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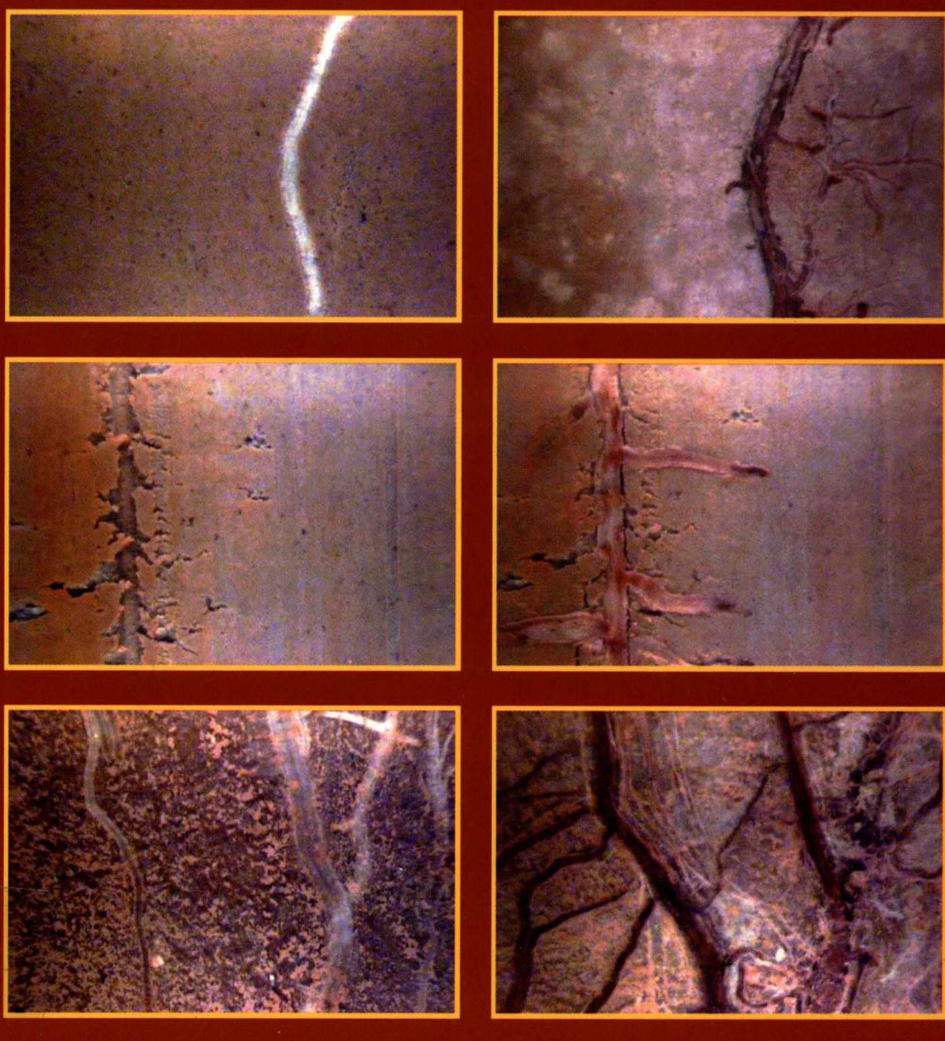

Vol. 68 No. 4 July–August 2004

SSSJD4 68(4):1131–1470 (2004)

Soil Science Society of America Journal

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Official Sources

1. Spelling: Webster's *New Collegiate Dictionary*.
2. Amendments to the U.S. system of soil taxonomy (Soil Survey Staff, 1975) have been issued in the *National Soil Survey Handbook* (NRCS, 1982–1996) and in *Keys to Soil Taxonomy* (Soil Survey Staff, 1996). Updated versions of these and other resources are available at http://soils.usda.gov/technical/classification/tax_keys/.
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4. Chemical names of pesticides: *Farm Chemicals Handbook* (Meister Publishing, revised yearly).
5. Soil series names: All names for both active and inactive U.S. soil series are maintained by the Soil survey Staff and can be accessed through the Soil Series Classification, Database (Soil Survey Staff, 2004) at http://soils.usda.gov/technical/classification/scfile/.
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8. *The Glossary of Soil Science Terms* is available both in hard copy (SSSA, 1997) and on the SSSA Web page (www.soils.org/sssagloss/). It contains definitions of more than 1800 terms, a procedural guide for tillage terminology, an outline of the U.S. soil classification system, and the designations for soil horizons and layers.

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May 2004

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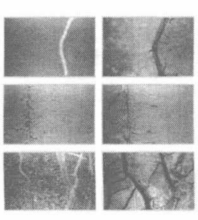

This issue's cover: Paired minirhizotron images showing roots of a canola cover crop (left) in compacted plowpan soil in April/May 2002 and soybean roots (right) observed at the same locations in the soil in July/August 2002. The soybean roots can be seen to follow channels made by the preceding canola roots. Cover crop roots penetrate compacted plowpans in winter, when the soil is wet and has low strength. As these roots decay, they provide low resistance paths for roots of subsequent crops growing in summer when the soil is drier and has much greater resistance to penetration. High penetration resistance in the plowpan during dry summer weather can restrict the access of crop roots to water stored in deeper soil layers. See p. 1403–1409, "Crop Cover Root Channels May Alleviate Soil Compaction Effects on Soybean Crop" by S.M. Williams and R.R. Weil.

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SOIL SCIENCE SOCIETY OF AMERICA
JOURNAL

VOL. 68 JULY–AUGUST 2004 No. 4

DIVISION S-1—SOIL PHYSICS

Time Dependence of Soil Mechanical Properties and Pore Functions for Arable Soils

Rainer Horn*

ABSTRACT

Progressive soil degradation due to tillage operations affects crop production and its yield uncertainty, soil erosion by wind and water, and gas emission. The possibility of soil regeneration due to natural or anthropogenic processes is of major concern to sustain soil functions. Material properties like precompression stress, shear strength, and hydraulic conductivity are time dependent, while bulk density is less sensitive to time effects. The hypothesis that the change from conventional to conservation tillage affects mechanical soil strength and pore functions was tested for a stagnic Luvisol derived from glacial till in northern Germany. For more than 7 yr precompression stress, shear strength, and hydraulic conductivity were determined at three depths down to 60 cm. Approximately 3 yr after starting with the Horsch system (annual shallow chiseling in autumn down to an 8-cm depth) as a kind of conservation tillage, soil strength, and the hydraulic conductivity increased in the topsoil by more than 50 kPa and 500 cm d^{-1}, respectively, even at a higher bulk density as compared with the corresponding values for the conventionally tilled plots. Within the following 2 to 3 yr, these changes were also detected at the 30- to 35-cm soil depth. At the depth of 55 to 60 cm the same trend started after around 7 yr. These changes can be only detected, if the tillage systems were applied continuously and if all tillage and soil operations were performed with light machines, which enable the preservation of newly formed pores and the rearrangement of soil particles creating a more stable soil structure. Thus, the susceptibility to soil deformation will be reduced due to an increased shear strength, which in turn improves pore functioning.

