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Hysteresis between wetting and drying processes as affected by soil aggregate size

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Abstract. The impact of different sizes of soil aggregates on the hysteresis of their water retention characteristics was determined. Soil aggregates were separated from the arable layer of Orthic Podzol, Eutric Cambisol and Haplic Phaeozem. The results of the study showed that the impact of aggregate size was significant. It was found that differences in water content during the drying and wetting processes varied not only for the chosen soil water potential and aggregate size, but also for the type of soil. The maximum differences in water content between the drying and wetting processes at the same soil water potential reached nearly 15% vol. in absolute values. Thus it can be stated that negligence of the hysteresis effect can cause inaccuracy of estimation of soil moisture.

Keywords: soil aggregation, water retention curve, hysteresis

INTRODUCTION

Soil not only transforms rainfall into surface and subsurface water, but also determines the values of water balance components through water capacity and transmission properties (Connoly, 1998). Water retention and transmission properties of the soil depend on the parameters of its structure (Horn, 2002; Kutilek and Nielsen, 1994; Weisskopf *et al.*, 1999). The physical properties of the soil arable layer which can be changed in different soil managements include, first of all, bulk density and aggregate size distribution, because both of these characteristics are directly responsible for the total porosity and pore size distribution of soil (Gupta *et al.*, 1989; Lipiec and Hatano, 2003; Pagliai *et al.*, 2004; Piccolo *et al.*, 1997). The complex nature of the pore space in the soil and the water held therein makes it difficult to specify directly the force fields acting on the water. The description of soil-water relationships depends upon not only the quantification of the force fields but also on the specification of the solid matrix geometry (Dexter, 1988; Hajnos *et al.*, 2006). These factors affect the soil-water system at all times (Carter, 2002; Cornelis *et al.*, 2001; Dexter and Bird, 2001).

Water content in the soil can be changed in two directions *ie* it can be decreased in the drying process or increased in the wetting process. Because most functional characteristics of the thermodynamic variables in the real process show hysteresis, the hysteresis effect in the water potential-water content (moisture) relation can be observed for soil. Thus, this relation is non-explicit and the course of hysteresis is determined by the colloidal-porous properties of the soil and by the history of the system, that is by the way in which a given state was obtained. The water content (moisture) in the soil reached in the drying process is always higher than the corresponding water content reached in the wetting process. Measurements of the wetting curve are seldom made, because its determination is both time and labour consuming, and also requires the use of expensive special equipment (Durner and Fluhler, 1996; Kaszubkiewicz, 1997; Rose, 1971). The results of several investigations concerning this subject show that this effect is significant (Witkowska-Walczak, 2003).

In all investigations of water in soil the knowledge of the precise value of water potentials and its quantity after any history of changes of these quantities is necessary. It is especially important for agricultural areas under irrigation, where the quantity of water supplied to the soil profile and utilised by plants can be distinctly decreased.

The aim of this paper is to show the impact of the size of different soil aggregates on the hysteresis effect of their water retention characteristics.

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MATERIAL AND METHODS

The soils under study were Orthic Podzol (OP), Eutric Cambisol (EC) and Haplic Phaeozem (HP), samples of which were taken from the arable layer (0-15 cm). After air-drying at room temperature, soil aggregates were classified by the standard dry sieve method into six fractions: ≤0.25; 0.25-0.5; 0.5-1; 1-3; 3-5 and 5-10 mm. Then, aggregates of each particular fraction were repacked into cylinders ($V = 100$ cm^3, $h = 5$ cm) using a vibrator to obtain uniform density (30 s). These monoaggregate samples were subjected to 5 successive wetting-drying cycles from full saturation to the air-dry state. This procedure allowed soil samples to reach an equilibrium (stable physical characteristics) (Sarmah *et al.*, 1996; Shiel *et al.*, 1988; Walczak and Witkowska-Walczak, 1981). The basic properties of the six soil aggregate fractions are shown in Table 1.

The characteristics of water potential-water content in the process of drying and wetting were determined using a gypsum plate with an automatic regulation system of pressure in the soil water potential range of 0.1-50 kJ kg^{-1} (drying curve) and 50-0.1 kJ kg^{-1} (wetting curve) (Walczak *et al.*, 1985).

The magnitude of the hysteresis effect at a chosen potential of soil water (0.2, 1, 3.1, 10 and 16 kJ kg^{-1}) was calculated by the difference of water content between the drying and wetting processes. The area of hysteresis loops (P) *ie* the surface area between the drying and wetting curves, was measured using a planimeter.

