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THE INFLUENCE OF SHORT TERM SOIL SEALING AND CRUSTING ON HYDROLOGY AND EROSION AT BALATON UPLANDS, HUNGARY

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Abstract Soil porosity increase on arable fields is mainly the result of cultivation while sealing and crusting are natural processes. The first is a rapid change the latter is slower, however, little is known about the time scale of soil sealing and crusting. Crusting rainfall simulation experiments were carried out to investigate the role of single rainfall events on soil sealing and crusting, on an intensively cultivated arable field. To follow porosity changes trough out the year, undisturbed samples were analyzed. High seasonal differences were identified in bulk density and porosity during the vegetation period that appeared to be the results of tillage. The results of rainfall simulation underline the rapid influence of a single storm in sealing and crusting of a Cambisol by decreasing the final infiltration rate and increasing runoff and sediment load. Porosity reduction manifested first of all in surface crust formation, however, kaolinite was the dominating cay mineral in the investigated Cambisol. Bulk density of the tilled soil layer enhanced by 15% in case of structural and 40% in erosion crust. The higher value could be the result of the continuous deposition according to Stoke's law creating a clay film cover on the surface. The sealing and crusting effect of a single storm could be of the same order as the influence of tillage on soil porosity runoff and soil loss. The porosity created by tillage can collapse during one precipitation event.

Keywords: Surface sealing and crusting; Rainfall simulation; Crust mineral composition; Selective erosion; Kaolinite dominated soil

1. INTRODUCTION

Soil degradation is a serious problem that concerns more than 15% of the landmass. Arable land is the most affected land use type from the aspect of soil degradation (Szilassi et al., 2010). Intensive tillage operations can reduce the humus contentment and destroy the soil structure on the long run (Lal 2005). Physical properties of the topsoil play an important role in soil erosion processes especially by influencing infiltration volume, overland flow and soil loss (Barta, 2005).

Topsoil properties are not the same over the whole vegetation period, mainly because of tillage operations, plant cover development and changing soil moisture conditions. Short term influencing factors like occasional heavy rainfall events from the point of view of runoff, infiltration and erosion processes (Centeri et al., 2009). According to Imeson & Kwaad (1990) the soil system will be altered by the interactions between rainfall and the soil system. Selective erosion, surface sealing and crusting are important consequences of this interaction.

Soil crusts compose two main groups, namely those of physical (inorganic) and biological (organic) crusts. Within each group there are three main subtypes, i.e. (i) structural crusts formed due to the impact of splash erosion, (ii) erosion crusts formed by wind or water erosion, and (iii) deposition crusts developed by the sedimentation of the delivered soil particles (Valentin & Bresson 1992). A physical crust could be an indirect consequence of selective erosion when aggregates detach to smaller components and different soil particles are moved differently (Stavi & Lal 2011; Nagy et al., 2012, Farsang et al., 2012). Physical crust formation is a rapid process that may take place during one precipitation event. Biological crust development takes a long time and it has successional stages (Lan et al., 2012). While physical soil crust definitely decreases water infiltration and increases runoff volume (Valentin & Bresson 1992), there are ambiguities on biological crust (Belnap, 2006). According to Malam Issa et al. (2011) the contradiction is the result **of** the interaction between the biological crust and the underlying physical crust type. Moreover biological crust has an important role in soil structural stability improvement, too (Jimenez Aguilar et al., 2009).

Although there are many studies dealing with the background of sealing and crusting phenomena (Poesen & Nearing 1993), the everyday use of the results is still rare (Chamizo et al., 2012). Imeson & Kwaad (1990) pointed to the fact that because of different responses of the soil to rainfall, in terms of runoff and erosion, the relationship between rainfall, runoff and erosion can be very varied. Zhang & Miller (1993) proved the difference of the effect of stable surface crusts in a moist and in a dry state. In the moist state, stable crusts decrease interrill erodibility over time whereas with drying, a new supply of erodible sediments will be produced leading to high soil loss levels.