THE EFFECTS OF TILLAGE systems on crop yield, water and nutrient uptake efficiency have been repeatedly described and have resulted in a very detailed description of the minimum time required to adjust site properties. Ehlers et al. (1980) and Baeumer (1992) have shown that after approximately 7 yr of continuously applied no tillage (NT) an identical net yield was obtained for no-tilled compared with conventionally tilled sites as a consequence of the increased saturated hydraulic conductivity and pore continuity in the root zone. Horn (1986) determined the effect of long-term tillage on soil mechanical properties and found that, in general, soils subject to conservation tillage are stronger and therefore less susceptible to deformation induced changes in physical properties compared with conventionally tilled soils. However, in those investigations no seasonal changes were analyzed. Wiermann et al. (2001) measured the effect of wheel traffic on changes in physical properties in a Luvisol derived from loess (Reinshof/Goettingen) and in a Mollisol derived from loess (Gross Obringen). They found for the conservation tillage system an increase in soil strength of about 50 to 100 kPa at comparable soil depths and further showed that a decline in saturated hydraulic conductivity or air permeability occurred only if mechanical stresses applied by machines exceeded the soils precompression stress. At the virgin compression load range, the saturated hydraulic conductivity as well as the air permeability decreased linearly if plotted on a lognormal scale with increasing applied mechanical stress.

Van Ouwerkerk and Soane (1994) summarized much of the present knowledge about the effects of wheel traffic on soil physical properties and functions, but as they described mainly short-term effects of conventional tillage systems using more general parameters, no recommendations have been derived for example, for producers. The same is true for the papers of Håkansson et al. (1987), Håkansson and Reeder (1994), and Håkansson and Lipiec (2000) because they dealt primarily with soil bulk density (i.e., mass per volume) and apart from that restricted their research on the plowed topsoil layers.

Or and Ghezzehei (2002) defined mechanical differences between tillage treatments by calculating the elastic modulus (Hooke's Law), including data taken from mechanical measurements of Wiermann (1998) and Kühner (1997). Both the latter authors investigated soils under conventional and conservation tillage systems and classified the conservation tillage systems as more sustainable. Horn et al. (2000) addressed the subject of "Subsoil compaction—processes, consequences and distribution"

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Published in Soil Sci. Soc. Am. J. 68:1131–1137 (2004).
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and focused on the mechanical processes, which can be used for a more detailed analysis of soil deformation. Wiermann et al. (2001), Kühner (1997), Fleige et al. (2002) pointed out that the determination of shear strength parameters and soil precompression stresses, as indicators for the maximum internal soil strength, aids the quantification of pore functions such as hydraulic conductivity and air permeability. Data sets have yet to be developed that can be used to correlate tillage effects on bulk density to soil hydraulic properties. Baumgartl et al. (1995) and Baumgartl and Horn (2001) demonstrated a similarity between the stress strain and the water-retention curve, which may facilitate the derivation of one from the other. Schjønning et al. (1999) determined the effects of tillage on several soil parameters but did not report pronounced time dependent differences between treatments.

Thus, a better understanding is needed of the soil deformation processes following changes in tillage systems to document time effects on changes in soil strength and pore functioning. This paper presents the results from a long-term experiment to provide evidence to support the following hypotheses:

- —The increases in soil stability and pore continuity develop slowly requiring a number of years.
- —The increase in soil strength depends on the shear stress per particle contact point, which results from the rearrangement of particles during swelling and shrinkage processes.
- —The particle rearrangement leads to an increased hydraulic conductivity and/or air permeability provided that conservation tillage systems have been applied over several years employing light agricultural machinery to not exceed the soils precompression stress.
- —Soil strength, defined as precompression stress, must exceed the external stress applied to sustain the rearrangement of particles irrespective of wheel traffic during swelling and shrinkage.

MATERIALS AND METHODS

Soils and Experimental Setup

The experiments were performed at the experimental farm of the University in Hohenschulen/Kiel where the main soil type is a stagnic Luvisol (according to World Reference Base [WRB]) derived from weichselian glacial till. From 1991 until 1999, plots, which were originally conventionally plowed, were subdivided into conservation (= Horsch System = chiseled to an 8-cm depth) and conventionally tilled plots. Both treatments received mineral fertilizers and/or manure at various times. Only the 240 kg N ha^{-1} fertilized plots under the two tillage treatments were studied. The selected sites were either conventionally tilled to a 25-cm depth each year in autumn or they were chiseled to an 8-cm depth (= conservation tillage plot) at the same period. These tillage systems (four row moldboard plow or chisel) were identical throughout the experiment and the machine mass used for all treatments was only 49.1 kN (Fendt tractor: type Farmer 308 LSA, Marktoberdorf, Germany), which resulted in an average contact area pressure of 90 kPa with a tire inflation pressure of 200 kPa. The lug height was 30 to 40 mm. The tire type was Pirelli TM 200 S 13.6 R24 (front) and Pirelli TM 300 S 16.9 R34 (rear) (Pirelli, Milan, Italy). All required field operations were performed at the same time and the soil water content was below field capacity especially for moldboard plowing or chiseling. The chisel "type Horsch" retained during the operation all residues of the conservation tillage plots on the surface to further improve the biological activity.

We determined changes in soil properties on both conventional and conservation tillage treatments over 9 yr up to three times per year at three depths. The depths were 10 to 15 cm (plowed seedbed or just below the chiseled soil layer), 30 to 35 cm (the actual or former plow pan layer), and 55 to 60 cm (clay enriched Bt horizon). Investigated soil properties were the stress strain behavior using a confined compression test (i.e., the horizontal stress is not defined because of the wall stiffness) and the shear strength under consolidated drained conditions (frame shear test) at a constant pore water pressure of −30 kPa.

The precompression stress value, that is, the transition from the reloading curve to the virgin compression line, was defined by the method of Casagrande (cited in Horn, 1981). Casagrande proposed an empirical construction to obtain from the void ratio–log stress curve the maximum vertical stress for soil samples that had acted on it in the past, referred to as the precompression stress. If the precompression stress value is exceeded by higher vertical stresses, soil samples show virgin compression behavior. The transition from the recompression to the virgin compression line (= precompression stress value) was derived from stress strain measurements with 10 undisturbed soil cylinders (diameter 100 mm, height 30 mm) per depth, which were equilibrated to a pore water pressure of −30 kPa and stressed for 23 h with one defined stress. This pore water pressure value defines the hydraulic stress situation encountered in summer within the upper 1 m of the soil profile.

The shear box tests were performed on all prestressed samples immediately thereafter and the parameters of the Mohr Coulomb failure line were derived from the shear strength as a function of the applied vertical stresses. The shear strength τ was originally expressed by Coulomb as a linear function of the normal stress σ on a plane at the same point by:

$$\tau = c + \sigma_n \tan\phi,$$

where c and ϕ are the shear strength parameters: cohesion (= intercept) and angle of internal friction, that is, the slope of the Mohr Coulomb failure line.

Changes in the saturated hydraulic conductivity were measured to quantify the changes in pore functions over time.

The bulk density was determined at all depths and times on undisturbed soil cores as an average value of 12 replicates. The particle density was determined by submerse measurement. The particle-size distribution and chemical properties were also measured. More detailed descriptions of these tests are given in Hartge and Horn (1992), Horn and Baumgartl (1999), and Schlichting et al. (1995).

