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SPANISH JOURNAL OF SOIL SCIENCE

Diagnosis of soil hydrophobicity linked to pig slurry use in a calcareous soil

Diagnóstico de la hidrofobicidad del suelo provocada por la fertilización con purines porcinos en un suelo calcáreo
Diagnóstico da hidrofobicidade do solo associada ao uso de chorume de suíno em um solo calcário

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Received: 28.06.2019 | **Revised:** 08.08.2019 | **Accepted:** 28.08.2019

ABSTRACT

Pig slurry fertilization in dryland agriculture of semiarid areas is a matter of concern because of the increasing intensity of livestock farming. Slurry is a nutrient source but if it triggers soil water repellency (SWR), this could constrain its application over the surface in the crop cycle. In SWR tests, choice of a suitable drying soil temperature is a key point, as temperature affects its expression. Its determination must also be easily integrated with the different standard analytical procedures in laboratories. In this study we evaluated the persistence and the severity of the SWR in undisturbed soil samples dried at 40 °C. Soil samples came from a long-term fertilization experiment where five slurry treatments plus a control were implemented. Soil samples were taken seven times during a 51 days (d) period, starting 4 d before slurry application and up to 47 d after. The maximum recorded SWR persistence and severity was classified as *moderate* and *severe*, respectively. As soil dried at 40 °C was able to express hydrophobicity after pig slurry fertilization, the SWR tests can be easily included in the framework of routine procedures for soil sample analysis where this effluent has been applied. Further research is needed in slurry rainfed fertilized areas to evaluate SWR variability (annual and between cropping seasons) and its additional impacts in these agricultural systems.

RESUMEN

En sistemas agrícolas de secano de zonas semiáridas, la fertilización con purines porcinos es un tema de preocupación debido al incremento de la actividad ganadera en estas zonas. Los purines son una fuente de nutrientes, aunque su potencial influencia en el desarrollo de hidrofobicidad en el suelo (SWR) podría limitar su aplicación directa sobre el mismo. En las metodologías de evaluación de la SWR, la temperatura de secado de la muestra es un aspecto clave, ya que la temperatura condiciona el grado o intensidad de su expresión. En este estudio se evaluó la persistencia y la severidad de la SWR en muestras inalteradas de suelo secadas a 40 °C. Las muestras de suelo se obtuvieron de un experimento de fertilización a largo plazo con cinco tratamientos con purines y un tratamiento control. Los tratamientos consistieron en dosis distintas de purines aplicados en pre-siembra y/o en cobertera. Se realizaron siete muestreos durante un periodo de 51 días (d), justo antes de la aplicación de purín en cobertera (4 d) hasta 47 d después. La persistencia y severidad máxima de la SWR registrada se clasificó como moderada *y* severa*, respectivamente. El secado a 40 °C permite detectar la hidrofobicidad asociada a la fertilización con purines, por lo que los test de SWR pueden fácilmente incluirse en los protocolos rutinarios de preparación de muestras para su análisis químico, particularmente, cuando se aplican estos residuos ganaderos. La evaluación de la variabilidad anual e interanual de la SWR en áreas de secano donde se aplican purines requiere de investigación complementaria para evaluar los impactos de esta propiedad del suelo durante el ciclo de cultivo.*

DOI: 10.3232/SJSS.2019.V9.N3.02

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RESUMO

Em sistemas agrícolas de sequeiro de zonas semiáridas, a fertilização com chorumes de suinicultura é tema de preocupação devido ao aumento, nestas zonas, da atividade pecuária. Os chorumes são uma fonte de nutrientes, embora a sua potencial influência no desenvolvimento da hidrofobicidade no solo (SWR) possa aí limitar a sua aplicação direta. Nas metodologias de avaliação da SWR, a escolha da temperatura de secagem da amostra é um fator chave, pois que a temperatura condiciona o grau ou intensidade da sua expressão. Neste estudo, avaliou-se a persistência e severidade da SWR em amostras inalteradas de solo seco a 40 °C. As amostras de solo foram obtidas a partir de um ensaio de fertilização a longo prazo com cinco tratamentos com chorumes e um tratamento controlo. Os tratamentos consistiram em doses diferentes de chorumes aplicados em pré-sementeira e/ou em cobertura. Realizaram-se sete amostragens durante um período de 51 dias (d), começando 4 d antes da aplicação de chorume em cobertura até 47 d depois. A persistência e severidade máxima registada da SWR foi classificada, respetivamente, como moderada e severa. A secagem a 40 ºC permite detetar a hidrofibicidade associada à fertilização com chorumes. Os testes SWR podem ser facilmente incluídos nos protocolos de rotina de preparação das amostras de solo para análise química quando se aplicam estes tipos de efluentes. A avaliação da variabilidade (anual e entre as épocas de cultivo) da SWR em áreas de sequeiro onde se aplicaram chorumes requer investigação complementar para avaliar os impactos desta propriedade do solo nestes sistemas agrícolas.

KEY WORDS
Cereal tillering fertilization, Mediterranean rainfed agriculture, molarity of ethanol droplet test, soil water repellency, water drop penetration time test.

PALABRAS CLAVE
Agricultura mediterránea de secano, fertilización con purines en el ahijado de cereal, repelencia al agua del suelo, test de las gotas de etanol a distinta molaridad, test del tiempo de penetración de la gota de agua.

PALAVRAS-CHAVE
Agricultura mediterrânica de sequeiro, fertilização com chorumes no afilhamento de cereis, repelência à água do solo, teste das gotas de etanol com diferentes molaridades, teste do tempo de penetração da gota de água.

