Long-term fertilization with dairy cattle slurry in intensive production systems: effects on soil porosity and pore morphology

Fertilización a largo plazo con purín de vaca lechera: efectos sobre la porosidad del suelo y la morfología de poros

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Abstract

In Mediterranean environments, livestock effluents might improve soil physical properties. The study was located in an intensive crop production system of northwest Spain. After nine consecutive years of dairy cattle slurry (DCS) use as fertilizer, the aim of the experiment was to evaluate the impacts of DCS on soil porosity and pore shape. Soil texture was loam. The applied DCS rates were equivalent to 170 and 250 kg N ha^{-1} (170DCS and 250DCS, respectively) and they were complemented with mineral N up to 450 kg N ha^{-1} (two crops). A nonfertilized control was included. Digital binary images were obtained from soil thin sections. Pores with an apparent diameter (AD) >30 µm were analysed. The 250DCS treatment improved soil porosity (>30 µm): it doubled in comparison with the 170DCS and the control. The application of DCS favored the presence of pores with an AD >400 µm, the roughness for AD >100 µm and the elongation in the AD interval of 100-200 µm. From the study, the 250DCS treatment is recommended as it increases macroporosity (compaction reduction) and produces more elongated and tortuous pores, which will be a constraint for fast drainage but it will be advantageous in coarse textured soils.

Keywords
double-cropping • organic fertilizer • soil pore shapes • micromorphology of pores

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Resumen

En zonas Mediterráneas del noroeste español bajo producción intensiva, la aplicación de deyecciones ganaderas podría mejorar las propiedades físicas del suelo. Tras nueve años de fertilización con purín de vacas lecheras (DCS), se planteó evaluar los efectos del DCS sobre la porosidad edáfica y la morfología de los poros. La clase de familia textural era franca gruesa. Las dos dosis de DCS evaluadas equivalían a 170 y 250 kg N ha^{-1} (170DCS y 250DCS, respectivamente) y se complementaban con N mineral hasta 450 kg N ha^{-1} (dos cultivos). Se incluyó un control, sin fertilización. A partir de láminas delgadas de suelo se obtuvieron imágenes digitales binarizadas. Se analizaron los poros de diámetro aparente (AD) >30 μm. El tratamiento 250DCS duplicó la porosidad (>30 μm) respecto a 170DCS y el control. La aplicación de DCS favoreció la presencia de AD >400 μm, la rugosidad para AD >100 μm y la elongación de poros en el rango 100−200 μm. La dosis de 250DCS es recomendable al incrementar la macroporosidad (implica una disminución de la compactación) y favorecer unas formas de poros más alargadas, con mayor tortuosidad, que dificultarían el drenaje rápido, lo cual es beneficioso en suelos con contenido importante de arena.

Palabras clave
doble cultivo • fertilizantes orgánicos • forma de poros edáficos • micromorfología de poros

Introduction

The intensification of forage production by means of double-annual cropping, is linked with a dynamic agricultural system that enhances the circular economy, since the plant biomass harvested becomes livestock feed, and the animal excrements are used to cover the nutrient demands of the forage crops (14, 16, 34).

In the European Union areas which have been designated as vulnerable to contamination of subsurface waters by nitrates, the application of N from organic sources is limited to 170 kg N ha^{-1} $year^{-1}$ (Directive 91/676/EEC) (9), although the rates applied can be complemented with mineral N. This regulation covers the N demand of many annual crops. However, in a double-annual cropping system, the application of 250 kg N ha^{-1} $year^{-1}$ from livestock excrements (manures and slurries) is an alternative to maintain high forage yields while saving expenses on additional mineral N (3, 32, 33).

Furthermore, organic fertilizers introduce organic matter (OM) into the soil, which is especially needed in Mediterranean climates where soils are characterized by their low levels of OM (17).

In the European Union, the Common Agricultural Policy includes "conditionality" in order to maintain the potential productivity of land resources and prevent soil degradation (10).

Conditionally is a set of legally defined good agricultural and environmental practices that farmers, who receive direct (or for rural development) subsidies, are obliged to implement. These requirements include the maintenance of soil OM, an objective which is significantly covered by the use of livestock waste in fertilization schedules.

The addition of OM affects soil physical properties such as porosity (23). In addition, porosity affects soil ecosystem services (1). Thus, porosity becomes an indicator of the sustainability of a specific agricultural management method.