Statistical Analysis

Analysis of variance (ANOVA) was performed for the effect of land use on bulk density, soil strength, and hydraulic conductivity (SPSS11.0). The differences of means between land uses were assessed by least significant difference (LSD) tests.

Stepwise regression analyses were also performed and the type of regression between tillage effects and correlations in physical properties with time (days) since this study began were determined using standard statistical procedures.

RESULTS

General Soil Description

From the physical and chemical properties of the soil (Table 1) it can be seen that the stagnic Luvisol has a

Table 1. General description of the physical and chemical properties of the investigated stagnic Luvisol derived from glacial till under two tillage systems (conventional = yearly plowing down to the 25-cm depth; conservation = Horsch system, chiseling down to 8 cm).

Horizon	Depth	Sand	Silt	Clay	C org	pH	Spec. density
	cm		%		%		g cm^{-3}
Ap (sub.-crumb)	0–25	59	29	12	1.47	6.5	2.56
AlSw (platy)	25–55	61	27	12	1.28	6.6	2.57
Bgt (pol-pris)	55–150	56	25	19	<0.2	6.2	2.64
Cg (platy)	>150	53	25	22	0	7.2	2.65

characteristic amount of organic C in the Ap and Al horizons. The soil is free of calcium carbonate down to 150 cm, but the pH values range only between 6.2 and 6.6. The pH decreases with depth in the upper soil horizons (up to the Bgt horizon) resulting from the annual fertilization of the topsoil and increases again in the parent material (Cg). While the Ap horizon is well structured (subangular blocky to crumbly), the Al horizon has a tillage-induced platy structure and a slightly coherent structure at greater depth, which is followed by the Bgt horizon with a blocky to prismatic structure. The C horizon encountered at a depth >150 cm below the Bgt horizon shows a platy structure due to its geological deposition (= glacial preloading); the parent material is calcareous with pH values >7. The initial bulk density values of the various horizons vary between 1.45 g cm^{-3} in the topsoil down to 1.8 g cm^{-3} in the C horizon, which is typical for this soil. The AlSw horizon shows a platy structure with a slightly increased bulk density of 1.65 g cm^{-3}, which results from plowing.

Time Dependent Effects

The statistical analyses of the measured data under the two tillage treatments over more than 8 yr prove significant differences. Apart from the nonsignificant changes in the precompression stress and hydraulic conductivity at the third depth (55–60 cm), all changes were significantly different ($P < 0.05$) during the whole tillage history (from 0 to >2880 d). However, the precompression stress and the hydraulic conductivity at the third depth are still significantly higher in the conservation tillage plots than in the conventional ones during the period of 2170 to 2880 or 2295 to 2880 d, respectively ($P < 0.05$) (Table 2).

Bulk Density

The changes in bulk density throughout the study are small under both tillage systems for all depths (Fig. 1). The yearly plowed plot has significantly smaller bulk density values in the Ap horizon than the yearly chiseled conservation tillage plot. The linear equations and the correlation coefficients are as follows:

$$\text{Conventional tillage: bulk density} = 1.52 + 3.98 \times 10^{-5}\, d;\quad R = 0.63^{**}$$

$$\text{Conservation tillage: bulk density} = 1.49 - 3.43 \times 10^{-5}\, d;\quad R = -0.48^{*}$$

Below the plow pan layer the values are nearly identical down to 60 cm (not shown). The standard deviation of the bulk density data was nearly identical for both treatments and all depths (s.d. = 0.05 g cm^{-3}).

Precompression Stress

The changes in the precompression stress over time and depth show significant differences in between the two treatments for the first and second soil horizon. In the 10- to 15-cm depth, soil strength increases after an intermediate time of smaller precompression stress values for nearly 3 yr, which is significantly different from the trend in the conventionally plowed soil (Fig. 2a). Tillage reduces the internal soil strength of the topsoil (A horizon). The same trend can also be seen at the depth of 30 to 35 cm where strength increases after approximately 4 to 5 yr (Fig. 2b). At the depth of 55 to 60 cm the same trend starts only after around 7 yr (Fig. 2c), however, these trends are not significantly different over time. The time dependent changes in the precompression stress values can, apart from the depth 10 to 15 cm conventionally tilled plot, be highly significantly described by second-order equations (Table 3).

Table 2. Results of ANOVA of different variables under conventional and conservation tillage treatments.

Property	Depth	Tillage treatment: Conventional	Tillage treatment: Conservation	Significance
	cm			
Bulk density, g cm^{-3}	10–15	1.45 (0.05)	1.57 (0.06)	<0.005
	30–35	1.56 (0.05)	1.58 (0.05)	0.91
	55–60	1.62 (0.06)	1.64 (0.05)	0.98
Precompression stress, kPa	10–15	57.6 (12.6)	81.2 (16.6)	<0.005
	30–35	65.3 (17.1)	90.4 (23.0)	<0.005
	55–60	86.1 (15.4)	86.3 (19.7)	0.976
Cohesion, kPa	10–15	19.8 (7.9)	37.4 (23.1)	0.002
	30–35	27.2 (10.9)	38.1 (16.5)	0.016
	55–60	35.1 (10.2)	39.2 (9.8)	0.776
Hydr. conductivity, cm d^{-1}	10–15	228 (134)	428 (312)	0.014
	30–35	130 (122)	409 (476)	0.013
	55–60	301 (280)	426 (361)	0.254

† Standard deviation is in parentheses.

Table 3. Second-order equations and their correlation coefficients between precompression stress, cohesion, hydraulic conductivity (=y), and time(d) (=x) under conventional- and conservation-tillage treatments.

Depth	Tillage treatments	Precompression stress		Cohesion		Hydraulic conductivity	
		kPa		kPa		cm d^{-1}	
10–15 cm	conventional	$Y = 64.63 - 0.007X + 2.27 \times 10^{-6}X^2$	$R = -0.27$	$Y = 23.94 - 0.005X + 9.39 \times 10^{-7}X^2$	$R = 0.28$	$Y = 139.7 + 0.09X - 1.63 \times 10^{-5}X^2$	$R = 0.27$
	conservation	$Y = 81.33 - 0.018X + 8.78 \times 10^{-6}X^2$	$R = 0.57$*	$Y = 43.29 - 0.035X + 1.55 \times 10^{-5}X^2$	$R = 0.61$*	$Y = -122.2 + 0.58X - 1.06 \times 10^{-4}X^2$	$R = 0.73$**
30–35 cm	conventional	$Y = 85.75 - 0.024X + 4.41 \times 10^{-6}X^2$	$R = 0.64$**	$Y = 35.53 - 0.006X - 1.42 \times 10^{-7}X^2$	$R = 0.54$*	$Y = 93.2 - 0.048X + 3.73 \times 10^{-5}X^2$	$R = 0.51$
	conservation	$Y = 87.77 - 0.030X + 1.54 \times 10^{-5}X^2$	$R = 0.80$***	$Y = 43.49 - 0.03X + 1.40 \times 10^{-5}X^2$	$R = 0.77$***	$Y = 122.5 - 0.21X + 2.08 \times 10^{-4}X^2$	$R = 0.85$***
55–60 cm	conventional	$Y = 88.75 - 0.029X + 1.36 \times 10^{-5}X^2$	$R = 0.88$***	$Y = 39.7 - 0.021X + 8 \times 10^{-6}X^2$	$R = 0.3$	$Y = 92.32 - 0.10X + 1.19 \times 10^{-4}X^2$	$R = 0.90$***
	conservation	$Y = 86.54 - 0.042X + 2.06 \times 10^{-5}X^2$	$R = 0.95$***	$Y = 41.4 - 0.0177X + 6 \times 10^{-6}X^2$	$R = 0.32$	$Y = 91.38 - 0.033X + 1.27 \times 10^{-4}X^2$	$R = 0.87$***

* Indicates the significant level at $P < 0.05$.
** Indicates the significant level at $P < 0.01$.
*** Indicates the significant level at $P < 0.001$.