1. Introduction

Slurries are a source of water and nutrients in rainfed agricultural systems (Yagüe et al. 2012) where water availability is the main limiting factor for crop growth. In Mediterranean rainfed winter cereals, under conventional tillage, slurries are applied before sowing and at the tillering development stage (Bosch-Serra et al. 2015).

Despite the yield benefits of slurries (Bosch-Serra et al. 2015) and their favourable influence on soil quality parameters such as soil aggregation (Cosentino et al. 2010; Blanco-Canqui and Ruis 2018), slurries might also have other potential negative impacts over other soil properties, such as the development of soil water repellency (SWR) or hydrophobicity (Jiménez-de-Santiago et al. 2019). Soil water repellency is considered a transient soil property originating from hydrophobic compounds contained in pig slurry (Gigliotti et al. 2002; Leelamanie 2014). Hydrophobicity is an important issue in rainfed agricultural systems as it can reduce plant water availability through a decrease of water infiltration (Wallach et al. 2005). Although the SWR character is normally regarded as transient, some authors working with liquid wastes reported a more prolonged effect with spatial variation (Wallach et al. 2005; Vogeler 2009). Besides, soil hydrophobicity is sensitive to soil moisture content and sample disturbance (Dekker et al. 1998; Doerr et al. 2000).

The Water Drop Penetration Time test (WDPT) and the Molarity of Ethanol Droplet (MED) test (King 1981; Roy and McGill 2002) are the most commonly used methods to assess SWR. The WDPT determines how long water repellency persists in the contact area of a water droplet. The MED test measures how strongly water is repelled (severity). Sample drying before testing is a common practice because the differences in soil moisture content are removed. In a previous study the effect of soil sample sieving and drying temperature (25, 65 and 105 ºC) were tested (Jiménez-de-Santiago et al. 2019), with undisturbed field-moist soil samples being the recommended way to evaluate actual SWR and the potential method being oven-drying samples at 105 °C; disturbance was found to mask repellency. In kaolinite-rich soils SWR can be strengthened after drying at high temperature (Daniel et al. 2019) or masked at low temperature (Dekker et al. 1998) by differences in soil water content. The intermediate temperature of 40 °C can be a plausible alternative to assess soil hydrophobicity as it is used in many laboratories for oven-drying before performing soil tests

(ISO 11464, ISO 2006; Sheppard and Addison 2006; Department of the Environment 2014). Besides, the 30-40 ºC interval of temperature is in the range of those experienced at the soil surface in the field (Sheppard and Addison 2006), mainly in dryland areas where gypsum may be present in soil samples (Porta and Herrero 1990). This temperature also allows the standardizing of soil water content (i.e. mitigating the effect of soil moisture in SWR tests) and it has been previously used in repellency analysis (De Jonge et al. 1999).

In the context of a slurry fertilization experiment in which SWR has previously been assessed (Jiménez-de-Santiago et al. 2019), this work has two aims: a) to evaluate the feasibility to detect SWR (persistence and severity) in 40 ºC oven-dried undisturbed soil samples, and b) to assess the potential interactions of previous slurry applications at cereal sowing on SWR expression at cereal tillering when a second slurry application can be performed.

2. Materials and Methods

2.1. Soil and climate conditions

The experimental field was located in Oliola, Lleida, NE Spain (41º 52" 34'N, 0º 19" 17' E) and is at 440 m a.s.l. The region has a semiarid Mediterranean climate with low annual precipitation and high temperatures in summer. The soil is deep (> 1 m), non-saline, calcareous with a pH of 8.2 (1:2.5 soil: distilled water). Kaolinite is the dominant clay mineral (Bosch-Serra et al. 2017). Soil is classified as a Typic Xerofluvent (Soil Survey Staff 2014).

2.2. Experiment description

A long-term experiment on different pig slurry fertilization strategies was established in 2002. Treatments have been maintained in the same positions on the plots since the start. Winter cereals were cropped on the experimental site, except during the 2007/08 and 2013/14 cropping seasons when soil was left under fallow. The rotation was barley (*Hordeum vulgare* L.) and wheat (*Triticum aestivum* L.) as the main crops, those commonly used in the area. Usually, the crops were sown in late October-early November and harvested at the end of June-early July. The agricultural management practices were those of the farm advisory system for the area.

Sampling and data recording for this present work was performed during the 2014/15 winter barley cropping season, the experiment was performed. Sowing was done on the 30th October 2014 and harvest on the 12th June 2015.

Pig slurry was spread by the splash-plate method before sowing (23th October 2014) and at cereal tillering stage (10th February 2015), (21-24 of Zadoks-Chang-Konzak decimal scale; Zadoks et al. 1974) on the 10th February 2015. Slurry was buried by disc harrowing on the same day after slurry application before sowing but it was left on the soil surface at cereal tillering.

Six treatments from the long-term experiment were selected following a split-block design with three blocks as repetitions (18 sampled plots). The treatments were chosen according to the amount of total organic C (TOC) applied with pig slurries (**Table 1**). At sowing (S-), three of them received slurry from fattening pigs (FP, code S2) and the other three did not (code S0). At cereal tillering (-T), the types of slurry applied were randomized against the block. Slurry from FP (code T4) and slurry from sows (SP, code T8) was topdressing applied at cereal tillering development stage. In the control (code T0), no slurry was applied, only PK mineral fertilization. The amount of slurry applied before sowing and at topdressing on treatments is shown in **Table 1**. TOC from slurries was obtained by combustion (TruSpec CN, LECO instruments). The hydrophobic C compounds from pig slurry were obtained following Gigliotti et al. (2002). The hydrophobic organic C represented 19% and 5% of TOC for FP and SP, respectively.

