent wheelings resulted in only smaller additional stress differences. In the unslotted soil volume the stress differences decrease with depth if the ratios, σ_1/σ_3 or the differences ($\sigma_1 - \sigma_3$) are compared. In the slotted soil volume at 35 cm depth, the same trend of decreasing differences in stress with repeated wheeling was found.

The effect of repeated wheeling on changes in bulk density of the conventionally-tilled soil is shown in Fig. 5. The bulk density values increase especially in the top 30 cm due to increasing compaction with increasing numbers of wheeling events. In contrast, at depths greater than 30 cm, the bulk density seems to decrease if the number of wheeling events exceeds 5. If the effects of wheeling are compared with the proctor density as a measure for highly-compacted soils, it can be seen thåt for the given material the proctor density value is nearly reached in the top soil and results in a very pronounced decline of the hydraulic conductivity values near saturation (Fig.6). After 10 wheeling events the hydraulic conductivity/

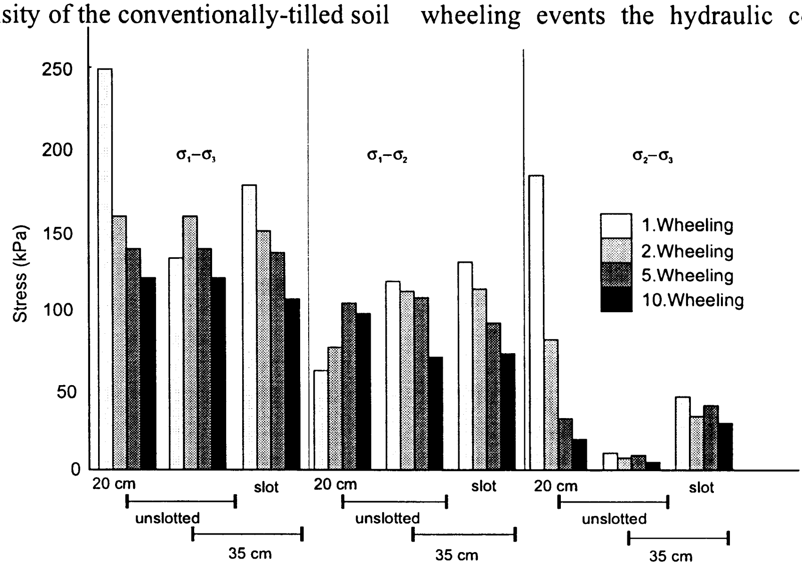

Fig. 4. Shear stresses between the 3 components of the principal stresses during repeated wheeling of the partly-reloosened gleyic luvisol.

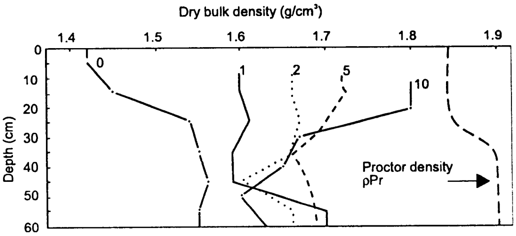

Fig. 5. Changes in soil bulk density with increasing number of wheeling events (0, 1, 2, 5 and 10). After 10 wheelings the value of the proctor density in the topsoil is nearly reached.

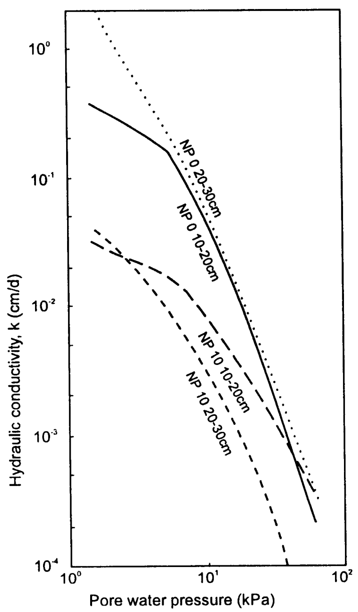

Fig. 6. Change in the hydraulic conductivity/pore water pressure relation due to repeated wheeling. NP 0 - initial relationship, NP 10 characterizes the relationship after 10 wheel passages over the normally-ploughed (NP - conventionally) gleyic luvisol.

pore water pressure curve is especially flattened up to -70 kPa pore water pressure and probably would show higher values for the hydraulic conductivity compared with the original (unwheeled) situation exceeding this pore water pressure value as a consequence of formation of finer pores out of the originally coarser ones.