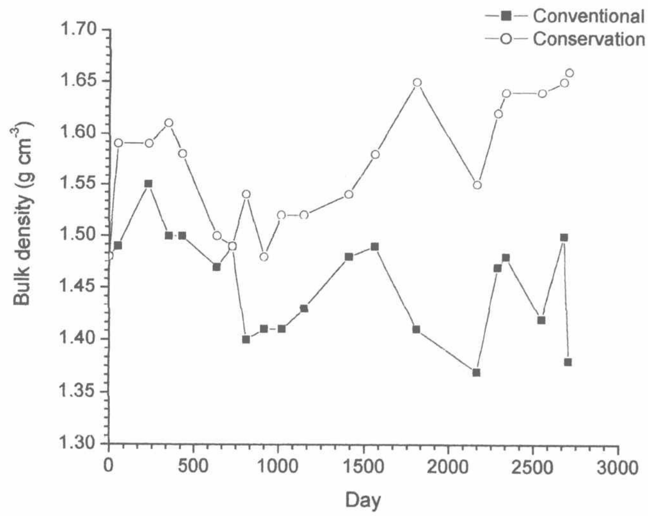

Fig. 1. Time dependent changes in bulk density at a depth of 10 to 15 cm.

Cohesion

The cohesion values increased with time in the conservation-tillage plot especially at depths of 10 to 15 and 30 to 35 cm. (Fig. 3). Both treatments significantly changed with time and depths. The pattern of the curves over time can apart from the topsoil under conventional-tillage be significantly fitted by second-order equations. At the depth of 55 to 60 cm, these trends are not significantly different over time (not shown).

Hydraulic Conductivity

Changes in saturated hydraulic conductivity with time can be detected in the topsoil layer treated by conservation tillage after a time delay of nearly 3 yr. The same trend can be also measured at 30- to 35- and 55- to 60-cm depth (Fig. 4). Although additional seasonal effects can be clearly defined, it is undoubtedly true that the functioning of pores is improved with time indicated by the increasing values of the hydraulic conductivity even at higher bulk density values. On the other hand, the values

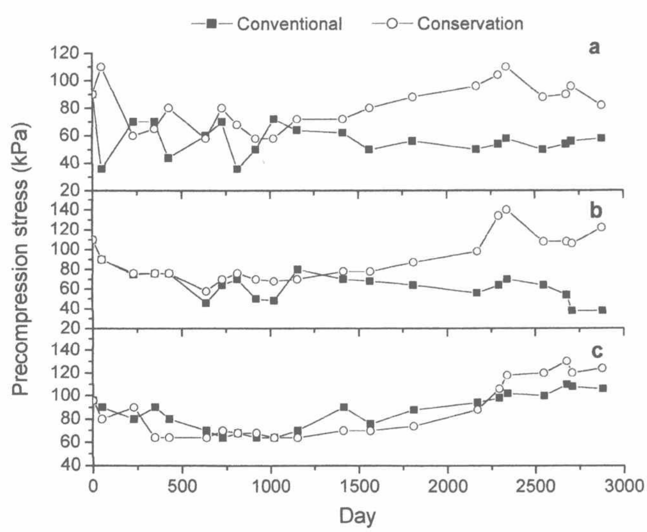

Fig. 2. Time dependent changes in precompression stress at a depth of (a) 10 to 15, (b) 30 to 35, and (c) 55 to 60 cm, respectively.

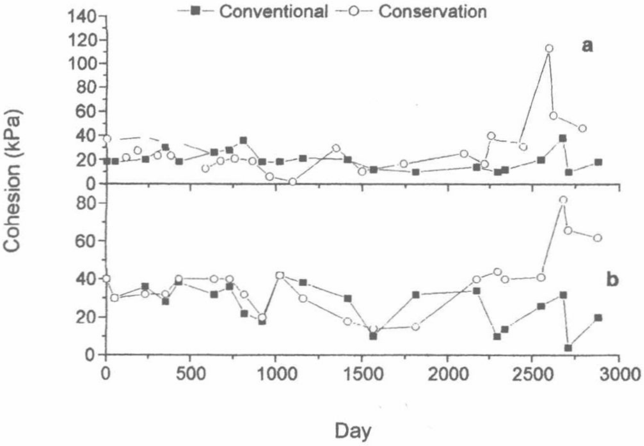

Fig. 3. Changes in soil cohesion at constant pore water pressure of −30 kPa with time at a depth of (a) 10 to 15, and (b) 30 to 35 cm, respectively.

determined in the conventionally tilled site further decreased, especially at the end of the investigation period, primarily due to a deeper plowing of the more compacted soil. Thus, the homogenization of the pore system results in smaller bulk density values and reduced values of the hydraulic conductivity. Therefore, pore function and pore volume do not coincide at this site.

With increasing depth the effect of the different tillage systems on pore functioning is less pronounced. However, after approximately 7 yr these changes become more obvious also at deeper soil levels.

DISCUSSION

Soil structure in general undergoes intense changes due to seasonal swelling, shrinkage, and the reformation of the pore system, which affects hydraulic or gaseous fluxes. In addition, the rigidity of the pore system is affected by the internal rearrangement of particles.

Hartge (1965), Horn (1981), and Junge et al. (2000) have shown that soils have a well-defined internal strength, which may be either derived from drying and wetting or from mechanical processes. Based on the effective stress equation, Toll (1995) proposed a conceptual model for the similarity between mechanical and hydraulic boundary "strengthening" or strength-limiting conditions. Fredlund and Rahardjo (1993) pointed out that the interrelation between the hydraulic and mechanical processes affect the overall strength of three phase systems. Baumgartl and Horn (1999) argued that the effective stress between single particles within or between aggregates could be altered through mechanical or hydraulic (i.e., pore-water pressure) stresses. Additional soil deformation/shrinkage can only be expected after exceeding the internal strength either by higher mechanical stresses or by a more intense drying. Horn (1995) described the stress dependent changes of the aggregation and of the structure dependent soil strength and quantified the boundary stresses for the various structure elements.

