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Soil moisture and its effect on bulk density and porosity of intact aggregates of three Mollic soils*

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Soil moisture affects many parameters that are of interest to agricultural production, forest management, soil conservation, and watershed management and modeling. It changes in a wide range throughout the year, it either varies with different soil types. This paper deals with changes in bulk density and porosity with the change in soil water content of three Mollic agricultural used soils from different sites of western Slovakia. For the purpose of this study the intact soil aggregates from surface horizon were used, for as much as the hydraulic properties of aggregates differ from the bulk material consisting of these aggregates and there is still a lack of information concerning the behaviour of soil aggregates when subjected to the actions of water. The obtained results confirmed the aggregate bulk density increase (from 1.75 to 1.93 g/cm^3 in mogmVRpe, from 1.46 to 1.83 g/cm^3 in haCH, from 1.52 to 1.82 g/cm^3 in ccmoFL) and aggregate porosity decrease with the decrease of water content, although the magnitude of change differed between particular soils.

The hydrologic cycle's interaction with the Earth's land surface occurs within a thin reservoir that stores and distributes water that falls on the surface in the form of rain or melting snow. This reservoir is commonly referred to as soil moisture (Engman 1997). Soil moisture affects the wide range of soil properties and processes, it is known to affect land-atmosphere interactions at multiple temporal and spatial scales (Buck and Brunsell 2008). Surface soil moisture affects the diurnal change of surface temperature (Zhang *et al.* 2007), near-surface wind speeds, and near-surface pollutant concentrations (Jacobson 1999). It also governs the intensity of evapotranspiration and rainfall runoff volume. Hohenegger *et al.* (2009) claims that soil moisture anomalies can even affect subsequent precipitation. The amount of water accumulated in the soil profile in the zone of aeration directly impacts the vegetation layer on the soil surface (Šútor *et al.* 2002) responsible for many important processes, including photosynthesis and crop production. Water in soil may alter several mechanical and physical soil properties, such as soil consistency, plasticity, compactibility (Hillel 1998), bulk density, porosity, wettability, infiltration rates, and diversity and activity of soil organisms.

Soil bulk density is defined as the ratio of the mass of dry solids to the bulk volume of the soil (Blake and Hartge 1986). The bulk volume includes both the volumes of the solid phase and the pore space. Soil aggregate properties are usually different from bulk soil properties (Horn 1990, Santos *et al.* 1997). However, most of the research focuses mainly on the role played by the soil matrix. Also, studies often use aggregate measurements as surrogates of the complex soil matrix (Six *et al.* 2004). Besides the size, aggregate density is identified as one of the most important properties of soil aggregates. It is used to estimate inter-aggregate porosity. The objective of this study is to quantify the effect of the change in aggregate water content on its bulk density in three Mollic agricultural used soils from different sites with respect to aggregate porosity. Soils that belong to group of Mollic soils in the Slovak classification system (SPS 2000) are classified as Vertisols, Chernozems and Mollic Fluvisols (WRB 2006), and the latter two are considered the best soils for agriculture suitable for growing highly demanding crops.

The sampling was conducted on well-aggregated agricultural soils at three different experimental sites (Fig 1) from 14 October to 16 October 2008. Mollic grumic Vertisol (pellic) (mogmVRpe) was taken from the site of Gbely (N 48°44´46.1´´, E 17°08´41.2´´), haplic Chernozem (haCH) was collected about 60 km in a bee-line southeast in Voderady (N 48°17´03.0´´, E 17°33´10.9´´), and calcic Mollic Fluvisol (ccmoFL) in the southern area near the Hungarian border, in Gabèíkovo (N 47°54´23.3´´, E 17°35´26.1´´). After removing an upper (5cm) layer from the surface, all samples were taken from the depth of 5–15cm. Undisturbed core samples were taken (by driving a metal corer with a volume of 100 cm^3 into the soil at the desired depth of A-horizon) for a

