Soil water retention under drying process in a soil amended with composted and thermally dried sewage sludges

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Abstract
We report soil water desorption modifications during air drying in a soil amended with six different sewage sludges (composted or thermally dried). The time required to change water retention from wilting point (-1.5MPa) to dryness (ψ = -25 MPa) was increased by composted sludges but not by thermally dried sludges, although both sludges were able to increase soil water retention under drying. Changes in the water desorption rates are hypothesised to be due to low wettability of the soil treated with composted sludges.

Introduction
Soil drying after wetting is a process that occurs continuously in the field, due to evaporation or infiltration. The soil water content (θ) and its corresponding energy state or suction (ψ) differs under wetting or drying processes. This arises from differences in the processes of filling or emptying soil pores (Braddock *et al.* 2001). However, while soil wetting can occur within minutes in some cases, soil drying requires hours (Ojeda *et al.* 2009a). This gives importance to the soil drying process in terms of water plant uptake or water availability to microbial activity. In soil reclamation processes, sewage sludge is currently used as organic amendment in order to improve many soil properties such as fertility, soil water retention and aggregate stability. Water is retained in soil by capillary forces at high saturations (low suction regime) (Nitao and Bear 1996) and by forces of molecular attraction at low saturations (high suction regime) (Pozdnyakov *et al.* 2006). However, due to the potential hydrophobicity of organic matter (Bachmann *et al.* 2008), the temporal dependency of soil water retention can be modified by sludge amendments. The main objective of this study is to assess the effects of two kinds of sewage sludge (composted or thermally dried) on the time involved in the drying process of a soil obtained from quarrying activities. We apply a segmented model to quantify temporal changes in soil water content. The relationship between water holding time and soil organic carbon was analyzed.

Proposed model
The critical gravimetric water content (w_c) was obtained using the relationship between gravimetric water content (w) and time (t), in both low and high suction regimes (Ojeda *et al.* 2009a):

$$w = -a_1\, t + b_1 \qquad t_e \le t \le t_c \qquad (1) \qquad\qquad w = -a_2\, t + b_2 \qquad t_c \le t \le t_\infty \qquad (2)$$

where a_1 and a_2 are constants, t_e is the time when air entry suction occurred and t_c is the time when low suction regime changes to high suction regime. The negative sign of a_1 corresponds to water losses during drying process. The interception of both straight lines (Eqs. 1 and 2), corresponding to the transition point where low suction regime changes to high suction regime, is determined by a change of slope (Figure 1a). The t_c and w_c values were calculated and the ψ_c value was determined from the water retention curve (WRC) using the w_c value (Figure 1b). The composite fractal model of Ojeda *et al.* (2006) was used to fit WRC, as this model covers both the low and high suctions regimes, where A_1 and A_2 (Figure 1b) are constants, while D_1 and D_2 are pore-solid and surface fractal dimensions, respectively.

Materials and methods
The soil samples were obtained from a limestone quarry (Begues municipality, Barcelona, Spain) that produces a soil resulting from excavation processes. It has characteristics of a red Mediterranean soil (*Spolic Technosol calcaric*), with a loamy texture, being low in organic matter (organic C = 0.47 %), but rich in lime ($CaCO_3$ = 39.3 %) and coarse fragments (62.0 %). The soil was amended with six types of treated sludge produced in various municipal waste-water treatment plants from medium-sized towns of Catalonia (NE Spain). All sludges were digested and partially dewatered (20% dry matter) before being subjected to either a composting or a thermal drying process (Table 1). Dewatered sludge from Manresa was composted with crushed pinewood bark, while dewatered sludge from Blanes and Vilaseca was composted with pinewood splinters. All sludges were applied to soil as granules, except the thermally dried sludge from Sabadell which was added as a pellet (1 cm in

diameter). A nominal dose of about 35 Mg ha^{-1} (dry weight) of each sludge was mixed with the soil and distributed in 28 lysimeters of 150 L with a surface area of 0.3 m^2. There were 4 replicates per treatment. The experiment was maintained in the quarry for 13 months. Samples were taken after one month (T1) and twelve months (T2) after the start of the experiment. Soil samples (0 – 20 cm depth) of each lysimeter were air-dried at room temperature, passed through a 2 mm sieve, and stored at 4ºC in the dark before analysis. Table 2 gives information about treatments and the main physicochemical properties of the amended soils at T1.