There are many other significant parameters influencing soil crusting dynamics including various physical and chemical soil properties. Organic matter content, clay content and exchangeable sodium percentage are of particular importance (Le Bissonnais & Bruand 1993). The effect of surface micro topography and antecedent soil water content was studied by Rudolph et al., (1997). Le Bissonnais et al., (1989) underlined that crusting during a rainfall is dependent on the antecedent soil water content.

Artificial surface crusts were applied for studying the mechanism of infiltration on a crusted soil by Hillel (1971). The crust has a positive, protecting effect against wind erosion (Lóki & Szabó 1997; Szabó 2002) which is also an important way of selective erosion (Farsang et al., 2011).

In the hilly countries of Hungary the main soil type under arable fields is Cambisol (Stefanovits, 1971). The present study deals with Cambisols because they cover a considerable part of hill slopes used for agriculture and because they are sensitive to crusting and prone to erosion. The main objective of this paper is to compare the changes in soil porosity (I) throughout the vegetation period and (II) in short term on arable field. An additional goal is to estimate the effect of a single precipitation event, on crusting, sealing, infiltration, runoff and soil loss.

2. MATERIALS AND METHODS

2.1. Study site

The research site is situated in Keszthely, (Fig. 1) near Lake Balaton in the experimental field of the Georgikon Agricultural Faculty of Pannon University, Hungary (N46.7966°, E17.2611°).

Figure 1 Location of the study site

The investigations were carried out on a hill slope with 12.3 % gradient, South-Eastern slope aspect, covered by haplic Cambisol. The study site is black fallow, which has been tilled continuously, without any vegetation. Table 1 contains the most important characteristics of the topsoil.

Table 1 Some chemical and physical properties of the topsoil

Soil properties	Values
$CaCO_3$ %	0.0
Humus %	1.1
pH_{dw} [a]	6.7
Munsell color	10YR 3/3
< 0.002 mm %	12.6
0.002 – 0.005 mm %	7.1
0.005 – 0.01 mm %	7.6
0.01 – 0.02 mm %	8.4
0.02 – 0.05 mm %	9.6
0.05 – 0.1 mm %	23.9
0.1 – 0.2 mm %	22.5
0.2 – 0.5 mm %	3.0
0.5 < mm %	5.3

[a] pH measured in distilled water

The sandy loam texture, the low humus content and the lack of $CaCO_3$ refer to poor structure and aggregate stability. Clay minerals are dominated by kaolinite inherited from the parent material (Végh, 1967).

2.2. Experiment design

Porosity conditions and bulk density were measured in order to follow the yearly changes of the tilled soils structure during the vegetation period. Four phases representing the most important cultivation operations spread out over the vegetation period have been chosen for sampling. The samples selected are as follows: (1) after chiseling (autumn), (2) after plowing (carried out in autumn, but the samples were taken in spring so that they reflect the influence of freezing and thawing in the winter as well), (3) seedbed conditions (late spring – early summer, after disking) and (4) stubble field (late summer). Eight undisturbed samples were taken by a 100 cm3 cylinder. Four samples were collected from the upper 0–7 cm and another four from the bottom of the tilled layer including plough pan, from a depth of 25–31 cm. The differential porosity and bulk density values were determined according to the simplified water saturation method (Fetter, 1994).

An attempt was made to remove (to cut) surface crust from the upper soil layer after the rainfall simulation experiments.

2.3. Rainfall experiments

Rainfall simulation experiments were applied to study the process of surface crusting and its role on surface runoff and erosion. The Pannon R-02 simulator was used to investigate surface crusting. A detailed description of the instrument and the method is provided by Centeri et al., (2011). The experimental plot has an area of 12 m^2. The slope was cultivated by disking just before the experiment. Two sets of experiments (i.e. two runs) were performed, the first one just after the disking, before the formation of the surface crust (designated by A) and the second one a week later under similar soil moisture conditions, after the formation of the crust (designated by B).