The obtained results about the changes in mechanical strength and hydraulic conductivity under conservation tillage can be therefore explained by combining the actual applied mechanical stress, the seasonal changes in swelling and shrinkage as well as the maximum soil dryness:

- While the conservation site was only mechanically stressed at the soil surface, the annual plowing at the 30-cm depth of the conventionally tilled site always resulted in a homogenization of the topsoil and a stress application to the subsoil.
- The external forces applied by the agricultural machines are smaller than the maximum internal soil strength at each depth in the conservation tillage site, which therefore does not change the existing pore systems and pore functioning but indirectly enhance the mobility and accessibility of particle surfaces.
- Junkersfeld (1995) found in field experiments at the investigated sites in Hohenschulen that water uptake by wheat, rape, and barley down to the 80-cm depth resulted in minimal pore-water pressure values of up to −70 kPa in the conservation tillage plots, while the water uptake in the tilled plot was mostly restricted to the topsoil and never decreased to less than −40 kPa below the plowpan layer. Furthermore, the hydraulic gradients between different soil horizons and/or distances from the plant at the same soil depth were greater in the conservation than in the conventionally tillage plots. Ehlers (1996) also supported these findings, that after several years of conservation tillage the root distribution was more pronounced to deeper depth and the result was a more homogenous water uptake. Consequently, the positive changes in soil structure and soil strength are generated by the long-term effects of repeated swelling and shrinkage, as a structure improving.
- Reorientation of soil particles by menisci forces can assume to be more pronounced in the conservation tillage site.

Horn and Dexter (1989) described the reorientation of soil particles in structure elements, which coincide with the alteration of aggregate strength and inter- as well as intraaggregate pore functions. They concluded that if soils are repeatedly wetted and dried throughout

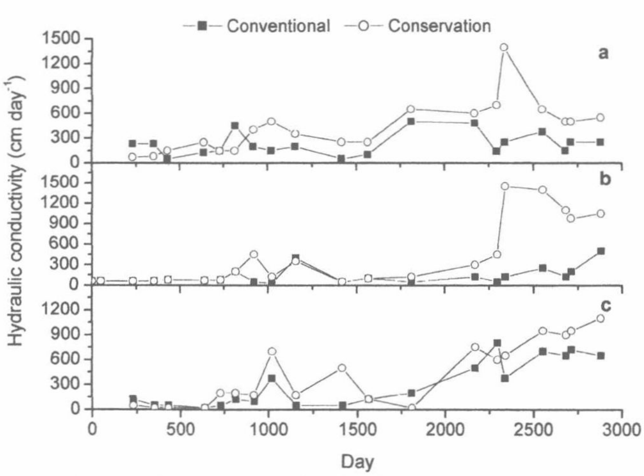

Fig. 4. Changes in the saturated hydraulic conductivity with time at (a) 10 to 15, (b) 30 to 35, and (c) 55 to 60 cm, respectively.

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the years, existing aggregates get dispersed starting from the outer skin, which results in the mobilization of particles. Consequently, the translocation of clay particles and colloids and their repeated rearrangement inside aggregates due to water menisci forces finally result in the formation of stronger, but at the same moment less dense aggregates. Additionally, the pore continuity is improved, which increases the air and water permeability. Furthermore, the mechanical strength of the non-tilled soils was much greater than of the tilled soils (Horn, 1986), which is in full agreement with the described data.

Thus, the presented results and trends reconfirm these findings and are also supported by the well-known processes, that

- Conservation tillage increases the mechanical strength of the soil, which is well known as structure strengthening;
- The formation of finer interaggregate pores due to shrinkage and the rearrangement of particles (Horn, 1995) are the basis for sustaining proper pore functioning and soil mechanical properties with time.

Consequently, increases in soil strength as it is defined by the parameters precompression stress or cohesion are to be expected when shifting to conservation tillage and the alteration of soil physical properties with time after the tillage system was changed are the result of aforementioned processes. The more intense the drying and swelling and the higher their frequency, the earlier can the strengthening and improved functioning of the pore system be detected even down to deeper soil depth.

Up to now all wheel traffic was done with small machines, which did not exceed the internal soil strength during field operations. We postulate that any stress application not accounting for the maximal internal soil strength (i.e., precompression stress value) must prevent or at least further delay any rearrangement of particles and reformation of stronger aggregates and coarser pores. There is no elasticity of this soil, which would be needed for such reformation processes (Horn, 2002). With regard to soil quality, we point out that the melioration of soil structure requires long-term stress release in combination with pronounced swelling and shrinkage. To what extent the climatic conditions in Northern Germany help to improve the site properties in comparison with the enhanced particle mobility under the wetter soil conditions has to be further analyzed in comparison with corresponding experiments performed under different climatic and site conditions.

CONCLUSIONS

Under a continuously applied system of conservation tillage, we can expect a more stable and a better functioning pore system at the same time after more than 7 yr down to a depth of 60 cm under the climatic conditions prevailing in northern Germany. These findings, however, can only be obtained if during all tillage operations the internal soil strength is never exceeded by the applied mechanical stresses. Presuming those boundary conditions, both shrinkage due to water uptake by plants and swelling when the soil is rewetted result in the rearrangement of soil aggregates and the creation of newly formed and more continuous pore systems. Aggregates as well as the soil structure are in addition to that much stronger. Hydraulic stresses, induced by the water uptake by plants and the generation of hydraulic gradients, both strengthen the existing soil structure by increasing the effective stresses between soil particles/aggregates. The strengthening through the rearrangement of aggregates and consequent changes in the pore system requires time and can only occur if the applied mechanical stresses are smaller than the internal soil strength, which is defined by the precompression stress.

How far these findings can be also extended to other regions and modified tillage systems have to be evaluated to develop a more general system of recommendations in view of sustainable agriculture.

ACKNOWLEDGMENTS

The author is highly indebted to: The German Research Foundation (DFG), which financially supported the long-term experiments by grants in the Special Research Programme (SFB) 192 (project C1); Mrs. Petra Koester, who carried out the numerous measurements; and Prof. Dr. A.R. Dexter/Poland for the improvements of the English text and the improving comments of the reviewers.

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Tillage Effects on Subsurface Drainage

Toshitsugu Moroizumi* and Haruhiko Horino

ABSTRACT

Tillage near the soil surface may greatly influence drainage discharge and pressure head values in the subsurface zone. In this study, a controlled comparative experiment was conducted in the field under natural weather conditions, using a tilled and an untilled column, to evaluate the effects of tillage on subsurface drainage discharge and pressure head values. There were no significant differences between the two columns in subsurface drainage before tillage treatment before the study, as checked by a preliminary experiment. After tilling one column of the two columns, cumulative subsurface drainage discharge was larger and occurred earlier for the tilled column than for the untilled column. The measured drainage discharge and pressure head values were evaluated using the water movement model, HYDRUS version 6.0, which numerically solves the Richards equation. The HYDRUS model reproduced measured values well for subsurface drainage discharge and pressure head values after the tillage, as determined by root mean squared error (RMSE), mean bias error (MBE), and R^2. Therefore, it is concluded that the model, which includes the effects of tillage on the hydraulic properties, can explain the reasons for differences in observed drainage in the two columns. Moreover, the effects of tillage depth on subsurface drainage discharge were simulated. The results implied that the effect of tillage on subsurface drainage were induced by the conditions of pressure head just before the first rainfall, and this effect was equal to, or greater than, the effects of changes in hydraulic properties due to tillage.

TILLAGE OF FARMLAND plays an important role not only as a soil management tool for improving the plant root environment, but also as a factor that impacts the hydrological cycle, including infiltration, surface evaporation, subsurface drainage, and groundwater discharge. Considering the fact that farmland covers large areas, the influences of tillage on subsurface drainage and groundwater discharge could be significant.