2.3. Soil water repellency analyses

Soil samples were taken on seven days, starting on the 6th February 2015 and stopped when the canopy fully covered the plot surface. The first soil samples were taken four days before slurry

Table 1. Treatments description according to the rates of pig slurry and total organic carbon (TOC) applied

Slurry origin	Sowing (S)		Tillering (T)	
	Rate (Mg ha^{-1})	TOC (kg ha^{-1})	Rate (Mg ha^{-1})	TOC (kg ha^{-1})
Not applied.	0 (S0)		0 (T0)	
Fattening pigs (FP)	25 (S2)	900	42 (T4)	682
Sows pigs (SP)			76 (T8)	1894

spreading at cereal tillering. Additional samples were taken at 7, 14, 21, 30, 35 and 47 days after pig slurry application. At each sampling date, two superficial soil samples (0-5 cm depth) were taken per plot using steel cylinders of 100 cm^3 (diameter of 5 cm) and samples were maintained undisturbed. To minimize the eventual heterogeneity due to slurry application over plots, soil samples were taken on two theoretical lines avoiding overlaying among samples; 3 m inside each plot and perpendicular to the pig slurry application.

Cylinders were pressed vertically into the soil, then carefully removed to avoid superficial disturbance, packed and closed to maintain field soil moisture content until they arrived at the laboratory.

Soil water repellency was evaluated with the two most common methods (WDPT and MED) for assessing the distribution of persistence and severity (King 1981).

The soil cylinder surface was randomly divided into two areas (defined by a virtual line). Hydrophobicity tests (WDPT and MED) were evaluated after drying the soil for 48 h at 40 ºC in a ventilated oven, followed by 24 h of cooling down using a desiccator. All the tests were done in triplicate in each cylinder, avoiding any superposition between the three droplets. Soil moisture content was obtained by weight difference.

2.4. Statistical analysis

The normal data distribution and homogeneity were assessed. Data (x) from WDPT (n = 18), were normalized using the log(x + 1) transformation. In MED scores, as a discrete value was obtained, the average of the measurements in each cylinder was calculated and used for the analysis, meaning that 6 values were obtained at each sampling time. MED averages had a normal distribution. The differences in SWR between treatments over time were evaluated by ANOVA. Tukey's multiple comparison analysis was performed when the interaction between treatments was statistically significant. If the interaction was not statistically significant, the effect of slurry application at sowing or at tillering on SWR was independently checked according to Duncan's multiple range test (α = 0.05). The statistical analyses were performed with the SAS version 9.4 statistical package (SAS Institute Inc. 2002-2013).

3. Results

Temperature and ETo increased throughout the experimental period (**Figure 1B**). Accordingly, soil water content decreased over time, except at the end of the experiment, after 6 days of brief rainfall (**Figure 1A**).

The methods used allowed us to detect SWR over time in the different fertilization treatments when compared with the control (**Figure 2**). Variability prevents the detection of more precise differences between treatments, although it is inherent to this soil property and to the composition of the organic matter (Hernández et al. 2013; Olorunfemi et al. 2014).

All samples were non-repellent four days before slurry spreading at topdressing and SWR was negligible 47 d after slurry spreading. The control samples remained wettable during the whole experiment (**Figure 2**). Plots receiving only slurry at sowing (S2-T0) still showed at cereal tillering a *low* or a *very low* SWR persistence (**Figure 3**). The

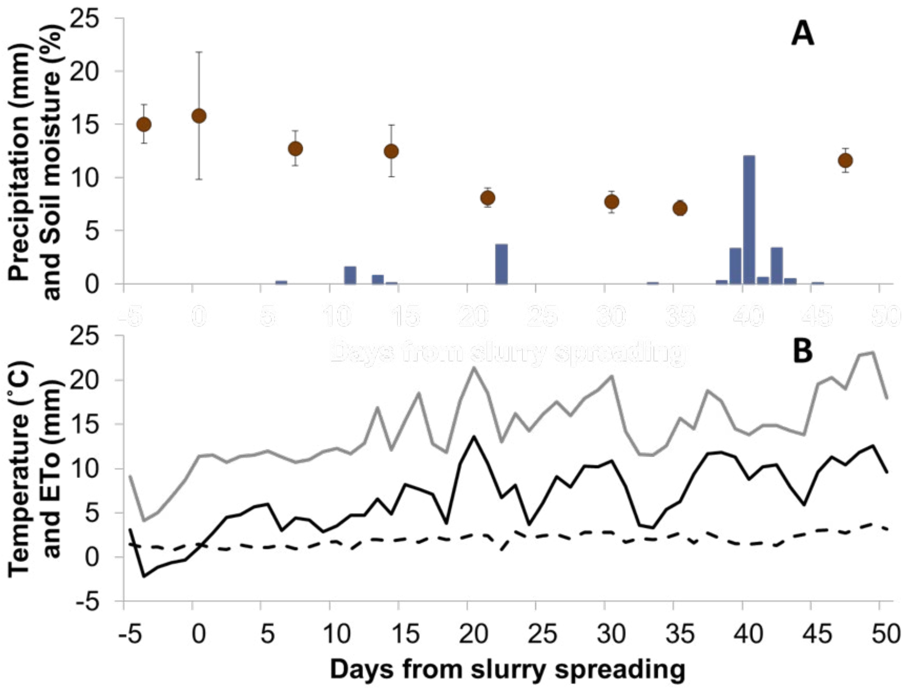

Figure 1. Meteorological and soil conditions over the experimental period. A) Points and bars represent the soil water content (SWC) and the daily precipitation, respectively; standard deviation is included for SWC. B) Daily average evapotranspiration (ETo according to Penman-Monteith equation, dotted line) and daily average (black line) and maximum (grey line).