The amount of the first simulated rain (A) was 26.8 mm with an intensity of 60 mm h^{-1} (duration: 26.7 min). The same intensity was applied in the second experiment (B) with an amount of 13.25 mm (duration 13.2 min). Surface runoff was registered continuously during the experiment so that runoff intensity could also be determined. A modified form of the Horton equation (Horton 1933) was adjusted to the measured values (cumulative runoff volumes parallel with time) describing the dynamics of infiltration and the final infiltration rate. The modified version is as follows (1 equation):

$$Y=P_0\,(X-P_1) - (P_0/P_2)\,(1-e(-P_2\,(X-P_1))) \quad \text{[1 equation]}$$

where
Y: Cumulative runoff
X: Time
P_0: Final rate of runoff (l min-1)
P_1: Time of runoff initiation (min)
P_2: Index of runoff change (min-1)
e: Euler number

According to this approach, under constant rainfall intensity cumulative runoff is primarily the function of time, whereas the other variables are represented by the three other parameters. Using the measured x and y data as an input the values of these parameters could be estimated with the iteration method.

2.4. Analytical procedures

Physical properties of the crust were determined by measuring porosity/infiltration of the crust and of the soil below. Compaction of the topsoil was tested by a proving ring penetrometer. Soil resistance measurements by penetrometer were carried out two hours after the second simulated precipitation (wet soil condition) and one week after the rainfall simulation experiments (dry soil condition). The crust itself could not be investigated by this method because of its thickness. Compaction values of the crust are reflected in bulk density measurement results concerning the upper 0–1 cm. The undisturbed crust samples were sealed with known amount of wax than the volume of the sample was determined using the water supplant method. Clay mineralogical characteristics of the formed crusts were identified by X-ray diffractometry performed on a Philips PW-1730 diffractometer using CuKα radiation (applying an acceleration voltage of 45 kV, and a tube current of 35 mA), at a data collection speed of 1 s/0.05 2θ. For investigation of micromorphologic properties thin sections were prepared and analyzed.

3. RESULTS AND DISCUSSION

3.1. Changes in soil porosity during the vegetation period

As it was expected a significant difference was found between seedbed and stubble field conditions in the tilled layer (Fig. 2), whereas no change could be observed in the layer beneath in terms of soil porosity and bulk density. Chiseling increased the porosity in the plough pan and topsoil layer to a similar extent. Plowing, however, increased the porosity only in the tilled layer whereas it has compacted the soil just under the tillage depth.

During the winter a continuous porosity reduction is presumed until the minimum value is reached before seedbed preparation.

It is also remarkable that the increasing porosity due to plowing is the result of the macropore (>50μm) formation. Precipitation percolates through this layer via these large pores without wetting the inner parts of the clogs. The volume of smaller pores which can reserve and transport soil moisture is as low as in the case of the plough pan layer. Among splash erosion processes this is another important reason of the rapid destruction and compaction of the soil surface and the tilled layer.

3.2. Crusting, runoff and soil loss

The influence of selective erosion, soil crusting and sealing is shown by the comparison of the rainfall simulations before (A) and after (B) crust formation. Infiltration capacity decreased below rain intensity three times faster in case B, although the initial moisture contents of the topsoil were similar (Table 2).