RESULTS

The aggregate distribution of stabilized soil samples initially composed of monofractions, their bulk density and total porosity after the wetting-drying cycles, are presented in Table 2. These data show that the water-stability of each fraction of aggregates depended on their size *ie* it increased with a decrease in aggregate size. The aggregates of 5-10 and 3-5 mm in diameter showed the lowest water stability (28-33%), while the highest water stability (73-76%) was observed for the aggregates of 0.25-0.5 mm in diameter. The influence of the wetting-drying cycles on microaggregates *ie* aggregates with diameters smaller than 0.25 mm, was aggregate-forming to a lesser extent (1%). The bulk density of the aggregate samples was the highest for the smallest aggregate fractions of Orthic Podzol (less than 1 mm) and Haplic Phaeozem (less than 0.25 mm), and the lowest for 3-5 and 0.5-1 mm aggregates of Eutric Cambisol.

Table 1. Basic properties of the investigated soil aggregates

Soil	Fractions of aggregates (mm)	Grain size distribution (%, dia in mm)			$C_{org.}$ (%)	Specific surface area (H_2O) (m^2 g^{-1})	pH_{KCl}	$CaCO_3$ (%)
		1- 0.1	0.1-0.02	< 0.02				
Orthic Podzol (OP)	< 0.25	9	61	30	3.0	44	4.0	0.06
	0.25-0.5	58	26	16	2.1	21	4.0	0.06
	0.5-1	56	26	18	2.5	25	4.0	0.06
	1-3	48	30	22	3.4	43	4.0	0.08
	3-5	48	30	22	2.7	37	4.0	0.18
	5-10	49	29	22	2.5	29	4.1	0.06
Eutric Cambisol (EC)	< 0.25	5	57	38	1.3	46	7.3	0.43
	0.25-0.5	22	38	40	1.8	54	7.2	0.10
	0.5-1	21	42	37	1.7	54	7.2	0.74
	1-3	15	43	42	2.0	55	7.1	0.62
	3-5	15	45	40	2.0	54	7.2	0.62
	5-10	14	48	38	2.0	53	7.0	0.29
Haplic Phaeozem (HP)	< 0.25	4	61	35	2.2	54	6.9	0.06
	0.25-0.5	11	50	39	3.3	73	6.9	0.12
	0.5-1	6	50	44	3.0	71	6.9	0.14
	1-3	5	50	45	2.9	72	6.8	0.16
	3-5	4	54	42	3.0	67	6.8	0.12
	5-10	4	54	42	2.9	73	6.8	0.14

Table 2. Structural characteristics of the stabilized soil samples built of the investigated soil aggregates

Soil	Fractions of aggregates (mm)	Aggregate size distribution (%, dia in mm)						Bulk density (g cm $^{-3}$)
		< 0.25	0.25-0.5	0.5-1	1-3	3-5	5-10	
Orthic Podzol (OP)	< 0.25	99	1					1.27
	0.25-0.5	26	73	1				1.70
	0.5-1	9	30	58	3			1.42
	1-3	9	10	19	60	2		1.06
	3-5	13	20	9	23	32	3	1.06
	5-10	22	27	7	6	10	28	1.13
Eutric Cambisol (EC)	< 0.25	99	1					1.08
	0.25-0.5	16	73	1				1.08
	0.5-1	12	23	62	3			0.98
	1-3	13	14	21	50	2		0.99
	3-5	11	16	19	23	29	2	0.91
	5-10	15	13	12	12	16	32	1.01
Haplic Phaeozem (HP)	< 0.25	99	1					1.27
	0.25-0.5	23	76	1				1.04
	0.5-1	23	26	50	1			1.10
	1-3	24	16	14	45	1		0.99
	3-5	21	18	10	18	33		1.04
	5-10	21	15	9	9	13	33	1.06

The water content of aggregates of different sizes from the three soils varied with water potential in the range of 0.1-50-0.1 kJ kg^{-1} during the drying and wetting processes (Fig. 1). Standard deviations for these data are presented in Table 3.