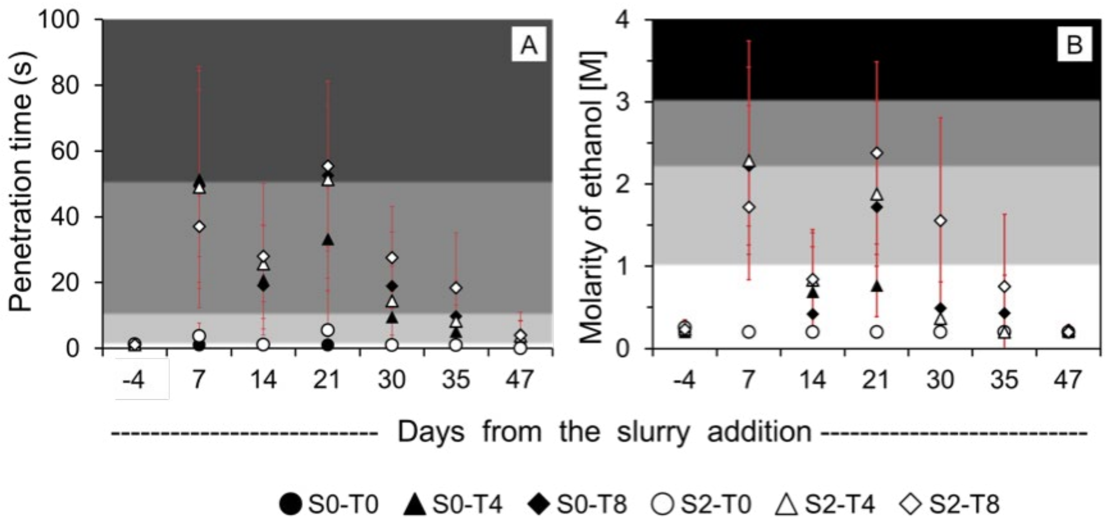

Figure 2. Soil water repellency assessed in different fertilization treatments with the WDPT (persistence, A) and the MED (severity, B) tests at -4, 7, 14, 21, 30, 35 and 47 d from slurry application at cereal tillering stage. Background colors indicate the degree of water repellency according to King (1981). SWR persistence degree: *non-repellent* (white), *very low* (light grey), *low* (grey), *moderate* (dark grey). SWR severity degree: *low* (white), *moderate* (light grey), *severe* (dark grey) and, *very severe* (black). The treatments codes at sowing are: S0, no slurry applied; S2, slurry applied at a rate of 900 kg TOC ha^{-1}. The treatment codes at cereal tillering are: T0, no slurry addition; T4, slurry from fattening pigs (682 kg TOC ha^{-1}); T8, slurry from sows (1894 kg TOC ha^{-1}).

SWR persistence had its maximum expression in treatments S2-T8 and S2-T4 where more than 50% of soil samples showed a *moderate* degree of persistence 21 d after the slurry application, while the severity degree of 75% of samples was included in the *severe* class. However, the SWR persistence expression decreased with time and severity was *low* at the end of the experimental period for all samples. These findings are lower than those reported in the work of Jiménez-de-Santiago et al. (2019). They found the highest persistence only 7 d from slurry spreading with higher values than ours probably due to the higher drying temperatures they used.