At depths of 20 - 30 cm, 10 wheeling events always resulted in a very pronounced reduction of the whole range of pore water pressure values, but a rearrangement of pores (creation of finer pores out of originally coarser ones) could not be detected. In addition Table 2 presents the parameters of the van Genuchten equation for the unwheeled situation and after 10 wheeling events. In addition the effects of slit ploughing on the changes in the hydraulic properties can also be seen. The α - and n -values were always greater in unploughed soil. Both the α - and n-values get smaller with increasing number of wheeling events. Differences in porosity decreased with depth but could easily be detected to a depth of 50 cm.

The effect of wheeling on hydraulic flow processes was investigated using the drainage ratio (Fig. 7). Drainage ratio is defined as the amount of water drained during time t divided by the amount drained at infinite time (Fig. 7). The drainage ratio was reduced significantly after 10 wheeling events, in comparison with the corresponding unwheeled plot. The increase of the drainage ratio with time is more pronounced in the unwheeled field than in the wheeled field after 10 wheeling events. Additional slight differences have to be considered between the curve patterns of wheeled and unwheeled sites slit-ploughed vs. conventionally-ploughed. The slope for the unwheeled plot is much greater than that for the wheeled plot, which corresponds with longer-lasting water ponding and significantly reduced reaeration of the site under the given climatic and hydraulic conditions.

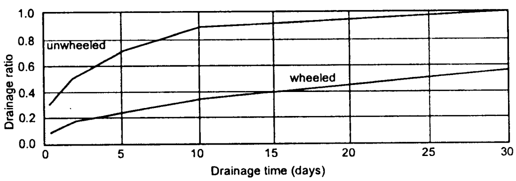

Fig. 7. Cumulative internal drainage ratio (Q/Q_t) of wheeled and unwheeled conventionally-ploughed treatments at a depth of 10-20 cm.

DISCUSSION

Each stress applied at the soil surface due to wheeling and ploughing increases the internal soil strength or mobilizes the corresponding shear resistance in order to attenuate the external forces. Whenever these forces exceed the internal soil strength, further soil settlement and an additional alteration of the hydraulic properties can be expected as long as a maximum shear

Table 2. Effect of wheeling on the van Genuchten parameters at different depths in conventionally and slit-ploughed gleyic Luvisol derived from glacial till. Data of the parameter of van Genuchten equations

Depth (cm)		θr (cm^3/cm^3)	θs (cm^3/cm^3)	α (1/cm)	n (1)	Ks (cm/d)
		Conventionally ploughed (NP) (unwheeled)				
10-20		0.055	0.432	0.0087	1.719	0.65
20-30		0.044	0.400	0.0144	1.509	4.08
30-40		0.067	0.382	0.0107	1.807	2.00
40-50		0.083	0.400	0.0162	1.623	3.83
		Slit ploughed (SP) (unwheeled)				
10-20		0.232	0.385	0.0172	1.786	0.78
26-31	slit	0.0	0.355	0.0066	1.359	0.30
26-31	unploughed	0.200	0.372	0.0129	1.871	0.29
42-47	slit	0.0	0.384	0.0069	1.213	1.83
42-47	unploughed	0.082	0.400	0.0162	1.624	3.90
		Conventionally ploughed (NP) after 10 wheeling events				
10-20		0.0	0.303	0.0037	1.347	0.01
20-30		0.0	0.361	0.0140	1.320	0.26
30-40		0.076	0.366	0.0113	1.998	2.05
40-50		0.069	0.380	0.0135	0.953	3.09
		Slit ploughed after 10 wheeling events				
20-30		0.168	0.334	0.0066	1.123	0.01