The main drying branches of the water retention curve were measured in the laboratory at 25ºC, using a WP4 Dew Point PotentiaMeter (Decagon Devices, Inc. Pullman, WA). Samples of approximately 1.2 g of air-dry soil (< 2 mm) from each plot were placed in sample cups (40 mm dia.×10 mm) resulting in a monolayer of aggregates that completely covered the bottom of the sample cups. Both the sample and sample cup were previously weighed and saturated by capillarity for 10 minutes using one band of filter paper in contact with a free water table approximately 10 mm above the soil surface. After this, excess water was removed. A balance and the WP4 Dew Point PotentiaMeter were then used to record w and ψ periodically over time, as the sample dried by evaporation. Approximately 8-12 paired measurements of w and ψ were obtained. The time required for the soil drying processes was measured using a chronometer and the relationships between gravimetric water content and time were analyzed. The drying time that elapsed between suction at -1.5 MPa (wilting point: $\psi_{-1.5}$) and suction at 25 MPa (dryness: ψ_{-25}), called Δt_{total} and its corresponding gravimetric water content (Δw_{total}) were considered as parameters. Total organic carbon was determined by the wet oxidation method.

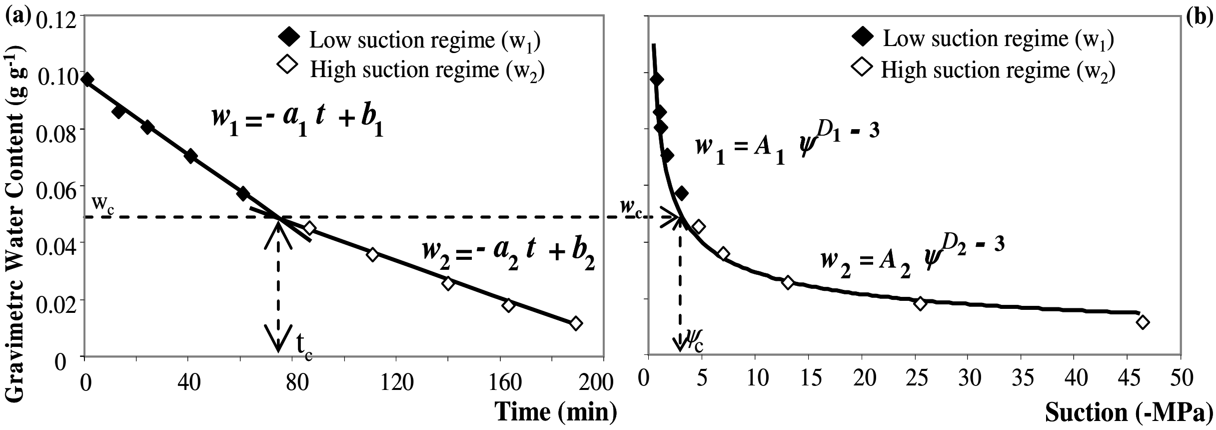

Figure 1. Determination of: (a) critical gravimetric water content (w_c) and the corresponding vapour wetting time (t_c), as the critical point that separates high and low suction regimes in the interception of w_1 and w_2 straight lines, (b) determination of the corresponding critical suction (ψ_c) from the soil water retention curve. Modified from Ojeda *et al.* 2009a.

Table 1. Treatments, composition and identification code of the sewage sludge types used as organic amendment (Ojeda *et al.* 2009a).

