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IMPACTS OF SOIL STRUCTURE ON CROP GROWTH

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Abstract. Intensive agricultural utilisation of soils may change the structural status and through it the erodibility and fertility of soils. Since soil structure has not been quantified explicitly, studying structure-related soil phenomena is still actual. The goal of the present study was to apply field measurements on structure related soil hydrophysical properties and to study their mutual effect on crop growth. Near hydraulic water conductivity, bulk density, water retention characteristics of soils were measured in a wheat and a maize field as well as the soil water content dynamics during the vegetation period. Simulation models (SOIL and SOILN) were applied for studying different effects of soil structural status on winter wheat and maize crop's developments and on yields. Simulation results showed that water limitation in fields having normal and high bulk density topsoil developed gradually. In the low bulk density field case, water limitation on crop growth is noticeable almost from the beginning of crop growth. Though the combined effects of soil water stress and rooting due to soil structure resulted in marked differences in simulated yields, the effect of the saturated water conductivity and bulk density on the crop yield alone proved to be non significant. However, when a consequence was introduced regarding the plant root distribution, which differs in different soil physical conditions, a strong effect on the crop's growth was detected. This finding demonstrates the complex nature of the phenomenon called structural status of soil, and it definitely requires further research.

Keywords: soil structure parameters, simulation modelling, root distribution, crop growth

INTRODUCTION

Goal of the study was to evaluate the effects of soil structural status on soil hydrophysical properties, moisture distribution, water and nitrogen utilisation as well as yield responses of agricultural crops as continuation of the international cooperation program on soil structure, initiated in 1993 [11].

Area of the Herceghalom State Farm in the Zsambek basin was used for the above purposes as study field, locating about 50 km NW from Budapest.

DESCRIPTION OF THE STUDY AREA IN THE ZSAMBEK BASIN

The area chosen was used to study, describe and interpret the spatial variability of soil hydrophysical characteristics in 1991-1993. The agricultural area studied is considered homogeneous in several hundred hectares extension by the conventional soil management and agricultural practice.

The study area is locating in the vicinity of Herceghalom village. The area was a part of the Herceghalom State Farm and now it is under privatisation. Its extent is 1483 hectares.

Location: The study area can be found in a tectonic basin formed between the Gerecse and the Buda hills about 50 km NW from Budapest (Lat. 47,47).

Geography: The basin is filled with Tertiary sediments several hundred meters in thickness. The surface litology is characterised by Sarmatian limestone, Pannonian clay, Quaternary loess and slope deposits. Relief is classified as moderately undulating having 2.3 m/km relief energy as an average [14].

Landscape is formed by elongated hills and valleys on NW-SE trend. The maximum relief difference is about 60 m, inclination of slopes is between 2-5 degree.

Soil cover and land use of the area

Soils of the area are pseudomiceliar chernozems, or more or less eroded chernozem-like soil varieties. They are favourable and productive for agricultural utilisation. Erosion is expressed in thickness variation of the humus layer. Wind erosion effects can usually be recognised on the tops of hills, while water erosion is mainly in the middle parts of the slopes. The cause of erosion is probably increased by the large-scale, high input agricultural practices such as ploughing, and the absence of permanent plant cover, etc. The area is slightly eroded. The types of land use and their extent are given as follows:

- maize (corn) 498 ha;
- winter wheat 485 ha;
- alfalfa 150 ha;
- grassland for fodder and grazing, 140 ha;
- others (forest, farm-houses, cow-sheds, etc.) 211 ha.

Soil description of the study sites

Soil profile of a winter wheat field

Date: 19-07-1993
Parent material: loess
Thickens of the humus layer: 35 cm
Classification: Typic Calciustoll
Profile description:

A11 0-30 cm: brownish-black (10 YR 3/2), dry; strong very fine crumby structure, loam, clay content is about 20%, slightly hard, strongly effervescent, many very fine pores, many fine roots, plant residues, boundary: abrupt and smooth.

A12 30-35 cm: brownish-black, (dry: 10 YR 3/2, wet: 10 YR 3/1), dry, fine crumby structure, loam, approx. clay content is about 20%, very hard, strongly effervescent, many very fine pores, many fine roots, boundary: abrupt and smooth.

AC 35-70 cm: brownish-black (dry: 10 YR 3/3, wet: 10 YR 3/2), dry, moderate fine crumb structure, loam, approx. 20% clay content, very hard, strong effervescent, many very fine pores, many very fine roots, abundant pseudomycelium of calcium carbonate, crotovinas, boundary: clear and smooth.

C 70- cm: olivebrown (2.5 Y 4/4), dry; loam; clay content is about 25%, slightly hard, strong effervescent, many fine pores.