The characteristics of the soil porous system have a direct relationship: (i) with the retention and movement of water and gases (18), (ii) with biological and chemical properties (31), (iii) with erosion risks and sediment transport, including contaminants (36), and (iv) with the development of the plant root system (28). In addition, the soil porous system is sensitive, mainly through macroporosity (30, 45), to changes induced by agricultural activities such as tillage, irrigation or fertilization. Nevertheless, the assessment of impacts on porosity requires knowledge of how it is distributed (range of apparent diameters (AD) and their shape).

The use of micromorphological techniques allows the study of macroporosity (>60 μm) in soil thin sections (19) and even the mesoporosity which, in this study, is associated with AD between 30 and 60 μm.

The double-annual forage cropping system increases machinery traffic over soil in comparison with a single annual crop system. Harvesting implies the carrying off of a substantial weight of fresh plant material, which is maximized when two cuts per crop are done (*e.g.* ryegrass).

The traffic over the soil surface can cause compaction (6, 35) and a decrease of soil porosity. In these intensive Mediterranean systems, there is only limited information available about the effect of organic fertilizers on macroporosity, since research has been mainly focused on cereal agricultural systems (5, 44) or on annual rotations (8) where pig slurry and cattle manure are used as fertilizers.

The hypothesis of this research is that the application of dairy cattle slurry (DCS) influences soil physical fertility. The study is carried out in the framework of a long-term experiment (2008-2016), under a dry Mediterranean climate. The main objective was to assess the effects of DCS, applied at different rates, on soil porosity and pore morphology.

Materials and methods

A fertilization experiment was established in 2008 in the Tallada d'Empordà, Girona, NE of Spain (altitude 18 m a. s. l., 42°03'02" N, 03°03'37" E) and was maintained for nine years (until 2016). The current study was conducted at the end of the 2016 cropping season.

Soil and climatic characteristics

The soil was classified as Oxiaquic Xerofluvent (42) and the family particle-size class was coarse-loamy. The surface soil horizon (0-0.30 m) had a loam texture (485 g sand kg^{-1}, 405 g silt kg^{-1} and 110 g clay kg^{-1}), a pH (potentiometry, water 1:2,5; w:v) of 8.2, an electrical conductivity (1:5, 25°C, w:v) of 0.18 dS m^{-1}, an organic matter content (Walkley-Black method) of 18 g kg^{-1} and 140 g kg^{-1} of equivalent calcium carbonate (Bernard's calcimeter method).

The area has a dry Mediterranean climate according to Papadakis classification (20). During the 2008-2016 period, the average annual temperature was 14.8°C, with a maximum daily average of 23.4°C registered in July, and a minimum daily average of 7.9°C registered in January.

The average annual precipitation and evapotranspiration (2) in the period 2008-2016 were 608 and 986 mm, respectively.

Experimental context

During the 2008-2013 period, a double-annual crop forage rotation: maize (*Zea mays* L.)-ryegrass (*Lolium multiflorum* L.) was established. Forage maize was sown in spring (May) and it was harvested in autumn (September) at the doughy grain stage. Ryegrass was sown in autumn (September) and it was harvested at maximum biomass before coming into ears, first harvest was done in March and last harvest in May (38).

In the 2013-2016 period, after the maize harvest, the rotation was modified and it included: rapeseed (*Brassica napus* L.) -grain maize (short cycle)-grain maize (long cycle)-rapeseed, which means four crops in three years. Rapeseed was sown in autumn (September) and it was harvested in June. Grain maize was sown in spring: (June, short cycle; April, long cycle) and it was harvested in October. Maize was irrigated (sprinkler system) during the spring-summer period and the rest of the crops were not irrigated. Stubble of rapeseed and maize (grain) was incorporated into the soil but the rest (stalks) was removed. Main tillage before sowing was done with a mouldboard or a disc harrow (~0.25 m deep).

The fertilization trial was designed as a randomized block, with three treatments and three repetitions per treatment (blocks). The plot surface area was 40 m^2 (5 m x 8 m).