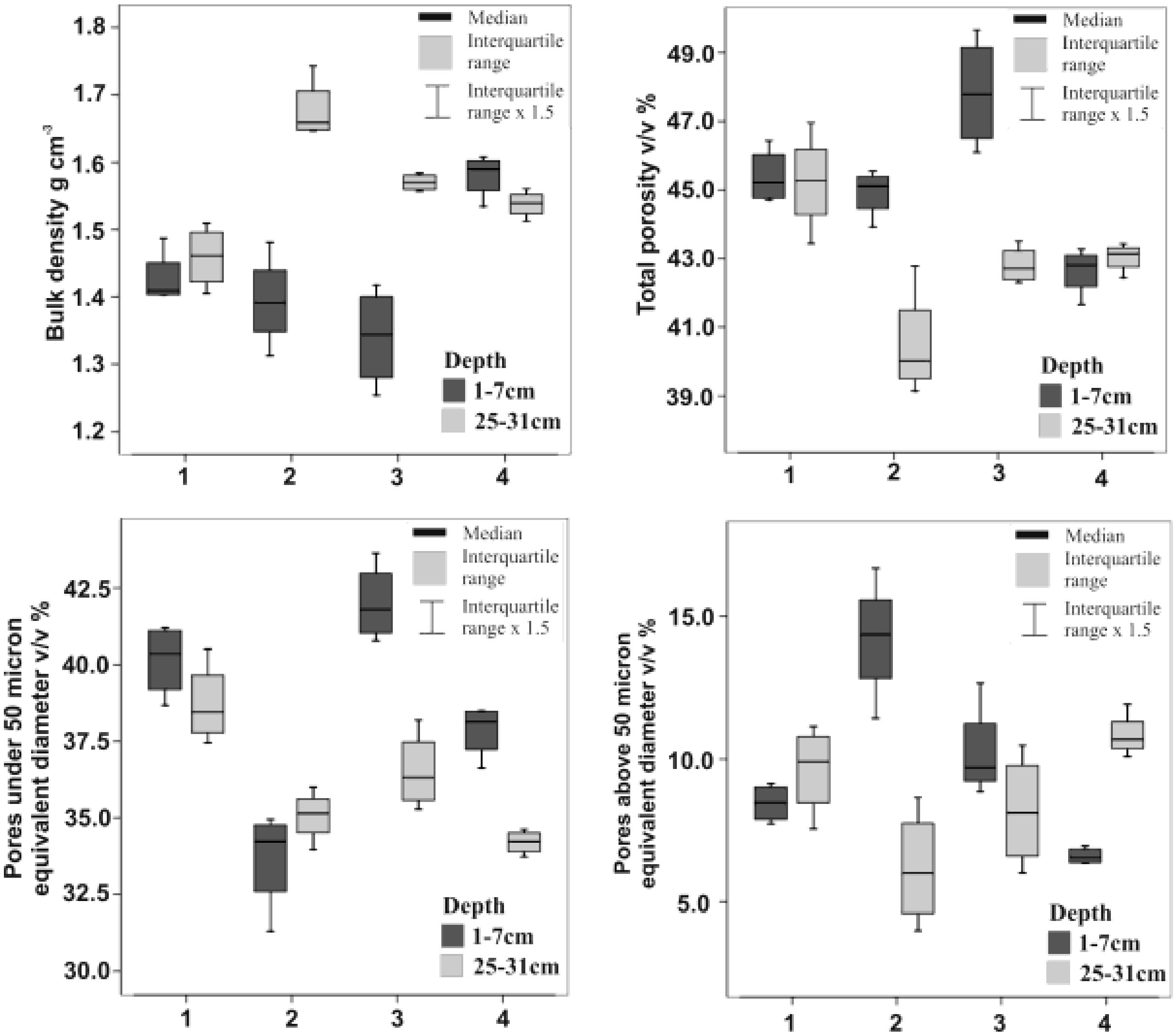

Figure 2. Porosity and bulk density conditions after different cultivation phases at two depths (in cm) of the study site (1: after chiseling (autumn), 2: after plowing, 3: seedbed conditions, after disking; 4: stubble field (late summer).

Table 2 Measured and estimated hydrological and soil loss parameters (A and B simulated rainfalls)

Simulated rainfall	Initial soil moisture content	Time of ponding initiation	Time of runoff initiation	Runoff rate	Estimated final runoff rate	SD[a]	Sediment load	
	$v\ v^{-1}$	min	min	%	$l\ min^{-1}$		$g\ l^{-1}$	$g\ min^{-1}$
A	11.2	2.1	6.2	18.0	7.2	1.6	8.9	16.3
B	13.9	0.7	0.9	18.9	9.8	15.6	10.6	21.9

[a] Standard Deviation

Since rainfall intensity is higher than the infiltration rate, ponding occurs. Selective erosion and sedimentation diminish surface roughness; consequently surface water storage is also reduced. This is in accordance with the lower infiltration capacity as a consequence of extremely rapid runoff initiation on the crusted surface.