Analytical data and particle-size data of the soil profile are given in Tables 1 and 2, respectively.

Soil profile of a maize field

Date: 20-07-1993
Parent material:loess
Thickens of the humus layer: 44 cm
Classification: Typic Calciustoll
Profile description:

Ap 0-20 cm: brownish-black (dry: 10 YR 3/3, wet: 10YR 3/1), dry; fine crumb blocky structure, loam, approx. 20% clay content, slightly hard, strongly effervescent, many very fine pores, many very fine roots, plant residues, boundary: clear and smooth.

A 20-44 cm: brownish-black, (dry: 10 YR 3/2, wet: 10 YR 3/1), dry, fine crumb

Table 1. Main charcteristics of the soil in the wheat field

Horizon	Depth (cm)	pH	$CaCO_3$ (%)	EC (mS/cm)	Salt (%)	OM (%)	Bd (g/cm^3)
A11	0-30	8.1	9.1	0.53	0.035	3.8	1.35
A12	30-35	8.1	9.1	0.53	0.035	3.8	1.40
AC	35-70	8.3	25.8	0.58	0.040	1.2	1.34
C	70-..	8.4	28.4	0.61	0.040	0.7	1.39

Table 2. Particle-size distribution of the soil in the wheat field

Horizon	Depth (cm)	>25	0.05-0.25	0.02-0.05	0.01-0.02	0.005-0.01	0.002-0.005	<0.002
					(mm)			
A11	0-30	1.9	10.7	32.9	13.7	7.0	8.7	25.1
A12	30-35	1.9	10.7	32.9	13.7	7.0	8.7	25.1
AC	35-70	0.5	10.0	32.7	11.0	7.1	8.2	30.5
C	70-..	0.4	10.7	36.5	13.1	6.7	7.5	25.1

blocky structure, loam, approx. clay content is about 20%, hard, strongly effervescent, many very fine pores, many fine roots, boundary: clear and smooth.

AC 44-75 cm: brownish-black (dry: 10 YR 3/3, wet: 10 YR 3/2), field capacity, moderate fine crumb structure, loam, approx. 20% clay content, hard, strongly effervescent, many very fine pores, few fine roots, abundant pseudomycelium of calcium carbonate, boundary: clear and smooth.

C 75- cm: olivebrown (2.5 Y 4/4), field capacity; loam; clay content is about 30%, slightly hard, strong effervescent, many fine pores, few medium roots, abundant pseudomycelium of calcium carbonate, organic matter coats, biogaleries.

Analytical data and particle-size data of the soil profile are given in Tables 3 and 4, respectively.

DATA USED IN MODELLING

Meteorological data

- daily mean air temperature (C^o)
- daily mean air humidity (%)
- average wind speed (m/s)
- sum of daily precipitation (mm)

The daily precipitation data were recorded at the Centre of the State Farm. The other data are from the nearest meteorological station in Martonvásár.

Soil hydrophysical parameters

The bulk density and the soil water retention characteristics (SWRC) were measured

Table 3. Main charcteristics of the soil in the maize field

Horizon	Depth (cm)	pH	CaCO$_3$ (%)	EC (mS/cm)	Salt (%)	OM (%)	Bd (g/cm^3)
A11	0-20	8.1	2.0	0.71	0.05	3.8	1.34
A12	20-44	8.2	5.3	0.49	0.03	3.1	1.36
AC	44-75	8.3	22.8	0.47	0.03	2.0	1.39
C	75-..	8.3	31.2	0.54	0.30	0.5	1.40

Table 4. Particle-size distribution of the soil in the maize field

Horizon	Depth (cm)	>25	0.05-0.25	0.02-0.05	0.01-0.02	0.005-0.01	0.002-0.005	<0.002
					(mm)			
A11	0-20	0.7	8.7	31.6	12.2	8.2	9.0	29.6
A12	20-44	0.5	8.3	31.8	11.5	7.6	8.8	31.5
AC	44-75	0.2	7.7	32.6	10.7	7..0	9.6	32.2
C	75-..	0.2	10.3	33.4	12.3	7.0	9.4	27.4

on soil cores taken from the genetic horizons of the soil profiles (Fig. 1).