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[*] Short note

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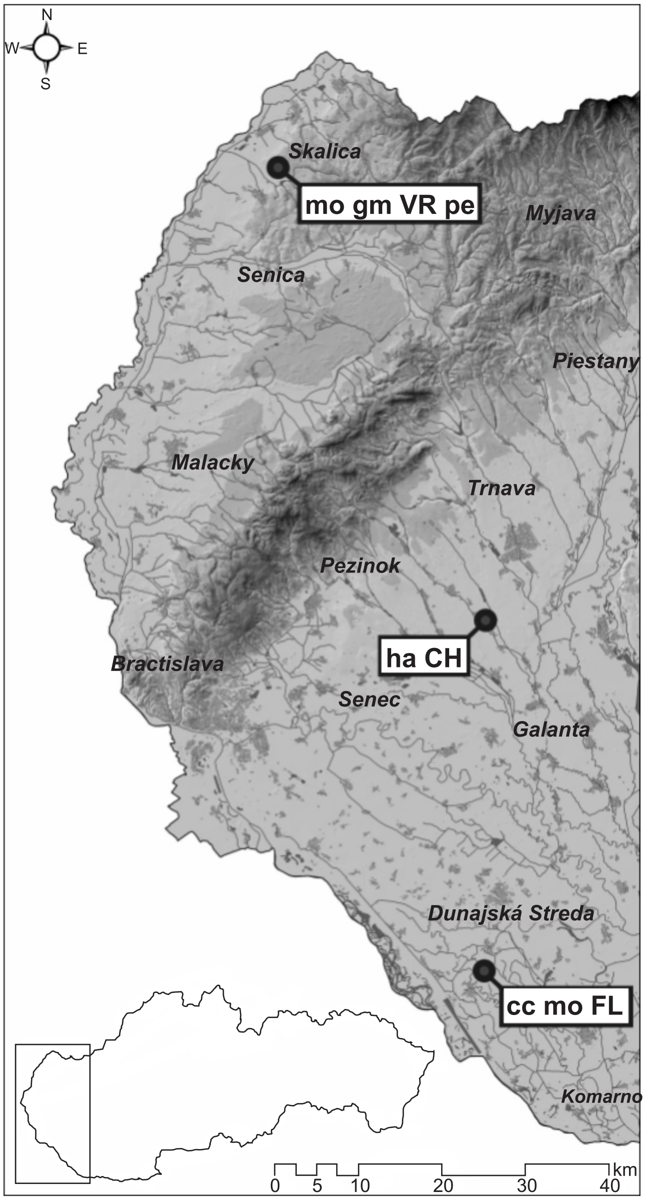

Fig 1 Location map of western Slovakia study area and associated soil pits

numerical expression of the mass-to-volume relationship. In order to study soil free of channels and large pores between aggregates, intact macroaggregates of 0.5–2.5cm size were separated. So as to determine aggregate bulk density and porosity at different moisture levels, aggregates of each soil type were divided into five sets. First set contained soil aggregates held at initial moisture content, second set consisted of aggregates left to dry at room temperature (22.5 ± 2.5°C) to the moisture content of 10% and aggregates from the third set were air-dried for one week to remove most of the aggregate water. The two remaining sets were exposed to temperature of 50°C for 24 and 7 × 24 hours. The temperature and time of exposure were chosen to simulate conditions that normally occur in nature. Although the daily range of soil surface temperature is approximately the same as that of the air temperature (Penman and Keen 1943), 50°C is warmth the bare soil can reach in the summer, in which the soil surface temperature exceeds that of the air for a considerable part of the day. For each soil type, more than 100 aggregates were collected and analyzed for moisture content and bulk density.

For the purposes of analyses of selected physical and chemical properties (particle size analysis, soil *p*H, $CaCO_3$, soil organic carbon (SOC) and soil organic matter (SOM) content, and particle density), a portion of soil aggregates of each soil type was air-dried, milled, sieved through a 2-mm mesh, removed from gravel and large plant debris and thus prepared for the analyses.

The time-series measurements of water amounts in the soil profile are not easy to realize in most cases, many times it is not possible or the procedures are far too time-consuming and technically demanding (Igaz *et al*. 2007). For these reasons, field and residual water contents of soils were determined gravimetrically (mean of 10 values for every examined moisture level of each soil type). Soil textural composition was determined by mechanical analysis (by Novak´s pipette method) (Fiala *et al*. 1999); contents of sand (2–0.05 mm), silt (0.05–0.002 mm) and clay (<0.002 mm) fractions were measured and results were classified according to USDA-FAO texture triangle (FAO, 2006). Soil *p*H was measured potentiometrically in deionized water with a soil:solution ratio of 1:2.5; $CaCO_3$ content using a Janko´s calcimeter (Fiala *et al*. 1999), SOC content by rapid oxidation of organic carbon with $KCr_2O_7 – H_2SO_4$ and titration of non-reduced dichromate (Walkley and Black 1934), SOM content through its TGA-DTA curves. Bulk density of individual clods (not including interclod cavities) was calculated from their mass and volume. The volume was determined by weighing the clod in air, coating the clod with paraffin wax melted at 60–70°C and by reweighing it first in air, then again while immersed in water, making use of Archimedes' principle (Blake 1965). Determination of bulk density of core samples involved the removal of a volume of soil which was dried for 24 hours in an oven (105°C) and weighed. The dry weight of the soil divided by its volume yields bulk density in g/cm^3 (Fiala *et al.* 1999). The volumes of capillary, semicapillary and non-capillary pores were computed from the parameters including porosity, 30 min. moisture and soil water retention capacity (Fiala *et al.* 1999). Particle density was determined by the pycnometer method (Hraško *et al.* 1962). Total porosity f of a soil sample was derived mathematically from bulk density ρ_b and particle density ρ_p measurements, using the equation:

$$f = \left(1 - \frac{\rho_b}{\rho_p}\right)100 \tag{Eq. 1}$$

Measured characteristics of studied soils are given in Tables 1, 2, 3.