Origin† (WWTP)	Type of digestion	Code*	Organic matter (%)	Stability degree‡ (%)	N (%)	P (%)	pH	EC (dS/m)¶
Blanes	Anaerobic	C_{BL}	56.6	29.0	3.2	7.0	6.5	7.6
Manresa	Anaerobic	C_{MR}	55.5	40.6	2.3	4.3	7.1	3.9
Vilaseca	Aerobic	C_{VL}	58.3	35.8	3.0	5.8	6.9	8.5
Besós	Physico-chemical	T_{BS}	72.3	8.6	2.2	4.0	6.1	1.4
Mataró	Anaerobic	T_{MT}	74.0	40.4	3.5	3.3	6.2	5.8
Sabadell	Anaerobic	T_{SB}	62.2	39.5	3.9	5.8	7.3	0.9

† WWTP: identification of municipal waste water treatment plant. * Composted sludge from Blanes (C_{BL}), Manresa (C_{MR}) or Vilaseca (C_{VL}), and thermally-dried sludge from Besós (T_{BS}), Mataró (T_{MT}) and Sabadell (T_{SB}). ‡ Stability degree: percentage of organic matter resistant to acid hydrolysis. ¶ EC: Electrical conductivity (1:5 water extract).

Table 2. Mean values of the physicochemical properties of <2 mm fraction of the soil amended with different types of sewage sludge (Ojeda *et al.* 2009a).

Type of sludge	Treatment†	Sand %	Silt %	Clay %	pH (H_2O)	E.C. (dS/m) 1:5	SOM* %	N %	P-Olsen mg/kg
Composted	C_{BL}	44,2	35,2	20,6	8,0	1,1	1,8	0,15	51
	C_{MR}	45,7	34,3	20,0	8,1	0,9	1,6	0,10	46
	C_{VL}	38,3	36,2	25,5	8,0	1,0	2,4	0,22	101
Thermally	T_{BS}	46,2	34,0	19,8	8,2	0,5	1,9	0,12	35
dried	T_{MT}	38,6	41,3	17,4	8,1	0,5	2,9	0,16	49
	T_{SB}	51,0	31,6	20,1	8,3	0,7	1,2	0,08	10
Control	O_{MS}	42,5	35,0	22,5	8,5	0,5	0,8	0,06	6

† See Table 1 to identify sewage sludge treatment. *SOM: organic matter. O_{MS}: soil without sludge.

Results

The measured values of *w* and ψ for amended soil under drying processes ranged from 0.01 to 0.15 g g^{-1} and from -0.5 to -50 MPa, respectively, where increases in ψ always resulted in decreases in *w*. The time required to air dry the non-amended soil from wilting point (-1.5 MPa) to dryness (-25 MPa) reached a maximum value of 82.5 min. Analyzing the Δt_{total} parameter, one month after sludge addition (T1) the soil treated with composted sludges required more air drying time (55 %) in a soil layer < 2 mm, whilst one year after sludge addition (T2) one of the studied thermally dried sludges was able to reduce the time required for water evaporation (27%). Comparing with the corresponding soil gravimetric water content retained between -1.5 and 25 MPa (Δw_{total}, Figure 2b), at T1 all sludges (except the thermally dried sludge from Sabadell) increased the soil water retention, whilst at T2 only the composted sludge from Vilaseca and the thermally dried sludge from Mataró showed a significative increase. This means that composted sludges were possibly more useful to increase the soil water content at short term, because the water desorption was slower during soil evaporation compared to the soil amended with thermally dried sludges.