For Orthic Podzol (OP), in the drying process the water content of aggregates $\leq$0.25 mm was higher than that of other aggregate sizes at a given water potential. These water content values were between 27 and 52%, vol. The amount of water bound with forces corresponding to the lowest potential was the highest for aggregates of diameter higher than 1 mm and it rapidly decreased by about 15% at the potential of 0.2 kJ kg^{-1}. The lowest water content, 36% vol., at 0.1 kJ kg^{-1} was bound by the aggregates of 0.25-0.5 mm. For potentials higher than 10 kJ kg^{-1} the differences in the amount of water bound by aggregates of diameters bigger than 0.25 mm were small and did not exceed several percent.

In the case of Eutric Cambisol (EC), the moisture at 0.1 kJ kg^{-1} potential was nearly the same (56-52%, vol.) for all the aggregates. Next, aggregates smaller than 0.25, 0.25-0.5 and 5-10 mm showed a higher water content between 0.2 and 10 kJ kg^{-1} than the others, and the differences between their water content values equalled 12-18% vol. The smallest differences of moisture were observed for aggregates of 0.5-1, 1-3 and 3-5 mm between potentials of 1-50 kJ kg^{-1}. They did not exceed 2-3%, vol.

For Haplic Phaeozem (HP), the highest moisture (59-62%, vol.) at 0.1 kJ kg^{-1} was held by aggregates larger than 1 mm, but at the potential of 0.2 kJ kg^{-1} the measured moisture rapidly decreased and it was lower by 19 to 23%, vol. At the highest potential they held between 17-20%, vol., of water. Aggregates smaller than 1 mm showed water content from 52 to 58%, vol., at 0.1 kJ kg^{-1} and from 22.5 to 26%, vol., at 50 kJ kg^{-1}.

It should be emphasised that the shape of the retention curves depended not only on the aggregate sizes but also on the type of soil they were separated from. An especially evident example of this fact is the shape of the retention curve for 0.5-1 mm aggregates of Orthic Podzol (OP) and Haplic Phaeozem (HP) or for 0.25-0.5 mm aggregates of Orthic Podzol (OP) and Eutric Cambisol (EC). In conclusion, it can be stated that the highest water content was noticed for Haplic Phaeozem aggregates, then for Eutric Cambisol, and the lowest for Orthic Podzol aggregates.

The differences in the water content at chosen soil water potential levels in the drying and wetting processes are shown in Fig. 2. Analysis of the data showed that these