The treatments were: one control (without fertilizer) and two rates of DCS. The rates (± standard deviation) of DCS were 52 (± 10) and 77 (± 14) m^3 ha^{-1}. These rates contributed to 170 and 250 kg N ha^{-1}, and they were distributed between two successive crops, prior to spring and autumn sowings (170DCS: 100 and 70 kg N ha^{-1}; 250DCS: 150 and 100 kg N ha^{-1}, respectively). The treatments with DCM were complemented in each rotation of two crops, with mineral N as topdressing (calcium ammonium nitrate, 27%) up to a total of 450 kg N ha^{-1} for spring and autumn sowings (170DCS: 200 and 80 kg N ha^{-1}; 250DCS: 150 and 50 kg N ha^{-1}, respectively).

The exception was the 2014-2015 cropping season where a summer crop (maize) was followed by a summer crop (maize) but the fertilization schedule for summer crops was maintained.

Previous to each application, a DCS sample was analysed. For the 2003-2016 period, the mean values (n = 15) of the DCS evaluated parameters were: pH of 8.4 (± 0.5) by potentiometry (1:5, soil:water), electrical conductivity (1: 5, soil: water, at 25°C) 4.6 (± 2.7) dS m^{-1}, dry matter of 8.7% (± 2.9) over fresh matter (by gravimetry at 105°C) and 75.7% (± 5.0) of OM over dry matter (by ignition at 550°C). Thus, during the 2008-2016 period, prior soil samplings, the 170DCS and 250 DCS plots have received an average amount of 25.4 Mg OM (dry) ha^{-1} and 37.6 Mg OM (dry) ha^{-1}, respectively.

There were no significant differences between yields associated with the evaluated DCS treatments (data not shown) and yields in the control were 36% lower (as an average). In DCS treatments, the average forage yield as ryegrass (two cuts/cycle) and maize were 10 and 21 Mg dry matter ha^{-1} (drying at 65°C), respectively; the grain yield average of rapeseed was of 2 Mg ha^{-1} (9% moisture content) and the grain yield average of maize was 10 and 15 Mg ha^{-1} (14% moisture content) for the short and long cycles, respectively.

Soil sampling and soil porosity analysis: pore-size distribution and shape

In June 2016 (~ eight months after the last DCS application), after the winter crop (rapeseed) harvest, rectangular blocks (depth 0.06 m, 0.09 m wide and 0.20 m long) of undisturbed soil samples (n = 9) were obtained from each treatment.

The blocks were dried at room temperature and impregnated with polyester resin with fluorescent dye (Uvitex ©). One vertical thin section (0.05 m wide, 0.13 m long) was made from each block according to the procedures described by Benyarku and Stoops (2005). From each thin section, two images (42 mm long x 31.5 mm wide) were obtained under two light scenarios: parallel polarized and crossed polarized. Cross polarized images were processed with the Olympus Stream program (26) to obtain digital binary images. These images were used to analyse total porosity, which included pores with an apparent diameter (AD) >30 μm (the minimum threshold for the established procedure). From each image, the analysis of pore-size distribution was based on an open mathematical algorithm: the Quantim4 library program (43).

The area occupied by pores was divided into five intervals according to the pores' AD: 30-60 μm, 60-100 μm, 100-200 μm, 200-400 μm and >400 μm. The pore shape, when its AD was >60 μm, was analysed by means of four descriptors according to Ferreira and Rasband (2012): circularity, aspect ratio (AR), roundness (R) and solidity (S).

The circularity [4π*(pore area)/(pore perimeter)^2] indicates a perfect circle when it reaches the value of 1. The AR or the ratio of the ellipse adjusted to the pore (major axis/minor axis) is an index that describes the pore elongation, so that at higher values, the pores are more elongated. The roundness [4*(pore area)/(π*(major axis)^2)] indicates whether the pore has rounded (leading to 1) or angled (leading to 0) edges. The solidity (area of the pore/convex area of the pore) assesses the roughness, irregularity and tortuosity of the pore walls (high values correspond to smooth pores and low ones to rough pores).

Statistical analysis

Statistical analyses were performed using the SAS program (33). The analysis of variance (ANOVA) was carried out after verifying the assumptions of normality and homogeneity of variances. Porosity percentages between 200-400 μm and >400 μm, were normalized by the square root transformation and for the range 30-60 μm they could not be normalized.

The solidity data in the 60-100 μm range could also not to be normalized. When the analysis detected significant differences, the means were compared by the Least Significant Difference (LSD) test, at the 0.05 probability level.