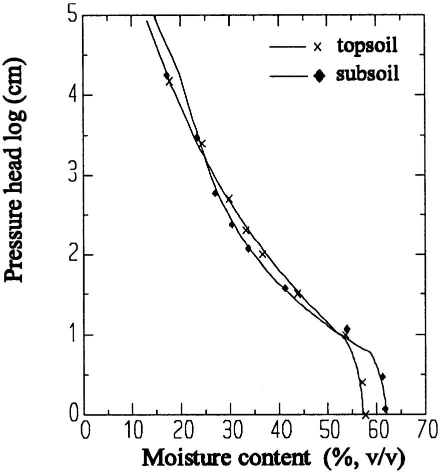


Fig. 1. Water retention characteristic curves for the topsoil and subsoil of the Herceghalom study area

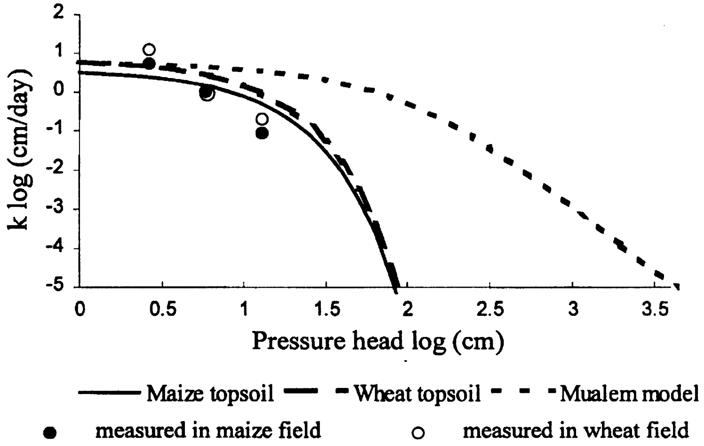


Fig. 2. Measured and estimated water conductivity functions of the topsoil in the Herceghalom study area. Measurements are based on tension infiltrometer readings, estimation is made by the Van Genuchten-Mualem model.

It was evident since the beginning of this study that saturated water conductivity (K_s) data of soils are required. Saturated water conductivity is included in the list of the most important hydrophysical parameters reflecting the structural status of the soil [27]. On the other hand, it is one of the necessary inputs of the SOIL simulation model, which we used for studying the soil water and heat flow. We accomplished K_s measurements using two different in situ methods:

Tension infiltrometer [4] method was used for determining K_s without macropores. This method we have already used in a prevous study [19].

We used the Guelph permeameter method [20] for measuring K_s with macropores. The instrument was produced by the workshop of the Technical University in Prague.

By tension infiltrometer we measured the near saturated water conductivity values at 3, 6 and 12 cm tensions in April at the wheat field, and in early June at the maize field of the Herceghalom study area in 1995. The saturated water conductivity was defined by the extrapolation of an exponential function fitted to the measured conductivity values (Fig. 2).

The Guelph permeameter was used to collect water conductivity data involving the macropore flow. The permeameter measurements in the extraordinarily dry soil did not provide comparable data to the conductivity measurements of the tension infiltrometer. Permeameter measurements on the same soil spot ought to be higher than infiltrometer data since it includes macropore flow. In our case permeameter measurements were somewhat lower than the infiltrometer data. So, we used K_s values determined by the infiltrometer method.

Measurements of soil moisture dynamics

Measurements of soil moisture content profiles of a winter wheat and a maize field (0-140 cm in 10 cm resolution) were performed in approximately 10 day intervals within the vegetation period in 1993 by two methods: the conventional gravimetric (dry-box) method, and a capacitance probe developed in the RISSAC [2,25].

Crop data

Fertilisation application and the yield data of the wheat and maize fields were used in the crop simulation model. Other crop parameters, such as leaf area index, root density and its depth and time distribution within the soil profile were handled by literature and specific field experiment data.

DESCRIPTION OF THE SIMULATION MODEL

To study the effects of different soil structural status on soil moisture flow and crop yield we applied the SOIL and SOILN simulation models developed in Sweden [7,11]. The main advantages of the use of these models are as follows:

- the SOIL water and heat flow model handles the main structural parameters of soils;
- the models can be tuned to the study area;
- the models are ‘connected’ through crop growth model (in the SOILN) and effects of water flow differences can be studied on the crop development and yield;
- our earlier results by the use of the SOIL model [3,24] could be extended in a new context.

The SOIL water and heat flow model

The SOIL model used in this study represents the water and heat dynamics in a layered soil profile covered with vegetation. As the solution to model equations is performed with a finite difference method the soil profile is divided into a finite number of layers. A detailed technical description of the model is presented by Jansson [11].

The soil profile is divided into layers which are treated separately regarding water flows and storage. Since a deep ground water table (>5 m) is characteristic in the study area, only the unsaturated part of the soil water flow was dealt with. Calculations are based on partial differential equations describing flows in a soil profile and are based on an extension of Richard’s equation assuming that soil water flow is laminar. Two soil physical functions must be known to solve the flow equation, namely the relation between soil water content and soil tension described by the Brooks and Corey [5] expression, and the function of unsaturated water conductivity. The unsaturated conductivity is calculated using the model given by Mualem [15]. To account for macropores the conductivity is increased when water content exceeds porosity minus 4%.