After converting from l min^{-1} to mm h^{-1} the estimated final runoff rate is 36 mm h^{-1} in the first experiment (A) and the final rate of infiltration is 24 mm h^{-1}. On the sealed surface (second experiment, B), the final runoff rate was calculated 49 mm h^{-1} and the final infiltration rate was 11 mm h^{-1} with a high standard deviation value. The conclusion is, therefore, that a single precipitation event on a Cambisol (sandy loam) with low humus content leads to soil destruction and half times lower final infiltration capacity.

During the experiments there were no remarkable differences in runoff rate pointing to the fact that the deviation increases with time before reaching the final infiltration rate. There is an important rise in soil loss values, 13% in sediment content of runoff and 34% in soil loss per minute (Table 2), mainly because of the decreasing surface roughness and sediment storage capacity.

Our results are in accordance with those of Malam Issa et al., (2011) who have not found a significant correlation between runoff coefficient and surface cover by only physical crust. According to Castilho et al., (2011) crust formation was not always accompanied by the decrease of total porosity, hydraulic conductivity and soil water retention. These results slightly differ from the expected and from those observed by Luk et al., (1993) who carried out experiments on a cultivated loess soil in China. They found that as a consequence of crusting and sealing, runoff was enhanced by up to 1.85 times, but the soil loss ratio of crusted and uncrusted surfaces ranged from 0.65 to 1.49.

An important reason of these ambiguities could be the complex connectivity among the study areas with various size ie. the results are hardly comparable because of the different scales of the experiments (Chaplot & Poesen 2012).

3.3. Morphological and physical properties of surface crust

According to the results of rainfall experiments two types of surface crust could be identified, based on the observation of topographical and morphological properties. The first micromorphological type is the erosion crust and the second is the structural crust (Valentin & Bresson 1992) (Fig. 3). They differ in form and also in surface characteristics. Erosion crusts develop because of the micro-topography where water is stored on the surface. This water can only infiltrate leaving a thin sediment layer behind. On sedimentary crusts there is a clay cover on the surface whereas the surface of structural crusts is coarser. Structural crust appears if surface water storage is negligible while erosion crust develops in the micro basins. In this case a fine clay film covers the surface including the coarse fraction and stable aggregates in the middle of the puddle. Cracks could only be observed on structural crust.

These two types were identified on small (50-200 cm^2) spots covering altogether 65% of the surface.

Bulk density was measured on six samples of the two micromorphological types (Fig. 4). The density (theoretically, without pores) of the original soil is 2.85 g cm^{-3}, the bulk density is 1.61 g cm^{-3}. The original soil refers to seedbed conditions before the experiment. The average value of bulk density of erosion crusts is 2.32 g cm^{-3}, that of structural crusts is 1.89 g cm^{-3}.

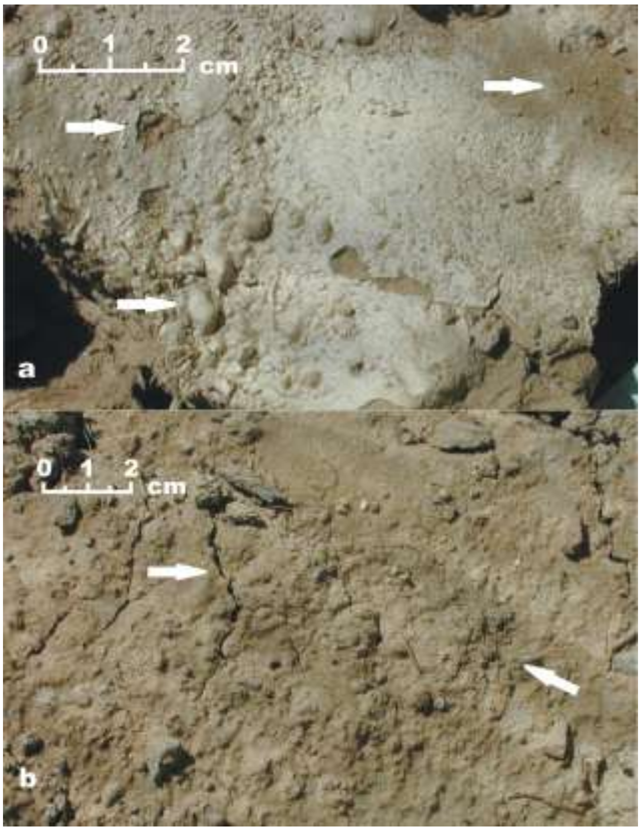

Figure 3. Morphology of erosional (a) and structural (b) crust Arrows indicate: a) coarse residual, removed clay cap, clay covered aggregate; b) cracks, flow direction