Changes in soil hydraulic properties of the surface soil induced by tillage can alter the infiltration rate of rain or irrigation and significantly affect the subsurface drainage discharge. Bulk density, porosity, and saturated hydraulic conductivity are better indicators of the tillage effects on soil hydraulic properties (e.g., Mielke et al., 1986; Benjamin, 1993). In general, soil tillage increases porosity and reduces bulk density, leading to changes in water retention function, hydraulic conductivity, and infiltration rate. Kribaa et al. (2001) showed that the tillage increased hydraulic conductivity, especially at pressure heads close to saturation.

Bulk density and porosity, however, were not sufficient to compare tillage effects on water flow through soils, and pore continuity was an important factor for water flow in soils for comparisons between the tillage systems (Ehlers, 1975; Ball et al., 1988; Sauer et al., 1990). Benjamin (1993) reported that the no-till system had a hydraulic conductivity equal to or greater than both the moldboard plow and chisel plow systems, owing to either a greater conductivity of pores or to water flow through a few very large pores. Wu et al. (1992) indicated that a no-tillage treatment had greater numbers of continuous macropores and equal or greater saturated hydraulic conductivity than the moldboard plow tillage.

Hill et al. (1985) and Hill (1990) reported that conventionally tilled soils drained more rapidly than soils under conservational tillage. Recently tilled soil also has rapid infiltration until settled by rainfall and irrigation. However, the effects of tillage on soil hydraulic properties, infiltration rate, and subsurface drainage discharge generally depend on spatial as well as temporal variabilities (Logsdon et al., 1993; Logsdon and Jaynes, 1996). Therefore, it is necessary to grasp the characteristics (subsurface drainage and pressure head values in this study) of experimental sites under untilled conditions to more accurately examine the effects of tillage under a controlled comparative experiment.

Through a controlled comparative experimental method, the degree of difference between tillage treatments can be evaluated more precisely. Moroizumi (1998) conducted a controlled comparative experiment in tilled and untilled areas, which proved to be an effective method for evaluating the effects of tillage on soil temperature, pressure head values, and evaporation. Moroizumi et al. (2001) also investigated the effects of subsoil breaking on surface runoff, pressure head values, and soil temperature in a sloping field with both a subsoil breaking area and a controlled area. It was clear that the subsoil breaking resulted in a decrease in the surface runoff and caused variations in pressure head values to be larger than in the controlled area.

A model analysis is a useful tool for evaluating quantitatively what factors induce the effects of tillage on subsurface drainage. Several studies have examined modeled tillage effects on water movement within tilled soils. Most of them included heat transport and were aimed at finding the effects of tillage on soil moisture, soil temperature, and evaporation by using the coupled water and heat transport model (e.g., Hammel et al., 1981; Yang and Zeng, 1988; Benjamin et al., 1990; Moroizumi and Horino, 2002). However, there have been few studies on modeling the impact of tillage on soil hydraulic properties and subsurface drainage. Mapa et al. (1985) demonstrated the impact of temporal changes in hydraulic functions on soil water movement, and com-

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Published in Soil Sci. Soc. Am. J. 68:1138–1144 (2004).
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Abbreviations: MBE, mean bias error; RMSE, root mean squared error; R^2, coefficient of determination.

pared these results with water content profiles predicted with a simulation model using input functions obtained before and after irrigation. Their results indicated that appropriate input hydraulic parameters sufficiently described a simulated water movement at different times when varying the deformation of tilled soil with wetting and drying over time. Ahuja et al. (1998) proposed two simple methods for predicting the water retention curve of a tilled soil from that of an untilled soil, and obtained a good approximation with RMSE of 0.0066 and R^2 of 0.99.

The objectives of this study were to estimate the influences of tillage on subsurface drainage and pressure heads using a controlled comparative experiment. Preliminary experiment was performed with two soil columns before tillage treatment to make sure that the two columns had similar soil properties. The experimental data were analyzed, using the one-dimensional water flow model, HYDRUS version 6.0. The model performance was verified by comparing the numerical results with the experimental data. Moreover, the influence of tillage depth on drainage discharge was simulated.

MATERIALS AND METHODS

Experiments

Field Experiment

Field experiments were performed on a 10 by 20 m bare soil area at the School of Veterinary and Animal Sciences, Kitasato University, in Aomori prefecture, Japan. This area is located in the northeastern part of the main island of Japan. The soil at this site has volcanic ash parent material, being an andosol that is called 'Kuroboku' soils in Japanese soil classification system. The general characteristics of 'Kuroboku' soil are low in bulk density (0.6–0.9 g cm^{-3}), high aggregation, high porosity (0.6–0.8 cm^3 cm^{-3}), and high permeability (10^{-2}–10^{-3} cm s^{-1}; Soma at el., 1983; Maeda and Soma, 1979). The apparent soil texture ranged from sandy loam to sand. Two soil columns were buried in the area to estimate the effects of tillage on subsurface drainage and pressure heads.

Each soil column (49.2 cm in diameter and 110.8 cm long) was fitted with a drain pipe (3.0 cm in diameter) at the bottom. The columns were packed from the surface with sand soil material between 50- and 100-cm depths and sandy loam from 0 to 50 cm; this layering was the same as the soil profile in the field around each column. The columns were also packed with coarse sand and gravel, as a filter material, below a depth of 100 cm. Pressure head values were measured at depths of 5, 10, 25, 45, 65, 80, and 100 cm, using tensiometers with pressure transducers, and were recorded automatically at 5-min intervals with a datalogger controlled by a portable computer. The data were converted to 1-h average values, which were used for numerical analysis. The subsurface drainage discharge at the bottom was measured manually every 2 to 9 h, using a graduated cylinder. The rainfall was measured with a tipping-bucket rain gauge.

Subsurface drainage discharge and pressure heads were measured intensively from Day 247 to 255 of 1993. The experimental results reflect the transitory, short-term effects of tillage operation because the period of the measurement was limited. This period corresponds to late summer in Japan. A preliminary experiment was conducted from Day 239 to 243 to confirm whether or not the two columns showed a difference with respect to subsurface drainage discharge before tillage treatment. As a result, pressure head values for the two columns were almost the same before tillage (Moroizumi, 1998). After the pre-experiment, one of the two columns (called Column 2) was tilled crosswise by hand, using a hoe to simulate a small hand-plow. The soil around the tilled column was also tilled so that it had the similar environmental conditions to prevent from an advection effect. The depth of tillage was approximately 4.5 cm. We emphasize that this shallow tillage was conducted to measure the impacts of hydrological processes. Tillage was conducted during 1010 to 1050 h on Day 244.

Laboratory Experiments

Some of the basic physical properties of the soils were measured in the laboratory. Eight undisturbed soil cores from each layer (0 to 50 cm and 50 to 100 cm in the untilled layer, and 0 to 4.5 cm in the tilled layer) were taken immediately after finishing the experiments. The size of core sampler was 5.0 cm in diameter and 5.1 cm in height. It should be noticed that the 0 to 4.5 cm in the tilled layer was sampled using this sampler. Dry bulk density and porosity were calculated by the gravimetric method using a dry oven. Saturated hydraulic conductivity was measured with a constant-head permeameter. Particle-size distribution was measured by a mechanical analysis (hydrometer method), and the soil textures were determined by a textural triangle. A pulverizability index indicated the soil is pulverized. A sample of tilled soil was separated into six aggregate groups using the five graded sieves with opening of 0.5, 1, 2, 4, and 8 cm. Pulverizability is calculated by dividing the mass of each clod group by the total mass of the tilled soil and expressed as a percentage (JSIDRE, 1992).