In the model the vegetation is seen as a link between soil water and atmospheric vapour.

The potential evapotranspiration is calculated with the Penman-Monteith equation [14]. Reduction in water uptake caused by low soil temperature and/or dry soil conditions are simulated by using empirical reduction factors. The Penman-Monteith equation is also used for calculating evaporation from soil and from canopy interception pool. The various types of evaporation sources differ in terms of available energy, surface resistances at soil-vegetation-atmosphere boundaries and the aerodynamic resistances above their surfaces. The net radiation is distributed between the canopy and soil surface according to Beer’s law.

The most important parameters describing the influence of vegetation are the leaf area index and the surface resistance. Root depth mainly affects the total storage of plant-available water. Water uptake by roots is described by defining the proportional distribution of roots among the different soil layers.

The model is driven by daily meteorological data such as air temperature, windspeed, air humidity, solar radiation and precipitation.

Model parametrization

The simulation period started in mid April in case of wheat and mid May in case of maize crop. Input data such as meteorological records and soil physical properties were determined by direct and indirect measurements. Model outputs in terms of soil water dynamics were compared to field measured soil moisture content data and thus uncertainties in parameter values used for the simulation could be adjusted.

Model parameters are related either to soil or stand properties. To the largest extent possible, we used field measured data (see above). For the rest of the model parameters data reported in the literature have been used.

The SOILN model

Crop growth is simulated within the SOILN model. The driving soil variables of the SOILN model are supplied by the outputs of the SOIL model. SOILN is a model simulating the daily nitrogen and carbon dynamics in the agricultural system, including plant growth and nitrogen uptake and turnover. The driving variables for SOILN model are data on solar radiation, temperature, manure and fertilization, the soil water and heat conditions and the ratio between actual and potential evapotranspiration which are inputs predicted by the SOIL model. The SOILN contains a biomass submodel called CROP-GROWTH model which simulates the plant production based on the conversion of absorbed light into biomass and empirical allometric functions. Growth is assumed not to be limited by nutrients other than available nitrogen.

MODEL APPLICATION

Application of the SOIL model

For 1993 soil water balance of wheat field was simulated and compared to measured soil moisture content data. The SOIL model was 'tuned' to the drought weather conditions. The simulated crop yield responded similarly as the observed one. However, at first it seemed hardly possible for us to demonstrate soil structure effects on crop development through soil aeration and soil moisture supply within the drought stress conditions of the 1993 year. But simulations within different soil structure situations clearly demonstrated different drought effects reflected by the crop yields.

In our simulation study the normal soil structural status was that we measured in the study field in Herceghalom. The degree of compactness was estimated from soil cores collected in the study fields. Higher bulk density samples were collected from tractor wheel traces. The loose and the compact soil bulk densities based on the collected core samples are given in Table 5. Other soil features such as SWRC and K_s of the lower and higher bulk density soils were estimated. The effect of bulk density on the water retention curve is significant in the low pressure head range (h <=100 cm) [26]. Using the quantitative relationship of our earlier study [18] we derived retention curves for soils having lower and higher bulk density. The predicted retention curves are shown in Fig. 3.

Table 5. Measured and estimated soil physical parameters

Bulk densities used (g/cm^3)	K_s without macropores (cm/day)	2C1280K_s with macropores (cm/day)	ASCALE model parameter
1.15	12.0	30.2	0.1
1.32	2.6	3.0	0.3
1.57	0.5	0.5	0.4

Saturated water conductivity of these samples we estimated by the Campbell's method which accounts of the soil bulk density beside particle-size distribution data [6]. The estimated water conductivity values for loose and compacted soils are given in Table 5. A SOIL model parameter called ASCALE was also used to take into account the bypass flow which passes through the macropores of soil during near saturated moisture condition.

We carried out the following simulation exercises, using the SOIL model:

- Studying the effect of different soil bulk densities on soil moisture content dynamics when saturated soil water conductivity is kept constant (Fig. 4);

- Studying the effect of different saturated water conductivities on the soil moisture content dynamics when bulk density is kept constant (Fig. 5);
- Studying the joint effect of different saturated water conductivity and bulk density