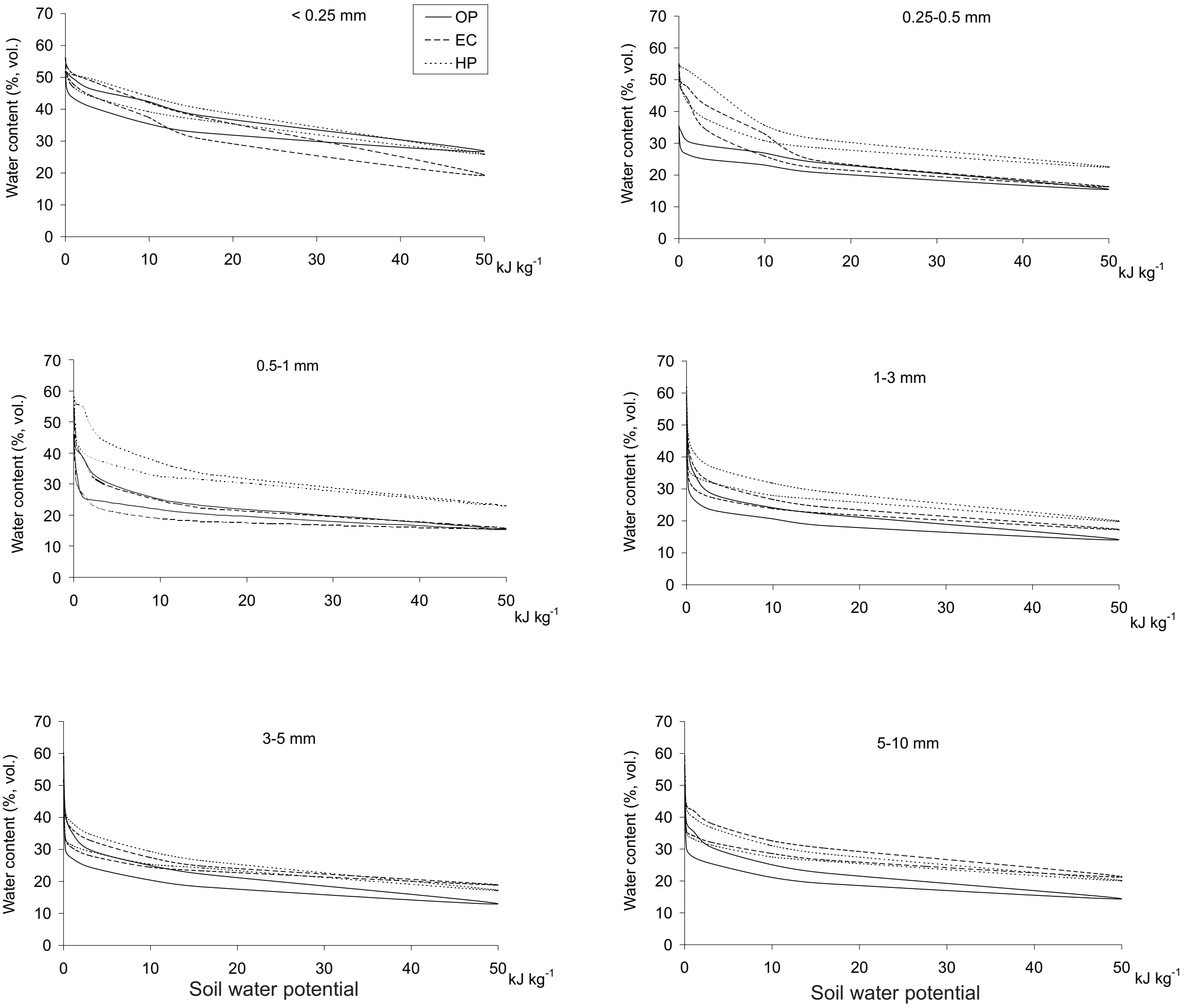

Fig. 1. Water retention curves in drying and wetting processes for samples created from different aggregates of the investigated soils.

differences were different not only for chosen soil water potentials and aggregate sizes but also for the type of soil. The greatest differences were noticed for 0.5-1 mm aggregates of all types of investigated soils at 1 kJ kg^{-1} – 12.8, 11.6 and 14.5%, vol., respectively. High values of hysteresis effect were also shown at 0.2 kJ kg^{-1} for 1-3 mm fraction of aggregates (11.5, 10.2 and 10.2%. vol.) The lowest values of hysteresis effect were observed at 16 kJ kg^{-1} for all the fractions of investigated aggregates, except for those under 0.25 mm. For Orthic Podzol the effect of hysteresis for aggregates smaller than 0.25 and 0.25-0.5 mm was nearly the same at all soil water potential values *ie* 5.8-7.3% and 3.5-5.2%, whereas for aggregates of 0.5-1 mm it showed a maximum at 1 kJ kg^{-1} – 12.8%, and a minimum at 16 kJ kg^{-1} – 2.7%, vol. For the smallest fraction of Eutric Cambisol the differences in moisture between drying and wetting increased with increase of soil water potential from 2.5 to 6.8%, vol., whereas aggregates of 0.25-0.5 mm showed a maximum at 3.1 kJ kg^{-1} – 7.7%, vol. and two minimal values – 2.2 and 2.3% at 0.2 and 16 kJ kg^{-1}, respectively. The hysteresis effect for 0.5-1 aggregates of Eutric Cambisol decreased with increase of soil water potential from 12.2% at 0.2 kJ kg^{-1} to 4.1% at 16 kJ kg^{-1}. For Haplic Phaeozem aggregates under 0.25 and 0.25-0.5 mm the moisture differences increased up to 3.1 kJ kg^{-1} soil water potential from 1.5 and 5.6% till 5.5 and 11.3%, respectively, and then they decreased to 3.6 and 2.8% at the lowest value of soil water potential. The absolute maximum of the value of hysteresis effect – 14.5%, vol., was recorded for Haplic Phaeozem aggregates of 0.5-1 mm at 1 kJ kg^{-1}. The measured hysteresis effect in the three investigated types of soils for aggregates of 1-3, 3-5 and 5-10 mm decreased systematically with increase of soil water potential *ie* for Orthic Podzol – 11.5-3.6, 11.7-4 and 8.2-3.3% vol.,

T a b l e 3. Standard deviations for water content values (% vol.) in drying and wetting processes for the investigated soil material