Results

The different fertilizer treatments had a significant influence on the porous area (pores with AD >30 μm) and on their distribution in the different ranges (table 1, page 253). The porosity in 250DCS (25.6%) significantly increased (nearly doubled) when comparing with the control and 170DCS (table 2, page 253). Differences were maintained in three different AD ranges of pores: 60-100 μm, 100-200 μm and 200-400 μm (table 2, page 253).

Table 1. Analysis of variance (DF= degrees of freedom, MS= mean squares, *P*= probability value) of the porosity (>30 μm) and their pore apparent diameter (AD) distribution (%) according to the fertilization treatments (TR).

Tabla 1. Análisis de varianza (DF= grados de libertad, MS= cuadrados medios, *P*= valor de probabilidad) de la porosidad (>30 μm) y distribución (%) del diámetro aparente (AD) de poros[a] en distintos rangos para los tratamientos (TR) de fertilización.

Pore-size (AD)[a]		**>30 μm**		**60-100 μm**		**100-200 μm**	
Source	DF	MS	*P*	MS	*P*	MS	*P*
Between TR	2	311.91	<0.0001	5.22	0.0003	35.31	0.0002
Between blocks	2	55.77	0.002	0.28	0.37	5.66	0.07
Between samples of TR	3	20.85	0.03	0.25	0.43	1.11	0.59
Within samples (residual)	10	4.64		0.25		1.64	

Pore-size (AD)[a]		**200-400 μm**		**>400 μm**	
Source	DF	MS	*P*	MS	*P*
Between TR	2	1.88	<0.0001	2.25	<0.0001
Between blocks	2	0.56	0.004	0.36	0.04
Between samples of TR	3	0.06	0.44	0.43	0.02
Within samples (residual)	10	0.06		0.08	

[a] The percentage pores with an AD between 30-60 μm could not be normalized.

[a] No se pudo normalizar el porcentaje poros de AD entre 30-60 μm.

Table 2. Average porosity (>30 μm) values (%) [a] (n=6) and its distribution in different pore apparent diameter ranges [b] for each fertilization treatment [c].

Tabla 2. Valores medios [a] (n=6) de porosidad (>30 μm) y de su distribución (%) en diferentes rangos de diámetros aparentes de poros [b] para cada tratamiento de fertilización [c].

Treatments	**Porosity (%)**	**Porosity distribution (%)**				
	>30 μm	**30-60 μm**	**60-100 μm**	**100-200 μm**	**200-400 μm**	**>400 μm**
Control	12.2 B	1.67	3.29 B	4.65 B	2.14 (1.40)B	0.44 (0.60)C
170DCS	14.1 B	2.29	3.65 B	4.06 B	2.26 (1.47)B	2.16 (1.42)B
250DCS	25.6 A	2.78	5.05 A	8.53 A	5.85 (2.40)A	3.43 (1.80)A

[a] Numbers in brackets are $x^{0.5}$ transformed values. Mean values in columns followed by different letters are significantly different according to the LSD test at 0.05 probability level.

[b] The 30-60 μm diameter interval does not fit the normal assumption for ANOVA.

[c] Treatments: control (without N) and dairy cattle slurry fertilization (DCS) where numbers indicate the N applied rates of 170 or 250 kg ha^{-1} $year^{-1}$.

[a] Los números entre paréntesis son los valores medios transformados mediante la raíz cuadrada. Los valores medios en las columnas seguidos de diferentes letras son significativamente diferentes en base a la mínima diferencia significativa.

[b] No se pudo normalizar el porcentaje de los poros con diámetro aparente entre 30-60 μm.

[c] Tratamientos: control (sin aporte de N) y fertilización con purín bovino de leche (DCS) donde los números asociados indican las dosis de N aplicado 170 o 250 kg N ha^{-1} $año^{-1}$.

The control and 170DCS only significantly differed in the range of AD of pores greater than 400 μm, where 170DCS had a higher percentage (table 2, page 253). These porosity differences between treatments were also qualitatively observed in the images from thin soil sections (figure 1, page 255).

The evaluated pore shape descriptors showed significant differences (table 3).