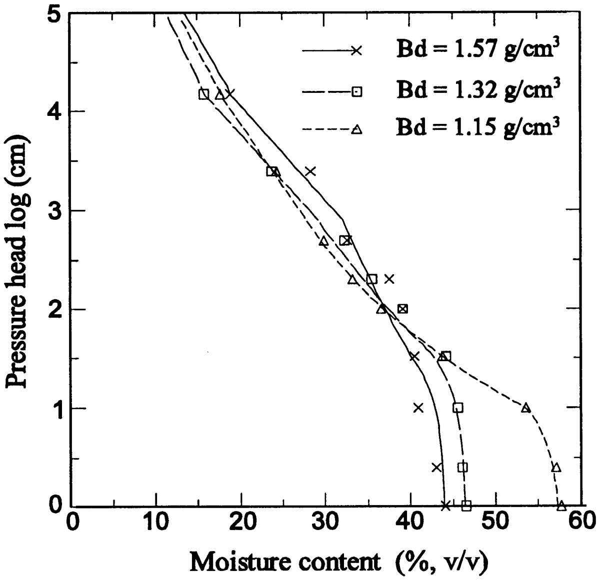


Fig. 3. Estimated water retention characteristic curves of different bulk density soils.

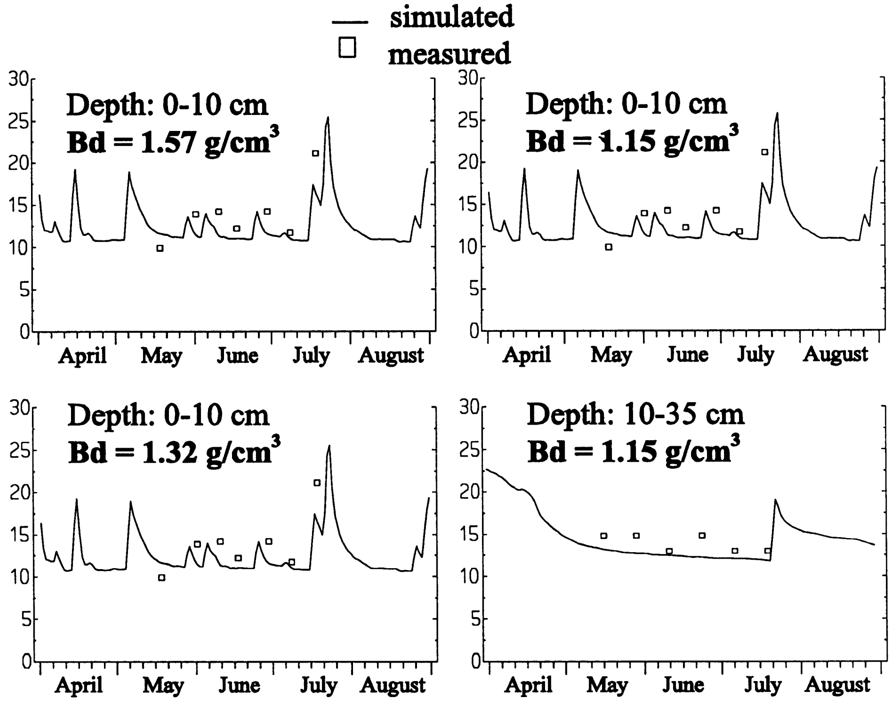


Fig. 4. Simulated and measured soil moisture content data of wheat field soils with different bulk densities and constant K_s.

on the soil moisture content dynamics. The measured and simulated soil moisture dynamics for two soil layers (0-10 and 10-35 cm) under wheat crop are shown in Fig. 6, under maize crop in Fig. 7. Since there was no significant differences between the measured water conductivity values of the wheat and the maize field, hydrophysical parameters of Table 5 were used for the simulations.

Results and discussion of modelling

Results show that simulated soil water content dynamics were in good agreement with the measured data for both wheat and

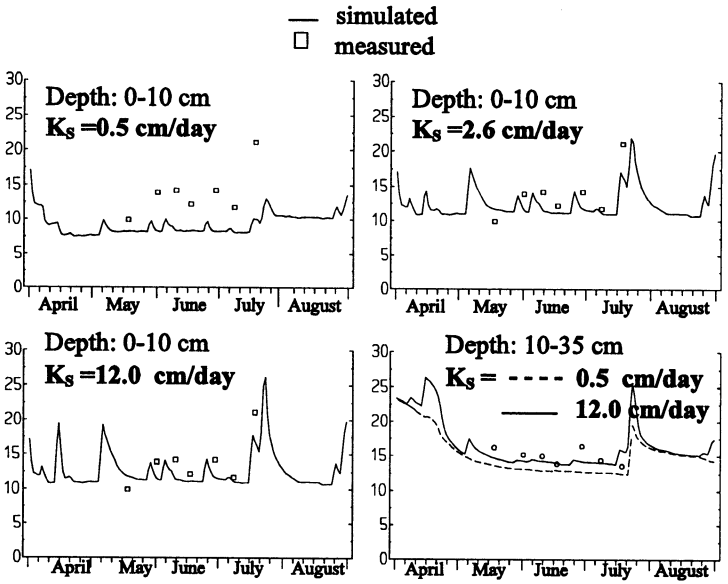


Fig. 5. Simulated and measured soil moisture content data of wheat field soils with different K_s and constant bulk density.