Table 1 Selected physical and chemical properties of studied soils

Physical and chemical properties	Soil type mo gm VR pe	 ha CH	 cc mo FL
2–0.05 mm (%)	3.7	4.6	4.4
0.05–0.002 mm (%)	30.3	63.4	54.6
< 0.002 mm (%)	66.0	32.0	41.0
SOC (%)*	1.18	1.21	2.32
SOM (%)	7.7	4.6	6.0
$CaCO_3$ content (%)**	0	0.26	23.5
pH/H_2O	5.75	7.30	7.77
Particle density (g/cm^3)*	2.64	2.67	2.77
Weight of studied aggregates (g)	0.816–5.820	0.300–4.407	0.335–5.476

* mean of three values, ** mean of two values, SOC: soil organic carbon, SOM: soil organic matter

The weight of aggregates taken out of the objects under investigation was ranging between 0.3 and 5.8g, whereby haCH formed the aggregates of smallest size. The shape of aggregates of studied soils was spherical to polyhedral. Soil aggregates were subjected to bulk density (ρ_b) measurements at five different moisture levels. Since moisture demonstrably affects the value of ρ_b, during the whole experiment the samples were treated in such a manner that loss or gain of moisture was avoided. Sampling took place within narrow time interval, when the weather was stable. The actual moisture ranged from 17.4% (mo gm VR pe) to 22.6% (ccmoFL). Likewise, after drying on air, the soils retained different amounts of moisture. The highest retained water content was observed in mogmVRpe (7.4%); the cause could be in high content of clay and organic matter, as well as in the highest volume of capillary pores. Capillary pores are responsible for water retention at low soil moisture. This soil also showed the highest moisture contents after oven-drying at 50°C for 24 and 7 × 24 hours.

Besides water content, the ρ_b of soil depends greatly on the mineral make up of soil and the degree of compaction. The density of quartz, the most abundant type of soil mineral, is around 2.65 g/cm^3 (Richardson *et al.* 2002) but the ρ_b of a mineral soil is normally about half that density, between 1.0 and 1.6 g/cm^3. Nevertheless, ρ_b of individual soil peds is higher than the density of soil mass, for as much as ρ_b determined with the core method includes the effect of both the intra- and inter-aggregate pore spaces (Table 2). The bulk densities of aggregates are greater where aggregate porosities are less (Table 3).

ρ_b was determined for each followed moisture level separately. In all samples, ρ_b showed an increasing tendency with decreasing moisture content, although in case of ccmoFL, drying on 50°C had no effect on further change in ρ_b value (Fig 2). When air-dried, haCH was the soil having the lowest ρ_b value (1.71g/cm^3), whereas mogmVRpe soil with the highest ρ_b value (1.91 g/cm^3). Soils that are loose, porous, and/or having higher portion of coarser particles have lower ρ_b than soils that are fine-textured and/or compacted. To objectively compare bulk densities of investigated soils, soil moisture content of all samples was adjusted to the same value (10 ± 1%); under these conditions, haCH was still the soil with the lowest and mogmVRpe the soil with the highest value of ρ_b.

Table 2 Differences between bulk density and porosity of air-dried single aggregates and soil mass

Physical and chemical properties	Soil type mo gm VR pe	 ha CH	 cc mo FL
Bulk density of soil aggregates (g/cm^3)	1.91	1.71	1.82
Bulk density of soil mass (g/cm^3)*	1.28	1.44	1.09
Aggregate porosity (%)	28	36	34
Soil mass porosity (%)*	50	46	59
Soil capillary pores (%)*	44	36	35
Soil semi-capillary pores (%)*	2	4	4
Soil non-capillary pores (%)*	4	6	20

*Data obtained by Fulajtár *et al.* (2008a, b)

ρ_b of mo gm VR pe, ha CH and cc mo FL showed strong negative linear correlation (r = – 0.938, – 0.985 and – 0.993, respectively) with aggregate moisture, statistically significant at the 0.05 level (P= 0.018, 0.002 and 0.0006, respectively). However, according to ANOVA statistical analysis there was no significant difference at $P < 0.05$ between the soil types in conjunction with the observed experimental data presented in Table 3.