Model Description

Governing Equation for Water Flow

One-dimensional vertical water movement in variably saturated soil is described by the following mixed form formulation of Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K\frac{\partial h}{\partial z} + K\right) \quad [1]$$

where θ is the volumetric water content (L^3 L^{-3}), h is the soil water pressure head (L), t is time (T), z is the vertical space coordinate (L), and K is hydraulic conductivity (L T^{-1}). The sink term due to plant water uptake is not included in Eq. [1] because the experimental data were collected under bare surface conditions. Equation [1] assumes that the water vapor movement due to thermal gradients can be disregarded, which is negligible during the infiltration process with rainfall and the wet condition of soils. For a relatively dry soil, however, the water vapor movement should be considered, and an analysis using the coupled heat and water flow model is required (e.g., Scanlon and Milly, 1994; Moroizumi et al., 1997).

Nonlinear partial differential Eq. [1] was solved numerically by the computer code HYDRUS version 6.0, which is free software revised and updated by Simunek et al. (1998). In this code, Eq. [1] is solved with a mass-lumped linear finite element scheme for the spatial discretization of the flow domain and a Picard iteration procedure at each time step. The time derivative is approximated by a fully implicit difference scheme. The element lengths are shorter when approaching the soil surface where pressure head values varied rapidly because of rainfall, irrigation, and evaporation (and also due to tillage).

Hydraulic Properties

The soil water retention property and hydraulic conductivity were expressed by the van Genuchten (1980) function with the Mualem pore-size distribution model:

Table 1. Physical properties of soils packed in the columns.

Treatment†	Depth	Soil texture‡	Soil particle density	Dry bulk density	Porosity	Saturated hydraulic conductivity
	cm		g cm^{-3}		%	cm s^{-1}
Untilled	0–50	Sandy loam	2.47	0.890*	63.6*	3.68×10^{-4}*
	50–100	Sand	2.53	0.746	61.3	3.06×10^{-4}
Tilled	0–5	Sandy loam	2.47	0.681*	71.8*	4.52×10^{-2}*

†Tillage was conducted in the one of the columns with an approximate tillage depth of 4.5 cm.
‡ Classification by the International Soil Science Society.
* Differences between the tilled and the untilled column were significant at 0.05 probability level.

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^{1-1/n}} \qquad h < 0$$

$$\theta(h) = \theta_s \qquad h \geq 0 \qquad [2]$$

$$K(S_e) = K_s S_e^l\{1 - [(1 - S_e^{n/(n-1)})]^{1-1/n}\}^2 \qquad [3]$$

where θ_r is the residual soil water content (L^3 L^{-3}), θ_s is the saturated soil water content (L^3 L^{-3}), K_s is the saturated hydraulic conductivity (L T^{-1}), α is the fitting parameter in the soil retention curve (L^{-1}), n is also the fitting parameter in the soil retention curve (dimensionless), and S_e is the effective water content [= $(\theta - \theta_r)/(\theta_s - \theta_r)$; dimensionless]. The pore-connectivity parameter l in the hydraulic conductivity function of Eq. [3] is 0.5; this was estimated as an average for many soils by Mualem (1976). The α and n were calculated to fit the laboratory water retention data using Powell's conjugate direction method (Powell, 1964). The water retention data were measured using the soil column method and the pressure plate method. The θ_r was measured in the laboratory on the basis of Bresler et al.'s (1978) definition.

Hydraulic conductivity $K(\theta)$ was estimated using the fitting parameters of the soil water retention curve.

Initial and Boundary Conditions

A surface boundary condition was specified by the Neumann condition, which was given by precipitation and the maximum potential rate of evaporation under atmospheric conditions. A seepage face at the bottom was used as a bottom boundary condition. This boundary condition often applies to a finite lysimeter, such as the one used in this study, which is allowed to drain under gravity (Simunek et al., 1998).

RESULTS AND DISCUSSION

Soil Physical Properties

The results of the basic physical properties of soils are presented in Table 1. The soil textures by the International Soil Science Society classification range from sandy loam to sand. They are "apparent" textures because these andosols usually do not disperse completely into separate particles by the common dispersion methods and the hydroxide particles remained aggregated (Moroizumi and Horino, 2002). The porosity and saturated hydraulic conductivity are greater in the tilled layer than in the untilled layer and the dry bulk density is reduced in the tilled, which is the general characteristic of the effects of tillage (Ahuja et al., 1998). The pulverizability of 0 to 1 cm in the tilled layer was 64.8%.

The relationship between measured and fitted soil water retention curves are showed in Fig. 1. The fitted parameters are also presented in Table 2. Figure 1(a) indicates that pressure heads in the tilled soil for a range in soil water content of 0.2 to 0.65 were larger (less negative) than those in the untilled soil. A decrease of bulk density by tillage decreased the soil water pressure head at the same water content (Gupta and Larson, 1979). The effects of tillage on pressure head were restricted to the wet range of soil water content; at less soil water content, the water retention was essentially unchanged (Ahuja et al., 1998). The α in the tilled soil was about ten times greater than that in the untilled soil because of the decrease in the air-entry pressure head in the tilled soil. It is inferred that $1/\alpha$ is related to the air-entry pressure head because the dimension of $1/\alpha$ is 'length'. The air-entry pressure head generally increases as the bulk density decreases as seen in the tilled soils (Gupta and Larson, 1979).

Figure 2 shows the hydraulic conductivity function $K(\theta)$ estimated using the fitting parameters of the soil water retention curve.

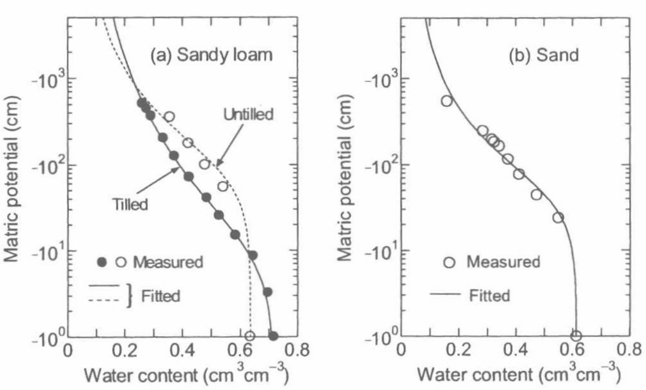

Fig. 1. Soil water retention curves for (a) sandy loam (tilled and untilled) and (b) sand.