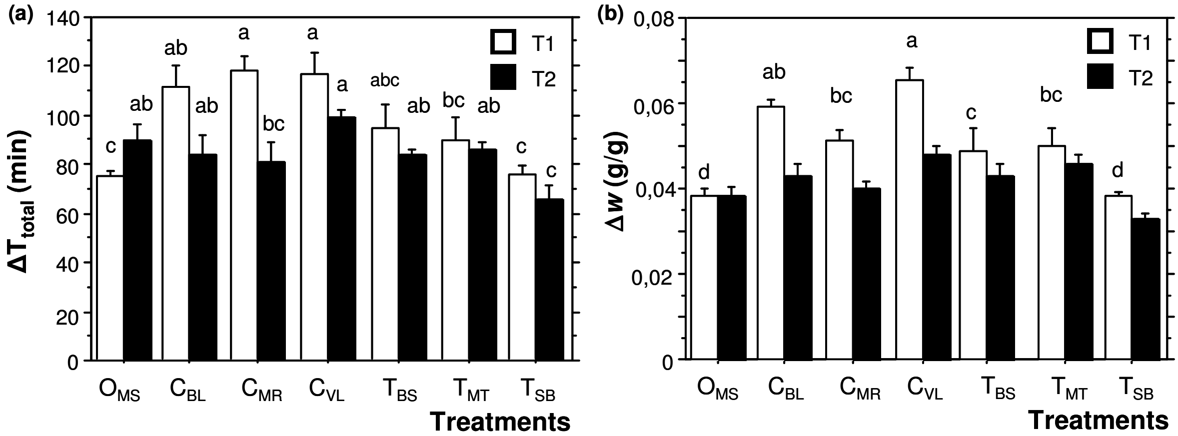

Figure 2. Mean values of (a) time elapsed between wilting point (ψ = -1.5 MPa) and dryness (ψ = -25 MPa) called Δt_{total} (from Ojeda *et al.* 2009a) and (b) its corresponding gravimetric water (Δw_{total}) for the different sludge treatments (see Table 1) at sampling time one (T1) and two (T2). Bars with the same letter are not significantly different at p<0.05.

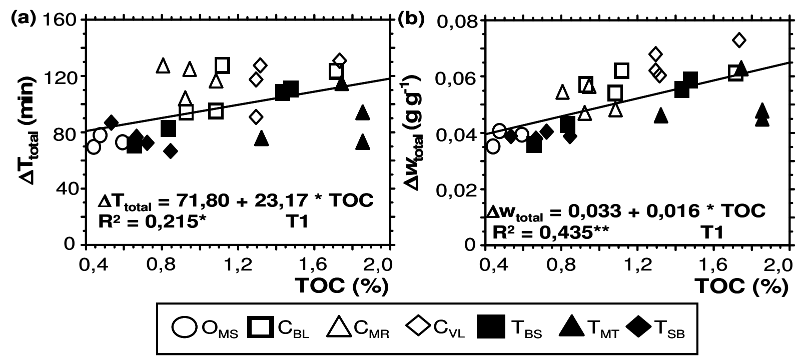

Figure 3. Relationships between total organic carbon (TOC) with (a) water holding time (Δt_{total}) (from Ojeda *et al.* 2009a) and (b) the corresponding gravimetric water (Δw_{total}) for the different sludge treatments (see Table 1) at sampling time T1.

With respect to the relationship between the total organic carbon (TOC) with the water holding time (Δt_{total}) and its corresponding gravimetric water content (Δw_{total}) (Figure 3), it was observed that increases in TOC corresponded with increases in Δt_{total} only at T1 and with Δw_{total} at both samplings. However, the r^2 values suggest that TOC could better explain the increases in Δw_{total} than the increases in Δt_{total}, because not all increments in TOC corresponded with increments in the water holding time. This is possibly due to the fact that sludge organic matter could be hydrophobic.

On the other hand, during wetting and drying processes, water is present in soil at different places e.g. totally filling pore soil, at the asperities of pore walls, in pendular rings between grains, in bridges between grains separated by small gaps, in pore throats between larger pores, or in structures formed by a combination of these water morphologies (Ojeda *et al.* 2009a). Ojeda *et al.* (2009b) observed that during wetting process composted sludges incremented the time required to the same soil to change its water content from dryness (-25 MPa) to wilting point (-1.5 MPa), possibly by low wettability induced by sludge amendments. Thus, it is possible that during drying process, when the water film that links the different water morphologies start to disappear, the isolated soil wet areas could be surrounded by soil dry areas with low wettability in the soil treated with composted sludge, which could reduce the movement of water on soil pores during air drying.

Conclusions

Composted and thermally dried sludges modified the water holding time and the soil water retention. Because of low wettability, composted sludges can increase soil water retention due to restrictions of water movement. Possibly, this is due to the fast drying of surface pores which were initially wetted recovering water repellency during the drying process, thus limiting the water desorption. Thermally dried sludges also increase soil water retention but without increasing the water holding time and in some case, reducing it. In terms of microbial water availability, composted sludge could be more useful as a soil amendment.

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