Porosity diminished remarkably in the crust (Fig. 4), however, Usón & Poch (2000) observed that total porosity did not decrease in the crust but pores were less interconnected

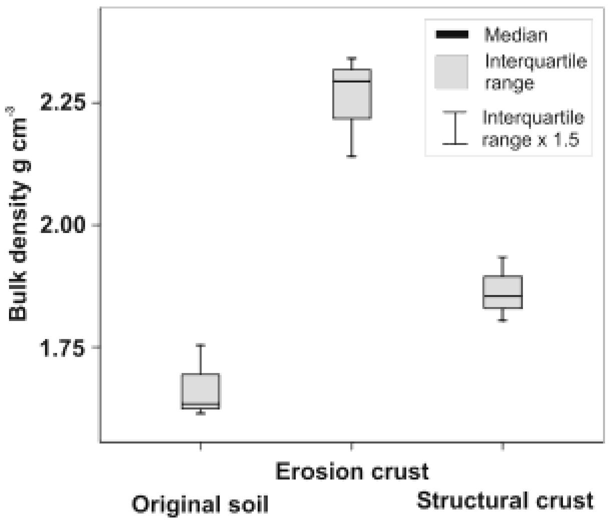

Figure 4. Bulk density values of the original soil and the formed crusts (n=3)

3.4. Soil resistance measurements

Right after seedbed creation the topsoil has theoretically uniform spatial resistance values that increase with time (Osunbitan et al., 2005). Figure 5 presents the relationship between soil depth and soil resistance under different moisture conditions after the two simulated rainfalls. Under wet conditions, resistance as an indicator of compaction starts to increase exponentially below the depth of about 10 cm. Under dry conditions resistance is much higher and it increases gradually with depth according to a linear function.

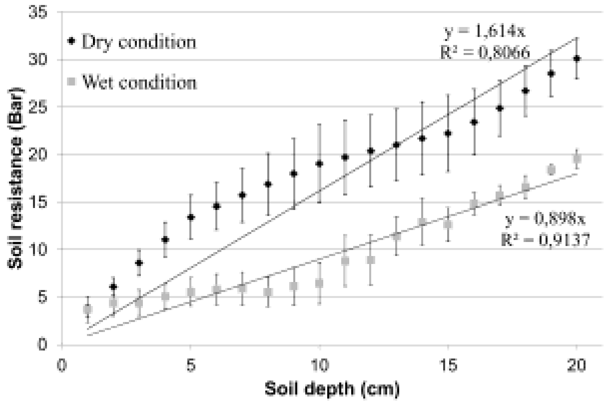

Figure 5. Soil resistance averages after two simulated rainfalls measured in dry (one week after the rainfall) and wet (two hours after the rainfall) soil conditions (Bars indicate standard deviation, n=34

The biggest difference in dry and wet soil resistance was measured in the 6–10 cm deep horizon. Theoretically soil resistance increases with depth in both cases but this horizon is an exception in wet condition since the resistance seems to be constant in it. These results also confirm the findings of Hamza & Anderson (2005) that the resistance of the damp soil is not the function of porosity but of moisture content. Based on the observations it can be assumed that the infiltrated water is stored in the upper 10 cm of the soil. From this depth the connection between resistance and depth is quasi parallel (Fig. 5).

The highest standard deviation value is also found in the middle section of the tilled layer in both cases referring to the highest inhomogeneity in this section.

It can be concluded that the decrease in infiltration capacity between the first and second rainfall simulation is not only due to crust formation but also to the sealing (compaction) effect of the rain.

3.5. Mineralogical characteristics of the crust

Tarchitzky et al., (1983) described the crust consisting of two layers, i.e. of a thin skin and of a lower layer below it. The actual erosion crust (0.1–0.3 mm), the below-crust layer (0.2–3 mm) and the whole upper soil layer (tilled horizon) were included in the analysis. Wakindiki & Ben-Hur (2002) observed the same thickness of the erosion crust on a kaolinite dominated soil.