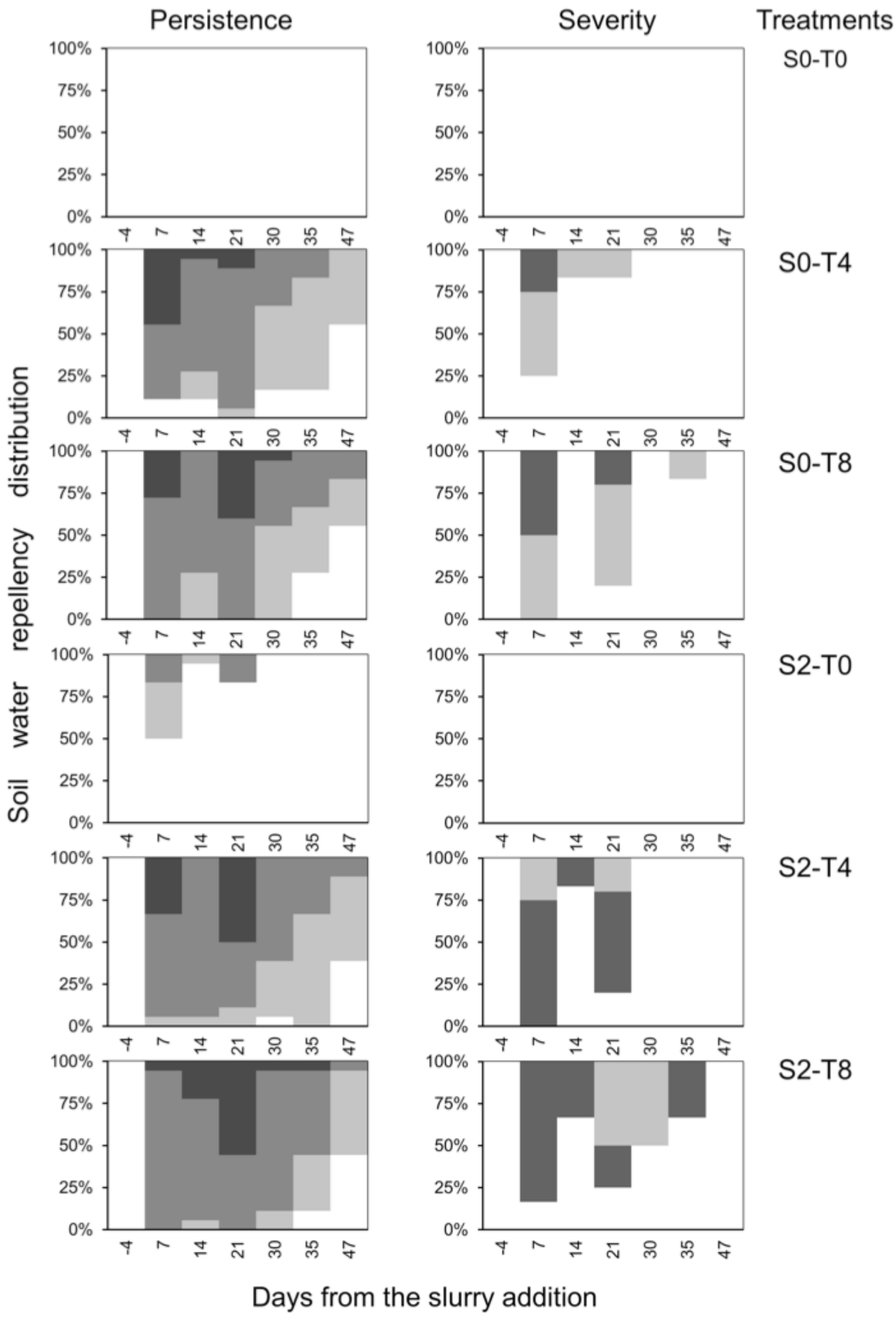

Figure 3. Soil water repellency (SWR) persistence and severity distribution (n = 18) over time. Color bars indicate the degree of water repellency according to King (1981). SWR persistence degrees: *non-repellent* (white), *very low* (light grey), *low* (grey), *moderate* (dark grey). SWR severity degrees: *low* (white), *moderate* (light grey), and *severe* (dark grey). The treatments codes at sowing are: S0, no slurry applied; S2, slurry applied at a rate of 900 kg TOC ha^{-1}. The treatment codes at cereal tillering are: T0, no slurry addition; T4, slurry from fattening pigs (682 kg TOC ha^{-1}); T8, slurry from sows (1894 kg TOC ha^{-1}).

Table 2 and **Table 3** show the results of the ANOVA applied for treatment over time using WDPT and MED methods, respectively. In some sampling dates, slurry application at sowing promoted a greater SWR persistence and severity after topdressing. After 35 d, significant interactions between both slurry application times (S- and T-) were found in SWR persistence (**Table 2**), however these differences were found 21 d to 35 d after tillering slurry application (**Table 3**), both cases with the driest soil conditions (**Figure 1A**). This means that SWR persistence, 35 d after slurry topdressing (T4, T8), was enhanced (**Figure 3**) if a previous application (S2) was performed at sowing. In the rest of samples, persistence of SWR was significantly affected by slurry application at tillering (T-) although it decreased from the initial *moderate-low* degree to a *very low*-degree over the experimental period (**Figure 2A**). This fact was observed whatever the applied rate (**Table 4**) except at the 35 d sampling and was probably linked to the described interaction with slurry applied at sowing (**Table 2**).

Persistence and severity of SWR found in this experiment are lower than those reported under natural conditions in other Mediterranean calcareous soils (Mataix-Solera et al. 2007; Badía et al. 2013; Benito et al. 2019). Despite SWR being a transient effect in the studied soil, our findings are much higher than those reported in other agricultural soils including those with no-tillage (García-Moreno et al. 2013; Cerdà and Doerr 2007; González-Peñaloza et al. 2012). These results highlight the importance of a proper combination between soil management and organic fertilizers that would incorporate hydrophobic organic compounds, as slurries, in dryland environments.

Table 2. ANOVA analysis of the soil water repellency persistence using the water drop penetration time test (normalised data) for treatments where slurry was applied before sowing (SW) or/and at topdressing (TD)

		Mean squares for different sampling days					
	DF	7	14	21	30	35	47
Block	2	0.28*	0.45***	0.07	0.35**	0.47***	0.26*
Block•SW	2	0.08	0.06	1.19***	0.07	0.25**	0.24*
Block•TD	4	0.07	0.22**	0.42**	0.21*	1.35***	0.07
SW•TD	2	0.25	0.07	0.06	0.16	0.19*	0.01
Error	94	0.08	0.06	0.11	0.07	0.04	0.06
SW[a]	1	0.16	0.34	1.12	0.62	0.76	0.03
TD[b]	2	16.24***	11.41**	16.23**	8.89**	3.91	3.55**

DF: degrees of freedom. * Significant at 0.05 probability level. ** Significant at 0.01 probability level. *** Significant at 0.001 probability level. [a] Test of hypothesis using the Block * SW as an error term (split-block design). [b] Test of hypothesis using the Block * TD as an error term (split-block design).

The interaction between slurry applications in MED measurements of the 21, 30 and 35 d sampling (**Table 3**) was indicated by the Tukey test. The later indicates a tendency on the enhancement of severity in T8 rates (30, 35 d) when S2 rate was previously applied at sowing (**Table 5**, **Figure 2**). At the 21 d sampling, severity achieved the maximum expression in treatments including slurry from sows (S0-T8 and S2-T8) probably due the highest TOC rate applied and the interaction was found in T4 (**Table 5**) where severity was enhanced with slurry spreading at sowing (S2).