Particle density (ρ_p) varies with the type of minerals present in soil as well as the SOM amount. SOM is considered to make the soil more resistant to compaction. SOM weighs much less per unit volume than soil minerals and thus readily influences ρ_p. Soils high in organic matter have lower ρ_p than soils similar in texture that are low in organic matter. ρ_p

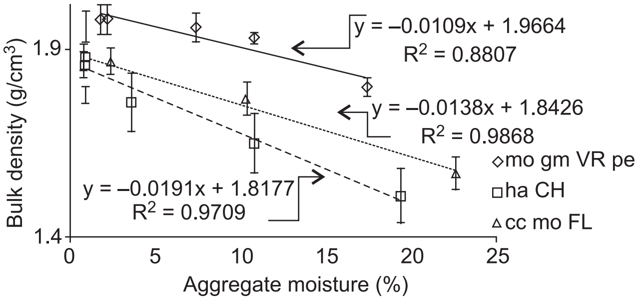

Fig 2 Relationship between bulk density and moisture in aggregates of three mollic soils

Table 3. Comparison of changes in bulk density and porosity of aggregates of three Mollic soils with change in water content

Soil type								
mo gm VR pe			ha CH			cc mo FL		
Agg. *W* (%)	Agg. ρ_b (g/cm^3)	Agg. *F* (%)	Agg. *W* (%)	Agg. ρ_b (g/cm^3)	Agg. *F* (%)	Agg. *W* (%)	Agg. ρ_b (g/cm^3)	Agg. *F* (%)
17.4 •	1.75	33	19.4 •	1.46	45	22.6 •	1.52	45
10.8 °	1.88	29	10.8 °	1.60	40	10.4 °	1.72	38
7.4 ~	1.91	28	3.6 ~	1.71	36	2.4 ~	1.82	34
2.2 □	1.93	27	0.9 □	1.81	32	0.9 □	1.82	34
1.8 ■	1.93	27	0.9 ■	1.83	31	0.8 ■	1.82	34

w, Water content; ρ_b-bulk density; *f*-porosity; • actual aggregate water content measured immediately after sampling; ° aggregate water content of approx. 10%; ~ aggregate water content of air-dried samples; □ aggregate water content after oven-drying at 50°C for 24 hr; ■aggregate water content after oven-drying at 50°C for 7 × 24 hr

for mogmVRpe was 2.64, for haCH 2.67 and for ccmoFL 2.77 g/cm^3; for comparison, ρ_p of most mineral soils is in the range of 2.6 to 2.7 g/cm^3 (Hillel 1998). Whereas ρ_p is the soil characteristic not dependent on soil moisture it was determined only in air-dried samples.

Aggregate porosities were 22–43% higher than soil mass porosities. Aggregate porosities were inferred from bulk and particle densities of investigated soils for each followed moisture level, according to Eq.1. The ρ_b of soil is inversely related to the *f* of the same soil; the more pore space in a soil, the lower the value for ρ_b. Thus, with a decrease in soil moisture the value of *f* decreased as well. In air-dried aggregates, it ranged from 28 (mogmVRpe) to 36% (haCH). In ccmoFL the effect of drying temperature (50°C for 24 and 7 × 24 hr) was negligible in the degree of further pore size change. Regarding the whole interval of values of *f*, haCH showed the highest range of values (45–31%), whereas mogmVRpe the lowest (33–27%). At the same time, these two soils differed in textural composition most markedly. Bulk density and thus porosity are of those physical attributes that greatly influence important soil and plant processes like water movement (Reichardt and Timm 2004), soil aeration (Stepniewski *et al.* 1994), soil compaction (Logsdon and Karlen 2004), and plant root system development (Boone and Veen 1994).

Regarding other soil properties, soils differed also in their texture, SOC, SOM and $CaCO_3$ content, and soil *p*H (Table 1) haCH and mogmVRpe were similar in SOC content, ccmoFL contained more SOC (2.32%). haCH contained 0.26%, ccmoFL 24.5% of $CaCO_3$, mogmVRpe was non-carbonated. The reaction of soils was slightly acid (mogmVRpe) and slightly alkaline (haCH, ccmoFL). According to the USDA triangle (FAO 2006), mogmVRpe was determined as clay soil, ccmoFL as silty clay and haCH as silty clay loam.

SUMMARY

The obtained results confirmed the changes in bulk density, and thus in porosity resulting from the change in soil water content. The bulk density of aggregates of three Mollic soils increased with decreasing content of water in samples, although there were differences among particular soil types. The aggregates of haCH showed a rather steady increase in bulk density with decrease in moisture content, aggregate bulk density of mogmVRpe remained unchanged after heating at 50°C for 24 hr, heating to 50°C even after a prolonged period had no effect on bulk density of ccmoFL clods.

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