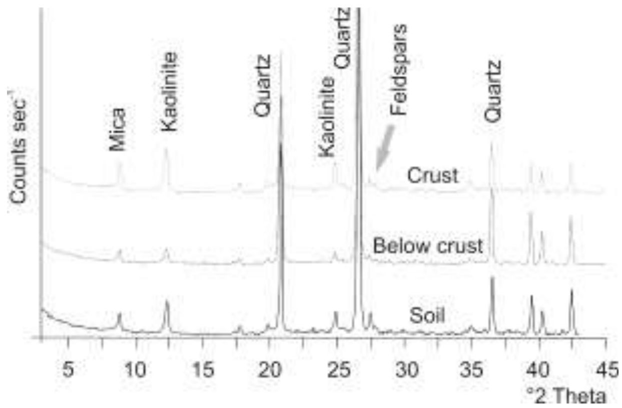

Figure 6. Mineral composition of the structural crust and the unsealed soil (Crust: 0.1–0.3 mm thin layer on the surface; Below crust: 0.1–3.0 mm thick layer below crust; Soil: recently tilled homogenous topsoil)

In the experimental area also kaolinite dominates the clay mineral composition of the investigated soil (Fig. 6) although Singer & Shainberg (2004) highlighted that kaolinite soils are less susceptible to crusting even if they contain some smectite (Lado & Ben-Hur 2003). Although XRD is not a real quantitative method it can be concluded that kaolinite and mica content is very high in the crust and much lower in the "below crust" layer (Fig. 6). Quartz content is higher in the below crust layer than in the crust itself. The diffraction pattern of the whole upper soil layer represents the average of them.

Aggregates destroyed by splash erosion disintegrated to elementary particles which have been carried away by runoff. When runoff entered a puddle the coarse particles were deposited while clay remained still in the stream thus forming the "below-crust" layer. At the end of the rainfall event runoff stops and the suspended clay content in the puddles encrusts the coarse layer (Fig. 7a-b).

Thus it can be concluded that the selectivity of erosion hardly depends on surface roughness. When the previously formed and dried erosion crust is attacked by the drops of another shower, the structure is destroyed by splash erosion and the small particles from the crust are leeched into the below crust layer. The deposition of the coarse particles (mainly quartz) begins on the former crust followed by the encrusting of the fine particles at the end of the rain. That is why the uppermost clay layer has very sharp boundary while the lower is thicker because of percolation (Fig. 7c). The enhanced ratio of puddles increases the coarse fraction storage capacity on the surface and also the clay content of soil loss. Structural crust (Fig. 7d) is generally a very simple and thin layer that is less important in infiltration reduction and deposition.

4. CONCLUSIONS

Although changes in soil porosity are mainly the consequences of tillage operations the results proved the important role of a single precipitation event on a black fallow. As an effect of a single rainfall event a crust developed on the investigated Cambisol, under seedbed conditions, decreasing final infiltration rate by 36%, increasing runoff by 5% and sediment load by 13%. Soil resistance enhanced linearly with increasing depth, however, the middle layer is definitely heterogeneous.

Porosity reduction manifested first of all in surface crust formation. Two types of crust formed in a small area as a result of micro topography.