Table 3. ANOVA analysis of the soil water repellency severity using the molarity ethanol droplet test and for treatments where slurry was applied before sowing (SW) or/and at topdressing (TD)

		Mean squares for different sampling days				
	DF	7	14	21	30	35
Block	2	0.90	0.29	2.75***	0.50	0.57***
Block•SW	2	0.36	0.02	0.36	0.44	0.08
Block•TD	4	1.0	0.367*	1.02***	0.52	0.57***
SW•TD	2	0.20	0.14	0.923**	1.01*	0.10*
Error	22	0.51	0.11	0.16	0.20	0.03
SW[a]	1	0.40	0.32	2.51	1.44	0.10
TD[b]	2	14.11*	1.04	10.58*	2.42	0.62

DF: degrees of freedom. * Significant at 0.05 probability level. ** Significant at 0.01 probability level. *** Significant at 0.001 probability level. [a] Test of hypothesis using the Block * SW as an error term (split-block design). [b] Test of hypothesis using the Block * TD as an error term (split-block design).

Table 4. Tukey multiple comparison analysis for the soil water repellency persistence using the water drop penetration time test (normalised data) 35 d after slurry application at cereal tillering (topdressing)

Treatments	S0-T4	S0-T8	S2-T0	S2-T4	S2-T8
S0-T0	< .0001	< .0001	1.00	< .0001	< .0001
S0-T4		0.27	< .0001	0.01	< .0001
S0-T8			< .0001	0.70	0.004
S2-T0				< .0001	< .0001
S2-T4					0.20

The treatment codes at sowing are: S0, no slurry applied; S2, slurry applied at a rate of 900 kg TOC ha^{-1}. The treatment codes at cereal tillering are: T0, no slurry addition; T4, slurry from fattening pigs (682 kg TOC ha^{-1}); T8, slurry from sows (1894 kg TOC ha^{-1}).

The SWR severity, 7 d from slurry application (Table 6) at topdressing, was significantly higher in treatments receiving slurries (T4, T8) vs. T0 despite differences in organic carbon. The severity degree was classified in all cases (T4, T8) between moderate and severe (Figure 2B). Due to the differences in the amount of TOC applied, the differences in SWR suggest that soil hydrophobicity could be related to the nature of the organic carbon more than to the total amount, as reported in other works (Woche et al. 2005; Hernández et al. 2013).

The results obtained agree in broad terms with previous findings from Jiménez-de-Santiago et al. (2019) when using higher drying temperatures (65 and 105 °C). Although in their work hydrophobicity lasted for a longer period at the highest temperature (105 ºC). The latter was probably linked to its impact over hydrophobic organic compounds which enhanced SWR.

The drying temperature of 40 °C allows detecting SWR differences in slurry fertilized plots at different TOC rates, so it provides a realistic way to perform SWR measurements. Despite the fact that slurry at sowing was applied 16 weeks before sampling, potential interactions between slurry application times were detected at three sampling days (21, 30 and 35 d, Tables 2 and 3). In such cases, the tests were performed on dry field soil samples and slurries had also been dried on the soil surface (21 °C was the maximum temperature for the sampling period, Figure 1B). These results agree with the findings reported by Doerr et al. (2000) who reported the highest persistence in dry soils, which declined as soil moisture increased. The interactions could be related to the entrance of waxy substances from slurries, as lipids, in soil which can coat the soil particles. Despite the dilution effect produced when burying, such substances and the evolution of the TOC applied and the

Table 5. Tukey multiple comparison analysis for soil water repellency severity using the molarity ethanol droplet test 21 d, 30 d and 35 d after slurry application at cereal tillering (topdressing)

Days			21		
Treatments	**S0-T4**	**S0-T8**	**S2-T0**	**S2-T4**	**S2-T8**
S0-T0	0.2	< .0001	1.0	< .0001	< .0001
S0-T4		0.002	0.12	0.001	< .0001
S0-T8			< .0001	1.0	0.3
S2-T0				< .0001	< .0001
S2-T4					0.3
Days			**30**		
Treatments	**S0-T4**	**S0-T8**	**S2-T0**	**S2-T4**	**S2-T8**
S0-T0	1.0	0.9	1.0	1.0	0.0004
S0-T4		0.9	1.0	1.0	0.001
S0-T8			0.9	1.0	0.01
S2-T0				1.0	0.0004
S2-T4					0.002
Days			**35**		
Treatments	**S0-T4**	**S0-T8**	**S2-T0**	**S2-T4**	**S2-T8**
S0-T0	1.0	0.2	1.0	1.0	< .0001
S0-T4		0.2	1.0	1.0	< .0001
S0-T8			0.2	0.2	0.02
S2-T0				1.0	< .0001
S2-T4					< .0001

The treatment codes at sowing are: S0, no slurry applied; S2, slurry applied at a rate of 900 kg TOC ha^{-1}. The treatment codes at cereal tillering are: T0, no slurry addition; T4, slurry from fattening pigs (682 kg TOC ha^{-1}); T8, slurry from sows (1894 kg TOC ha^{-1}).

Table 6. Mean values in different sampling days from the water drop penetration time (WDPT, n = 18) and the molarity of ethanol droplet (MED, n = 6) tests, related to soil water repellency persistence and severity, respectively

	Mean WDPT values (s)										Mean MED values (averaged molarity)	
Treatment	**7 d**		**14 d**		**21 d**		**30 d**		**47 d**		**7 d**	
T0	0.4	B	0.3	B	0.4	B	0.3	B	0.0	B	0.2	B
T4	1.6	A	1.3	A	1.6	A	1.0	A	0.5	A	2.3	A
T8	1.6	A	1.3	A	1.6	A	1.3	A	0.6	A	2.0	A

Letters indicate the treatment grouping obtained from the Duncan's Multiple Range Test. Treatment codes are related to the slurry applied at tillering stage: fattening slurry (T4, 682 kg TOC ha^{-1}), sow slurry (T8, 1894 kg TOC ha^{-1}) and no slurry (T0).

associated microbial activates could enhance water repellency at topdressing when soil dries.