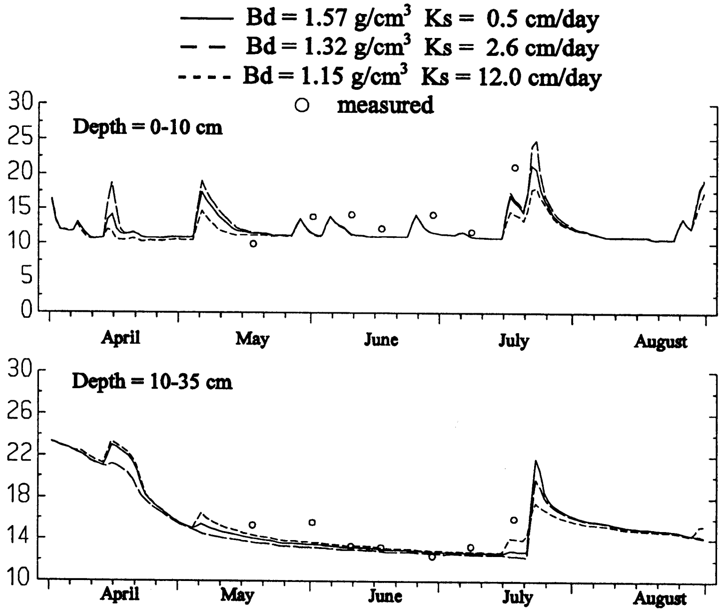


Fig. 6. Simulated and measured soil moisture content data of wheat field soils with different bulk densities and K_s.

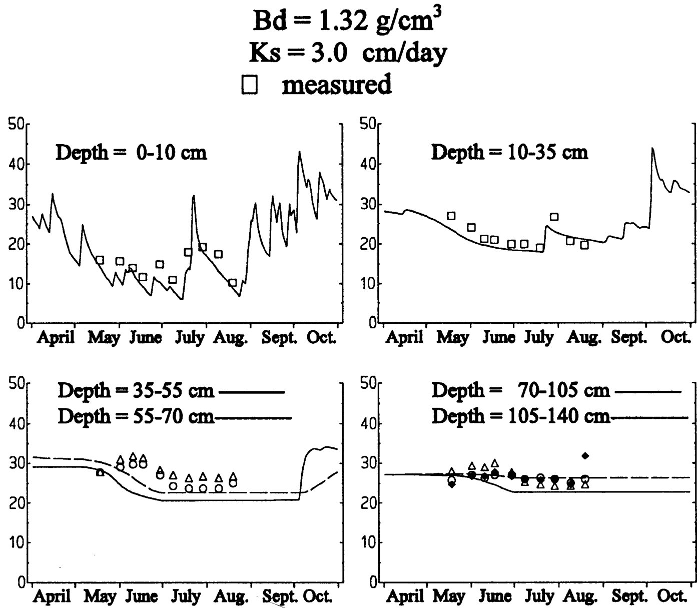


Fig. 7. Simulated and measured soil moisture content data of maize field soils with different bulk densities and K_s.

maize. Effects of the soil structural parameters as follows:

- K_S has a significant effect on soil moisture flow within the soil profile as it is shown for two soil layers in Fig. 5.; the soil moisture content dynamics is more 'impulsive' in case of the higher water conductivity.
- Bulk density which acts on soil moisture flow through the retention characteristics does not influence noticeably the soil moisture flow processes. No detectable effects are on simulated soil moisture content dynamics compared with the measured ones (Fig. 4).
- The effect of the saturated water conductivity on the soil moisture content dynamics was more expressed when joint changes with bulk density was applied. The studied soil physical properties affected soil water content dynamics the stronger the higher was the water content of the soil. This effect manifested after rain events (Fig. 6).

Application of the SOILN and the Crop-Growth model

The vegetation properties were evaluated by comparing simulated wheat and maize yields with the measured ones.

There is a wide range of factors that determine the crop growth, however we were interested only in the effect of soil structure on crop yield. Although all significant factors of crop growth are included in the SOILN model (like mineralization, microbiology etc.) we utilised only the direct effects of soil structure on crop growth. We considered root extension and distribution relating primarily to different soil physical environments [8]. Data for root growth and yield indicate the importance of the size of the root system in the fertile soil layer for the nutrition of field crops [12]. That is why in root distribution we modelled the effects of low and high bulk densities, different moisture profile distribution and aeration porosity. For generating the root distributions for the different soil environments we used experimental and literature data. Comparison of simulated crop yields has been accomplished for the different soil structural status. Effects of different soil structural status were presented through differences in soil moisture dynamics and some plant parameters.