Fractions (mm)	Soil water potenial (kJ kg^{-1})											
	0.1	0.2	1	3.1	10	16	50	16	10	3.1	1	0.2
	Drying							Wetting				
	Orthic Podzol											
< 0.25	1.9	3.0	2.5	2.4	2.5	1.0	1.0	1.0	2.0	2.1	2.2	2.8
0.25-0.5	1.7	2.7	1.5	2.6	1.0	1.0	0.6	0.9	1.3	2.0	2.1	2.5
0.5-1	2.3	2.2	1.0	1.6	1.3	1.1	0.5	1.0	1.0	1.5	1.0	2.3
1-3	1.0	2.0	0.9	2.0	1.4	1.0	0.9	1.0	1.3	1.6	1.5	1.5
3-5	1.9	1.8	2.0	3.0	2.0	0.7	0.6	0.8	1.5	1.4	1.4	1.0
5-10	2.8	2.2	2.0	3.3	1.9	1.0	0.5	0.5	1.1	1.0	1.5	1.5
	Eutric Cambisol											
< 0.25	2.9	3.0	2.3	3.0	2.0	0.8	0.9	0.9	1.5	2.9	2.0	3.0
0.25-0.5	2.1	2.5	2.5	2.0	1.2	0.9	0.7	1.0	1.2	2.0	3.0	2.4
0.5-1	2.7	2.0	1.1	2.1	1.0	1.0	0.5	1.0	1.0	1.3	1.3	2.0
1-3	2.9	2.4	1.4	2.0	1.2	1.1	0.8	1.3	1.3	1.4	1.4	1.7
3-5	2.8	1.8	1.6	1.6	1.3	1.1	1.0	1.3	0.9	1.6	1.5	1.5
5-10	2.9	2.0	1.0	2.0	1.5	1.0	1.1	1.4	1.2	1.6	1.5	2.0
	Haplic Phaeozem											
< 0.25	2.6	3.1	3.1	2.5	2.1	1.1	0.9	1.5	1.6	2.0	2.4	3.0
0.25-0.5	2.1	2.9	3.0	2.9	1.8	1.2	0.8	1.5	1.2	1.8	2.3	2.5
0.5-1	2.8	2.9	3.0	2.1	1.5	1.2	1.0	1.6	1.5	1.5	2.4	2.0
1-3	4.0	2.5	2.0	1.5	0.1	1.0	1.0	1.4	1.7	2.0	1.8	2.0
3-5	2.7	2.0	3.0	0.4	0.5	1.1	0.8	1.2	1.4	1.6	1.5	1.5
5-10	3.1	2.4	2.0	2.0	1.4	1.1	0.9	1.6	1.3	1.4	1.6	1.7