force and a maximum number of contact points is not reached [1]. However, soil may behave either as a rigid body during short-time loading or may react by an additional soil settlement if the internal soil strength is exceeded [5,19]. The greater the water content, the smaller the hydraulic conductivity at given pore water pressure and the shorter the stress application, the more likely it is that soils will behave as rigid bodies and will transmit applied stresses to greater depths. The higher the hydraulic conductivity and the more pronounced the pore continuity at a given internal soil strength, the greater are the deformations produced. Consequently, these deformations are most pronounced in the top soil, while at greater soil depths smaller deformations can be expected. In general this is an agreement with our data. However, because soil settlement is a time-dependent process [4], short-time loading never results in a new strength equilibrium of the corresponding soil layer, but the strength values are merely quasi-stationary. If during the initial short-time loading, the top soil gains further soil strength and will attenuate consecutive stress application more intensely, and behaves as a rigid elastically-deformable body, then deeper and weaker soil horizons are still compressed irreversibly. Repeated wheeling therefore can induce strength increases and additional soil settlement, even at greater depths and alter the physical as well as chemical properties of the soil. The data obtained completely support the theoretical approaches about stress propagation, stress attenuation and changes with time and number of loading events (see also [7,10,16]). When soil strength differs not only between various soil horizons, but also within single soil horizons, as a consequence of slit ploughing, further alterations of stress distribution, concentration and attenuation have to be considered. The weaker the soil, the more pronounced is the stress transmission, even if it is concentrated mainly vertically beneath the wheel. In stronger soil horizons at the same depth, stress attenuation is more pronounced, even if the concentration factor as a measure for the pattern of the equipotential stress lines in soils gets smaller [10]. If stresses are applied both on the untilled and the slit-ploughed soil volume, stresses will be partly attenuated in the solid volume, while inside the weaker soil material a more pronounced stress propagation to deeper depths has to be considered. Consequently, the kind of stresses and stress propagation depends mainly on the position of the external stresses applied in relation to the size of the weakened soil volume, i.e., slit width in comparison to the tyre diameter. In the present study, soils were always wheeled at right angles to the slit, in order to preserve the weaker soil conditions inside the slit while at the same time allowing the unslotted soil volume to react as a more complete stress attenuating rigid soil body. However, wheeling always induces dynamic forces and positive or negative slip processes [17]. Dynamic loading results in a further soil deformation, especially of the weak soil volume as well as in a divergent and shear process resulting both in a more intensive soil compaction at the weak top soil and in an additional soil compaction inside the slotted soil volume [25]. The latter is especially true because the material properties of the soil are mainly texture- but not structure-dependent and because there is in general no strength increase by bridging with the adjacent unslotted soil volume. If in addition the water content of the deformable top soil is very high, the refilling of the slotted soil volume occurs more intensely, because dynamic forces create greater pore water pressure values (i.e., less negative) at higher water contents and result in a complete homogenization of the slotted soil volume. In addition shear strength declines, material will be translocated into the slot where it further compacts the originally-weaker and less-compacted soil volume. These processes are supported by the data obtained. The higher the octahedral shear stresses are, the more intensive is the soil deformation at a given mean normal stress. The shear stresses are more pronounced in the soil slit at a given mean normal stress and it can also be shown from the data that the direction of the resulting shear process clearly defines the weaker soil volume and the direction of shearing inside the slot during wheeling. If we consider the ecological consequences of the slit ploughing and of the following wheeling event, we can differentiate the result of soil loosening as well as structure deterioration and soil recompaction.

When the bulk density was slightly reduced, the functioning of the newly-formed pores did not coincide with this soil weakening. It can be shown from the hydraulic conductivity parameters that especially at greater soil depths, the unploughed site was originally more permeable than the slotted soil volume which can be explained by the increased tortuosity of pores in the weaker slitted soil volume. It can therefore be concluded that bulk density as a material parameter of soils cannot be used to predict properties and processes (see also [12,15]. However, it can be shown that after 10 wheeling events the slit-ploughed soil volume has a much smaller hydraulic conductivity than the corresponding unslotted soil volume. This is in agreement with results presented by Horn *et al.* [13]. The intensive decline of the water-conducting pore system in the slit-ploughed soil after 10 wheeling events also results in a reduced rate of drainage of excess soil water and consecutive delay in soil drainage ratio. Both effects are reported in Soane and van Ouwerkerk [24], and are supported by the results presented here.

CONCLUSIONS

As a consequence of the above properties and processes it can be concluded that wheeling has to be restricted to hydraulic conditions under which the soil is strong enough to attenuate the applied stresses without any further deformation. If soil is overconsolidated and not rootable to deeper depths, it can be ameliorated by deep ploughing, but this technique requires a very dry soil with brittle failure behaviour. However, this amelioration results in a decrease of shear strength towards the values for completely-disturbed and homogenized soil which depend only on the soil texture. It also results in an increase in pore tortuosity under less-compacted situations. In order to combine plant growth and soil wheeling, partial reloosening by the slit-plough technique can be recommended, because it combines the intensive stress attenuation in the unslotted soil volume and the easier penetration of roots, gas, and water inside the slotted soil volume. However, the data illustrate the much greater sensitivity of such treated soils for recompaction under wetter soil conditions, even if they are wheeled at right angles to the slot and with very wide tyres. Soil deformation under wet soil conditions due to squeezing, shearing or kneading always results in the worst case as compared with the initial, unloosened case and therefore should be avoided. Farmers may estimate the worst soil case by using a very simple and fast sensory field test [18]. Up to now there are no data available on how long soil wheeling has to be reduced in order to reform a new and stronger soil structure which is able to attenuate applied stresses, but which does not prevent or restrict the growth of roots or the transport of gas and water. Further research on this topic is required.

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