Oven-drying soil samples at 40 °C could be recommended in laboratory practice for SWR assessment in calcareous soils, mainly when it can be easily introduced in the process of sample preparation previous to further chemical analysis. The importance of SWR development related to the addition of organic materials such as those contained in wastewater (Abegunrin et al. 2016; Bodí et al. 2012) or organic fertilizers

(Blanco-Canqui and Ruis 2018) need to be further investigated in soils with no-tillage, as it has been widely reported that this management practice enhances the SWR (García-Moreno et al. 2013; Blanco-Canqui and Ruis 2018) even in calcareous soils (González-Peñaloza et al. 2012), due to the SOM accumulation near the soil surface, reducing soil mixing, and increasing biological activity.

Furthermore, the SWR is remarkable in the context of climate change as the repellency issue will gain importance. It is forecast that increasing temperatures combined with low soil water content will promote SWR (Goebel et al. 2011). Thus, the demand for this type of diagnostic analysis will increase as hydrophobicity retards or prevents water infiltration and thereby increase the risk of water erosion on slope sites.

4. Conclusions

Soil water repellency tests (persistence and severity) applied over soil dried at 40 ºC established differences between soils receiving slurry fertilizers and non-slurry fertilizers. This drying temperature detected the effect of previous slurry applications at sowing when TOC slurry rates increased at topdressing of winter cereals. Differences in persistence (higher in plots receiving slurries) were maintained for 47 d after slurry spreading while differences in severity (also higher with slurries) disappeared at the last sampling time. The SWR associated with surface pig slurry application at cereal tillering could be defined as a transient effect, as our results indicated that pig slurry applied and buried at sowing enhanced the degree of SWR expression of slurries at topdressing. Further research is needed to elucidate the effect of slurry TOC rate and its nature on SWR.

5. Acknowledgements

This study was supported by the Spanish Ministry of Economy and Competitiveness and the Spanish National Institute for Agricultural Research and Experimentation (MINECO-INIA) through the project RTA2017-88-C3-3. Diana E. Jiménez de Santiago acknowledges Bank of Santander-University of Lleida for funding her PhD studies through the JADE-Plus scholarship. We wish to express our thanks to Josep Llop, Belén Martínez, and Noemí Mateo for field assistance.

REFERENCES

• Abegunrin TP, Awe GO, Idowua DO, Adejumobi MA. 2016. Impact of wastewater irrigation on soil physico-chemical properties, growth and water use pattern of two indigenous vegetables in southwest Nigeria. Catena 139:167-178. http://dx.doi.org/10.1016/j.catena.2015.12.014.

• Badía D, Aguirre JA, Martí C, Márquez MA. 2013. Sieving effect on the intensity and persistence of water repellency at different soil depths and soil types from NE Spain. Catena 108:44-49. https://doi.org/10.1016/j.catena.2012.02.003.

• Benito E, Varela E, Rodríguez-Alleres M. 2019. Persistence of water repellency in coarse-textured soils under various types of forests in NW Spain. J Hydrol Hydromech. 67(2):129-134. doi: 10.2478/johh-2018-0038.

• Blanco-Canqui H, Ruis SJ. 2018. No-tillage and soil physical environment. Geoderma 326:164-200. https://doi.org/10.1016/j.geoderma.2018.03.011.

• Bodí MB, Cerdà A, Mataix-Solera J, Doerr SH. 2012. Water repellent soils affected by fires and agricultural soils with different agricultural management and abandonment. Cuadernos de investigación geográfica 38(2):53-74.

• Bosch-Serra ÀD, Ortiz C, Yagüe MR, Boixadera J. 2015. Strategies to optimize nitrogen efficiency when fertilizing with pig slurries in dryland agricultural systems. Eur J Agron. 67:27-36. https://doi.org/10.1016/j.eja.2015.03.003.

• Bosch-Serra ÀD, Yagüe MR, Poch RM, Molner M, Junyent B, Boixadera J. 2017. Aggregate strength in calcareous soil fertilized with pig slurries. Eur J Soil Sci. 68(4):449-461. https://doi.org/10.1111/ejss.12438.

• Cerdà A, Doerr SH. 2007. Soil wettability, runoff and erodibility of major dry-Mediterranean and use types on calcareous soils. Hydrol Process. 21:2325-2336. https://doi.org/10.1002/hyp.6755.

• Cosentino D, Hallett PD, Michel JC, Chenu C. 2010. Do different methods for measuring the hydrophobicity of soil aggregates give the same trends in soil amended with residue? Geoderma 159:221-227. https://doi.org/10.1016/j.geoderma.2010.07.015.

• Daniel NRR, Mijan Uddin SM, Harper RJ, Henrya DJ. 2019. Soil water repellency: A molecular-level perspective of a global environmental phenomenon. Geoderma 338:56-66. doi: https://doi.org/10.1016/j.geoderma.2018.11.039.

• De Jonge LW, Jacobsen OH, Moldrup P. 1999. Soil water repellency: effects of water content, temperature, and particle size. Soil Sci Soc Am J. 63:437-442. doi: 10.2136/sssaj1999.03615995006300030003x.

• Dekker LW, Ritsema CJ, Oostindie K, Boersma OH. 1998. Effect of drying temperature on the severity of soil water repellency. Soil Sci. 163:780-796. https://doi.org/10.1097/00010694-199810000-00002.