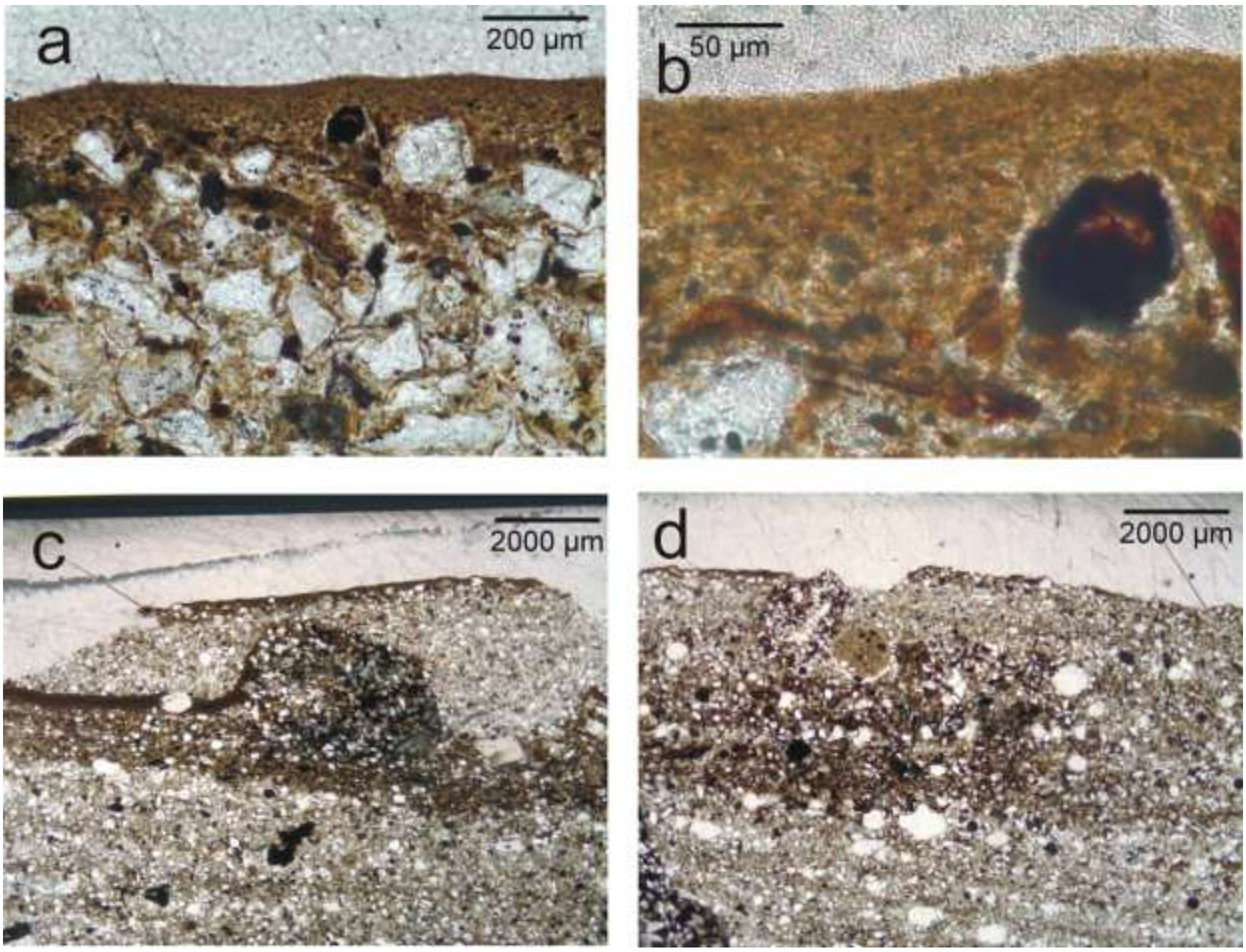

Fig.ure 7 Thin sections of the formed crusts a) Erosion crust with the fine particles on the top and quartz below them, b) Erosion crust contains iron and clay minerals, c) Crust formation on a previous crust with fine particle leaching, d) Structural crust

Among the structural crust spots erosion crust formed on the underlay of the puddles. Bulk density of the tilled soil layer enhanced 15% in case of structural and 40% in erosion crust. The higher value could be the result of the continuous deposition according to Stoke's law creating a clay film cover on the surface. Due to the following rainfall the colloids from this film are mixed (splash erosion) and leached (infiltration) downwards, meanwhile a new cover is created on the top of the sediment.

The sealing and crusting effect of a single storm could be of the same order reflecting the influence of tillage on soil porosity runoff and soil loss. The porosity created by tillage can collapse during one rainfall.

Future research should focus on the compaction effect of single precipitation events on soil sealing and crusting with special emphasis on colloid fraction redistribution after crust formation.

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