The plant parameters adopted to the different conditions of soil structure are the root development and density distribution. The root distribution within the soil profile of a maize field has been reported in many papers [1,9,16,17,22,23,29,30]. It is known that root penetration into compact soil layers linearly decreases as air filled porosity decreases. Effects of drought on root growth result in a lower root density within the entire soil profile. Root elongation and branching may be increased in an environment that is more favourable, while plant growth is simultaneously reduced in an unfavourable environment. So, with special attention on the low water storage of the soil profile at the start of the growing season, the time and spatial distribution of the root density was set in the simulation model based on the above observations, and field measurements regarding to compacted and loose soils by Végh [28]. The generated root distribution data are given in Table 6. For accounting such a complex influence of soil structure, crop growth response functions were calculated and used in three case studies for the soils parametrized, as are given in Table 5.

Results and discussions of modelling

Wheat simulation

On the first stage, effects of soil structure on the crop growth were studied by introducing differences in soil physical characteristics. Results on wheat yield are presented in Table 7. Simulated yields show a moderate effect of bulk density and hydraulic conductivity differences of the top soil horizon. The root distribution differences in this study were not taken into account.

Evaluating the simulation results for wheat one can conclude that no marked differences are observable on soil moisture content dynamics when only retention curve, saturated water conductivity and macropore flow parameter (when bypass flow is considered) is changed. Even no significant differences were realised in wheat yields. Since we did not have specific field data to handle plant parameters for the wheat crop grown in water stress conditions, no further simulation was completed in this direction.

Table 6. Vertical root distribution of maize

Depth (cm)	Root fractions in soil profile		
	normal	compacted	loose
0-10	0.25	0.09	0.08
10-35	0.25	0.34	0.20
35-55	0.22	0.38	0.28
55-70	0.15	0.08	0.37
70-105	0.08	0.08	0.05
105-140	0.05	0.02	0.02

Table 7. Simulated and harvested wheat yield

Bulk density (g/cm^3)	Hydraulic conductivity (cm/day)	Simulated yield (t/ha)	Recorded yield (t/ha)
1.15	12.0	3.4	
1.32	2.6	3.3	3.3
1.57	0.5	3.1	

Maize simulation

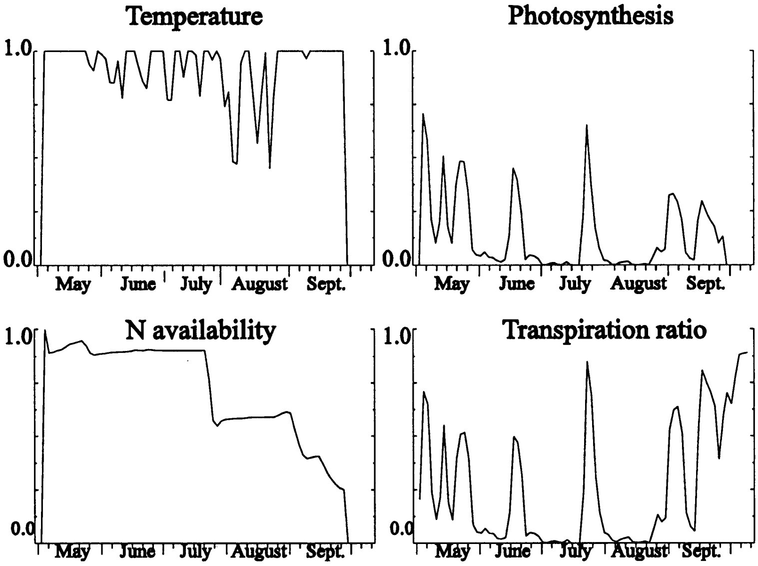
The response of maize development in field soils having normal, compacted and loose surface horizon are shown by growth response functions as:

1. Plant growth response function to temperature.
2. Photosynthesis response function containing combined effect of soil water stress, N availability and temperature.
3. Photosynthesis response function to N availability.
4. Transpiration ratio.