• Department of the Environment. 2014. Carbon Farming Initiative, Soil Sampling and Analysis Method and Guidelines. Available from: https://www.environment.gov.au/system/files/pages/b341ae7a-5ddf-4725-a3fe-1b17ead2fa8a/files/cfi-soil-sampling-and-analysis-method-and-guidelines.pdf [accessed 27 June 2019].

• Doerr SH, Shakesby RA, Walsh RPD. 2000. Soil water repellency: Its causes, characteristics and hydro-geomorphological significance. Earth Sci Rev. 51:33-65. https://doi.org/10.1016/S0012-8252(00)00011-8.

• García-Moreno J, Gordillo-Rivero AJ, Zavala LM, Jordán A, Pereira P. 2013. Mulch application in fruit orchards increases the persistence of soil water repellency during a 15-years period. Soil Till Res. 130:62-68. http://dx.doi.org/10.1016/j.still.2013.02.004.

• Gigliotti G, Kaiser K, Guggenberger G, Haumaier L. 2002. Differences in the chemical composition of dissolved organic matter from waste material of different sources. Biol Fertil Soils 36:321-329. https://doi.org/10.1007/s00374-002-0551-8

• Goebel MO, Bachmann J, Reichstein M, Janssens IA, Guggenberger G. 2011. Soil water repellency and its implications for organic matter decomposition – is there a link to extreme climatic events? Global Change Biol. 17:2640-2656. doi: 10.1111/j.1365-2486.2011.02414.x.

• González-Peñaloza FA, Cerdà A, Zavala LM, Jordán A, Giménez-Morera A, Arcenegui V. 2012. Do conservative agriculture practices increase soil water repellency? A case study in citrus-cropped soils. Soil Till Res. 124:233-239. http://dx.doi.org/10.1016/j.still.2012.06.015.

• Hernández A, Arbelo-Rodríguez CD, Rodríguez N, Notario del Pino J, del Arco M, Rodríguez-Rodríguez A. 2013. Effects of a Canary pine forest wildfire (Tenerife, Canary Islands, summer 2007) on selected soil properties and their relationship with short- to medium-term soil water repellency. Span J Soil Sci. 3(1):56-72. doi: 10.3232/SJSS.2013.V3.N1.04.

• ISO. 2006. Soil quality. Pretreatment of samples for physic-chemical analyses. Second Ed. ISO 11464:2006(E). Switzerland: ISO.

• Jiménez-de-Santiago DE, Yagüe MR, Bosch-Serra ÀD. 2019. Soil water repellency after slurry fertilization in a dryland agricultural system. Catena 174:536-545. https://doi.org/10.1016/j.catena.2018.11.040.

• King PM. 1981. Comparison of methods for measuring severity of water repellence of sandy soils and assessment of some factors that affect its measurement. Am J Soil Res. 19:275-285. https://doi.org/10.1071/SR9810275

• Leelamanie DAL. 2014. Initial water repellency affected organic matter depletion rates of manure amended soils in Sri Lanka. J Hydrol Hydromech. 62(4):309-15. https://doi.org/10.2478/johh-2014-0040.

• Mataix-Solera J, Arcenegui V, Guerrero C, Mayoral AM, Morales J, González J, García-Orenes F, Gómez I. 2007. Water repellency under different plant species in a calcareous forest soil in a semiarid Mediterranean environment. Hydrol Process. 21:2300-2309. doi: 10.1002/hyp.6750.

• Olorunfemi IE, Ogunrinde TA, Fasinmirin JT. 2014. Soil hydrophobicity: An overview. Journal of Scientific Research & Reports 3:1-35.

• Porta J, Herrero J. 1990. Micromorphology and Genesis of Soils Enriched with Gypsum. Developments in Soil Science 19:321-339. https://doi.org/10.1016/S0166-2481(08)70344-1.

• Roy JL, McGill WB. 2002. Assessing soil water repellency using the molarity of ethanol droplet (MED) test. Soil Sci. 167:83-97. doi: 10.1097/00010694-200202000-00001.

• SAS Institute Inc. 2002-2013. SAS/TAT. Software v 9.4. SAS Institute, Cary, NC.

• Sheppard SC, Addison JA. 2006. Soil sample handling and storage. In: Carter MR, Gregorich EG, editors. Soil sampling and methods of analysis. 2nd edition. Boca Raton, FL, USA: CRC Press, Taylor & Francis Group.

• Soil Survey Staff. 2014. Keys to Soil Taxonomy, 12th ed. Washington, DC: USDA-Natural Resources Conservation Service.

• Vogeler I. 2009. Effect of long-term wastewater application on physical soil properties. Water Air Soil Pollut. 196:385-392. doi: 10.1007/s11270-008-9785-x.

• Wallach R, Ben-Arie O, Graber ER. 2005. Soil water repellency induced by long-term irrigation with treated sewage effluent. J Environ Qual. 34:1910. https://doi.org/10.2134/jeq2005.0073.

• Woche SK, Goebel M, Kirkham MB, Horton R, Van der Ploeg RR, Bachmann J. 2005. Contact angle of soils as affected by depth, texture, and land management. Eur J Soil Sci. 56:239-251. https://doi.org/10.1111/j.1365-2389.2004.00664.x

• Yagüe MR, Bosch-Serra ÀD, Boixadera J. 2012. Measurement and estimation of the fertiliser value of pig slurry by physicochemical models: Usefulness and constraints. Biosyst Eng. 111:206-216. https://doi.org/10.1016/j.biosystemseng.2011.11.013.

• Zadoks JC, Chang TT, Konzak CF. 1974. A decimal code for the growth stages of cereals. Weed Res. 14:415-421. https://doi.org/10.1111/j.1365-3180.1974.tb01084.x