Experimental Results

The results of the preliminary drainage experiment before the tillage is shown in Fig. 3. Subsurface drainage discharge started at 9 h after the first rainfall. The total subsurface drainage discharge was 22.2 mm for Column 1 and 21.4 mm for Column 2 for a total rainfall of 32.5 mm. The subsurface drainage discharge between the two columns was not significantly different at 0.05 probability level by t test. The result implies that the characteristics for drainage discharge and infiltration of rainfall were the same between the two columns. Therefore, we

Table 2. Fitted parameters of the van Genuchten function (Eq. [2] in the text) for hydraulic properties.†

Treatment	Soil texture	θ_s	θ_r	α	n
Untilled	Sandy loam	0.636	0.052	0.010	1.52
	Sand	0.613	0.046	0.019	1.58
Tilled	Sandy loam	0.718	0.052	0.096	1.29

† Soils packed in columns with sand soil material between 50 and 100 cm depths and sandy loam from 0 to 50 cm (The depth of tillage conducted in one of the columns was at approximately 4.5 cm).

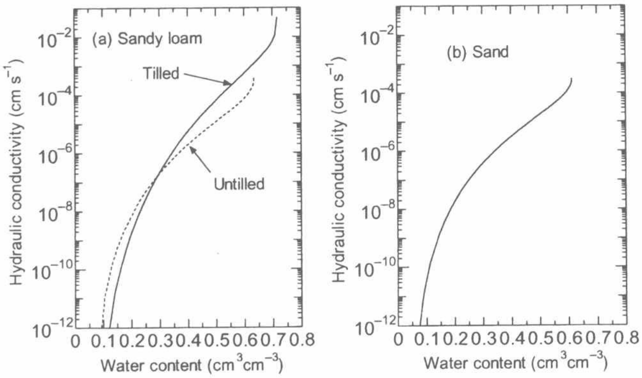

Fig. 2. Hydraulic conductivity as a function of water content for (a) sandy loam (tilled and untilled) and (b) sand.

concluded that it was possible to evaluate precisely the effect of tillage on subsurface drainage after tillage, using the two columns.

Figure 4 shows the initial condition for the pressure at the start of the experiment, which already included the effects of tillage on pressure heads in the drying process before the experiment. The dying process continued for 6 d, from Day 241 to 246.

Figure 5 presents the experimental results after one of the two columns was tilled. There were two main occurrences of precipitation on Day 247 to 248 and Day 251 to 253. The total amount of each precipitation was 45.5 mm for Day 247 to 248 and 52.0 mm for Day 251 to 253. Runoff and crust at the two columns were not observed. The onset of drainage for the tilled column was at 1700 h on Day 248, namely, 11 h earlier than that for the untilled column. The total amount of subsurface drainage discharge was 55.2 mm for the tilled column and 38.8 mm for the untilled column. The difference of 16.4 mm was significant at 0.05 probability level. We considered that the difference of drainage discharge would be mainly induced by the change of the water retention curve (Fig. 1) and hydraulic conductivity (Table 1).

Model Validations

Subsurface Drainage

Figure 5 also presents simulated values for the cumulative amount of drainage water in each column. Both

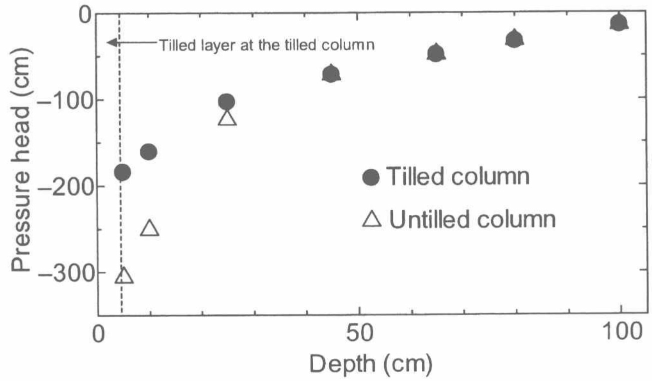

Fig. 4. Profiles of pressure heads at the start of the major experiment (0000 h on Day 247). This profile was used as the initial conditions for the drainage simulations.

simulated values were slightly larger than the measured values after Day 252. The simulated value for the tilled column at the end of the experiment was 60.5 mm, which was 5.3 mm greater than that for the measured value. Similarly, the simulated value for the untilled column was 45.7 mm, which was 6.9 mm greater than the measured value.

Statistical comparisons are very useful for quantitatively verifying model performance. For the tilled column, RMSE between measured and simulated values was 2.6 mm and the MBE was −1.4 mm. The untilled column showed an RMSE of 3.4 mm and a MBE of −1.29 mm. The R^2 was 0.991 for the tilled column and 0.988 for the untilled column. We judged from these statistical analyzes that the simulated and the measured values were in good agreement. These results indicate that the model satisfactorily reproduced the effect of tillage on subsurface drainage discharge.

Pressure Head

Figure 6 presents the simulated and measured pressure head values at depths of 5, 10, 25, 45, 65, and 80 cm for tilled and untilled columns. Several pressure head values (e.g., during the 1600 h on Day 249 to the 1500 h on Day 250 and the 0000 h to the 2400 h on Day 253)

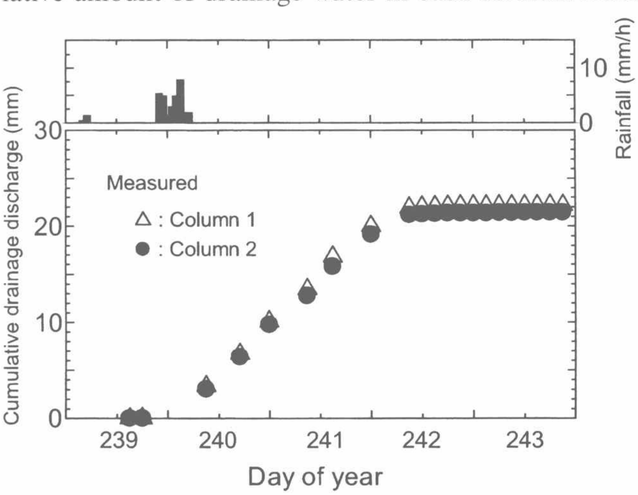

Fig. 3. Measured values for cumulative subsurface drainage discharge for Column 1 (solid circle) and Column 2 (open triangle) during the preliminary experiment from Day 239 to 243.

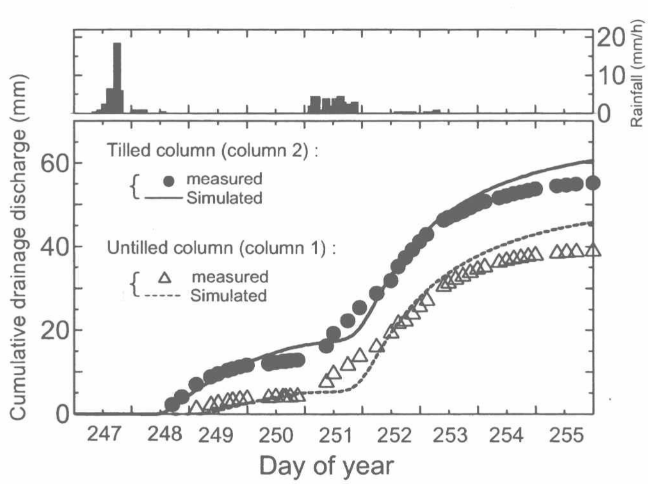

Fig. 5. Simulated and measured values for cumulative subsurface drainage discharge in the tilled and the untilled column, during Day 247 to 255 in 1993.

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