In Fig. 8 it is seen that maize yield reflected mostly the effect of plant available water supply in the root-room than other determining factors, while nitrogen supply met the N-demand of the crop which was suppressed by water stress. This is the consequence of the dryness of the study period. Photosynthesis response function shows that N availability was sufficient till mid July on the field with low bulk density topsoil (Fig. 8b), while for the normal and high bulk density maize fields N limitation is noticeable from June (Figs 8a and c). Soil moisture content was raised by precipitation in mid July, and for a short period without moisture limitation

a

Bd = $1.15\ g/cm^3$
Yield = 4.5 t/ha
Ks (with macropores) = 126 cm/day
Ks (without macropores) = 30.2 cm/day



Temperature

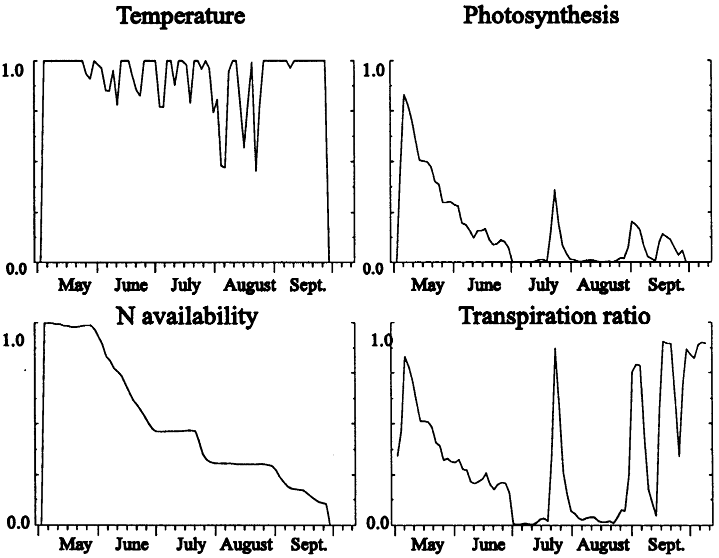
Photosynthesis

N availability

Transpiration ratio

b

Bd = $1.32\ g/cm^3$
Yield = 7.8 t/ha
Ks (with macropores) = 3.0 cm/day
Ks (without macropores) = 3.0 cm/day



Temperature

Photosynthesis

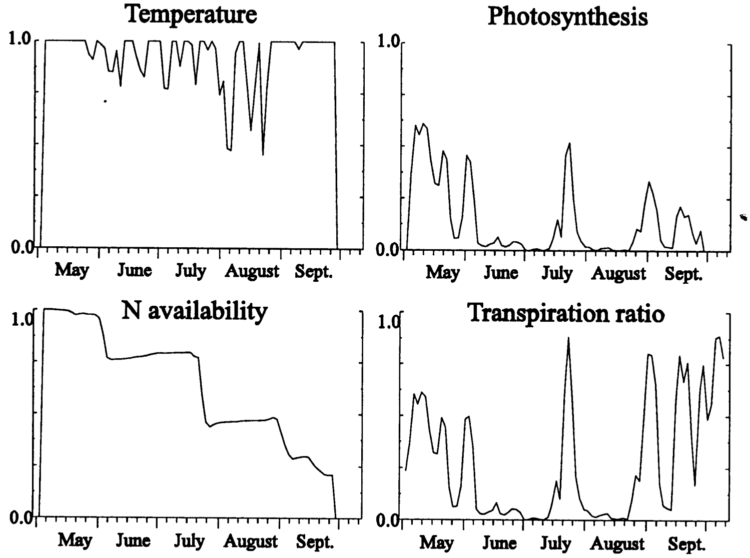
N availability

Transpiration ratio

Fig. 8. Response functions of corn growth for: loose (a), normal (b) and compacted (c) soils.

c

Bd = 1.57 g/cm^3
Yield = 5.7 t/ha
Ks (with macropores) = 0.5 cm/day
Ks (without macropores) = 0.5 cm/day


Temperature

Photosynthesis

N availability

Transpiration ratio

Fig. 8. Continuation.

N supply limited plant growth. From the beginning of September, N supply became the highest constraint of growth. However, water limitation in the normal and high bulk density topsoil fields developed gradually, while for the low bulk density field case, water limitation on crop growth is noticeable almost from the beginning of the crop growth. Though, the combined effects of soil water stress, rooting and soil structure were resulted in marked differences in simulated yields. The role of soil structural status on crop yield and on the stability of yield become more deterministic under more favourable moisture conditions. The above simulation results demonstrate the validity of the idea formulated as "Roots and yield as indicators of soil structure" by Selige and Vorderbrügge [21].

CONCLUSION

An important conclusion of the present study is that taking only a few parameters on the phenomena of different soil structural status into account we simplify the real processes and may get fault results. For example, the effect of the saturated water conductivity and bulk density on the crop yield alone proved to be non significant. However, when we introduced some additional consequences of different soil physical conditions on the plant root distribution strong effect on the plant growth was detected. This calls the attention on the complex nature of the phenomenon called structural status of soil, which definitely requires further research.

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