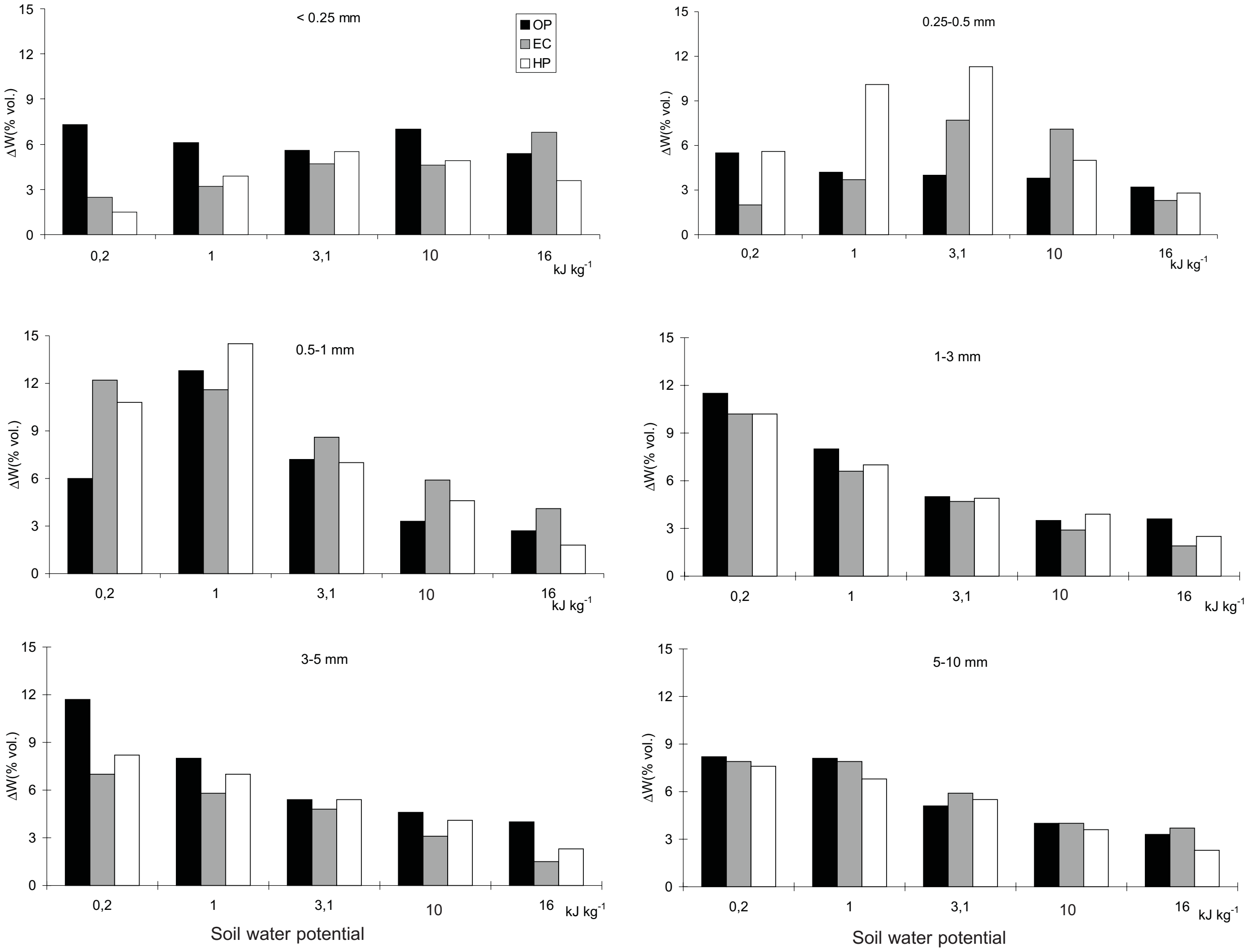

Fig. 2. Hysteresis effect of water retention curves (ΔW) at chosen water potential for samples created from different aggregates of the investigated soils.

for Eutric Cambisol – 10.2-1.9, 7-1.5 and 7.9-3.7% vol., for Haplic Phaeozem – 10.2-2.5, 8.2-2.3 and 7.6-2.3% vol., respectively.

The magnitude of the hysteresis was measured by the area between the drying and wetting retention curves for different sizes of aggregates. It is interesting that the hysteresis loop was nearly constant for Orthic Podzol aggregates – 3.6-4.8 cm^2, whereas for Eutric Cambisol and Haplic Phaeozem it showed clear maxima and minima. For both Eutric Cambisol and Haplic Phaeozem the maximum values of hysteresis loop area were observed for 0.5-1 mm aggregates, 5.8 and 5.5 cm^2, whereas the minimum values were noted for aggregates smaller than 0.25 mm – 2.5 and 2.6 cm^2, respectively. It means that the size of soil aggregates can change their moisture content by a factor of more than two.

Analysis of the hysteresis of soil water properties can be carried out knowing the values of soil water potential and of water volume *ie* quantities directly measured in experiments. According to the domain theory, a domain is an element of the capillary-porous system and is described by two parameters: volume and potential. Volume is represented by the pores in soil which have different diameters. The pore sizes respond to the water potential according to the bundle of cylindrical capillary theory. Because, dependent on the history of the system *ie* whether they were full or empty of water, at the same value of the potential they are filled with water or emptied, depending on the pore diameters. The structure of soil, especially caused by soil aggregation, texture, and bulk density, is the reason for the formation of its very complicated porous space.

The character of the shapes of water retention curves in the drying and wetting processes, in particular the differences in moisture at chosen soil water potential values (Fig. 2) and, generally, hysteresis loop magnitudes, showed that the sizes of soil aggregates can substantially change the water characteristics of soils. The results of the conducted investigations lead to the conclusion that negligence of the effect of hysteresis may cause inaccurate estimation of soil moisture.

CONCLUSIONS

1. The conducted investigations on the influence of the size of aggregates on the hysteresis effect of water retention in soils showed that its impact is significant and the negligence of the hysteresis effect may cause inaccuracy of soil water content estimation.

2. It can be stated that the differences in water content during the drying and wetting processes were different not only for the chosen soil water potential values and sizes of soil aggregates, but also for the type of soil.

3. The maximum differences in water content between the drying and wetting processes at the same soil water potential reach nearly 15%, vol.

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