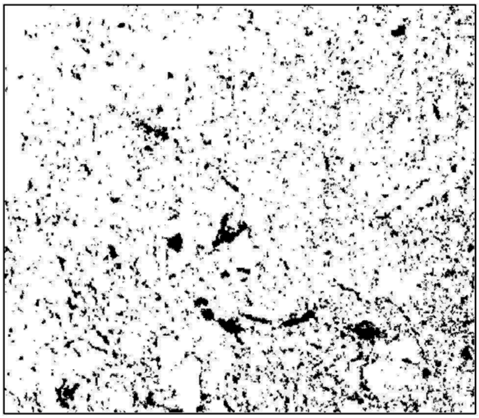
Table 3. Analysis of variance (DF= degrees of freedom, MS= mean square, *P*= probability value) of different shape descriptors for each fertilization treatment (TR) and for the different ranges of pore apparent diameters (AD).
Tabla 3. Análisis de varianza (DF= grados de libertad. MS= cuadrados medios. *P*= valor de probabilidad) para los diferentes descriptores de forma de los poros para los diferentes rangos de diámetro aparente (AD) de poros y tratamiento de fertilización (TR).

Pore-size (AD)	**Shape pore descriptors**		**Circularity**		**Solidity**[a]		**Aspect ratio**		**Roundness**	
	Source	DF	MS	*P*	MS	*P*	MS	*P*	MS	*P*
60-100 μm	Between TR	2	0.001	0.07	-	-	0.026	0.05	0.004	0.04
	Between blocks	2	$1.2E^{-4}$	0.75	-	-	0.002	0.77	$2.4E^{-4}$	0.79
	Between samples of TR	3	$4.0E^{-4}$	0.42	-	-	0.004	0.62	$5.4E^{-4}$	0.66
	Within samples (residual)	10	$4.0E^{-4}$		-		0.007		$9.9E^{-4}$	
100-200 μm	Between TR	2	0.004	0.05	$5.4E^{-4}$	0.02	0.032	0.01	0.003	0.02
	Between blocks	2	$1.0E^{-4}$	0.89	$5.6E^{-6}$	0.94	$5.1E^{-4}$	0.90	$5.6E^{-6}$	0.99
	Between samples of TR	3	$4.1E^{-4}$	0.70	$9.4E^{-5}$	0.42	0.004	0.50	$3.0E^{-4}$	0.61
	Within samples (residual)	10	$8.7E^{-4}$		$9.2E^{-5}$		0.005		$4.7E^{-4}$	
200-400 μm	Between TR	2	0.007	0.006	0.003	0.008	0.013	0.21	$5.4E^{-4}$	0.22
	Between blocks	2	$1.4E^{-4}$	0.84	$7.2E^{-5}$	0.81	0.009	0.34	$2.7E^{-4}$	0.44
	Between samples of TR	3	$7.7E^{-4}$	0.45	$2.3E^{-4}$	0.59	0.002	0.86	$7.2E^{-5}$	0.87
	Within samples (residual)	10	$8.1E^{-4}$		3.4^{-4}		0.007		$3.1E^{-4}$	
>400 μm	Between TR	2	0.005	0.002	0.004	0.003	0.029	0.07	$6.5E^{-4}$	0.07
	Between blocks	2	$7.1E^{-4}$	0.26	$9.3E^{-4}$	0.12	0.013	0.26	$4.2E^{-4}$	0.16
	Between samples of TR	3	$2.7E^{-4}$	0.63	$1.4E^{-4}$	0.76	0.002	0.86	$1.9E^{-4}$	0.44
	Within samples (residual)	10	$4.6E^{-4}$		$3.5E^{-4}$		0.009		$1.9E^{-4}$	

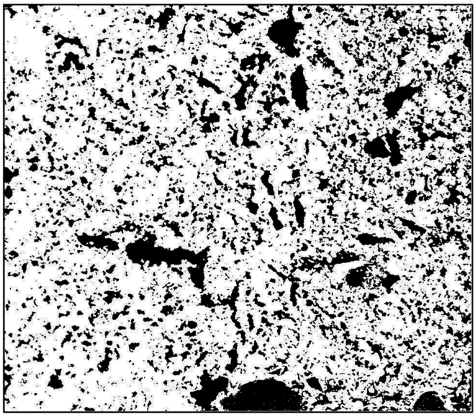
[a] The solidity values for pores with an AD between 60-100 μm have not been normalized.

[a] No se pudo normalizar los valores de solidez de los poros de AD entre 60-100 μm.

Control



250DCS



170DCS

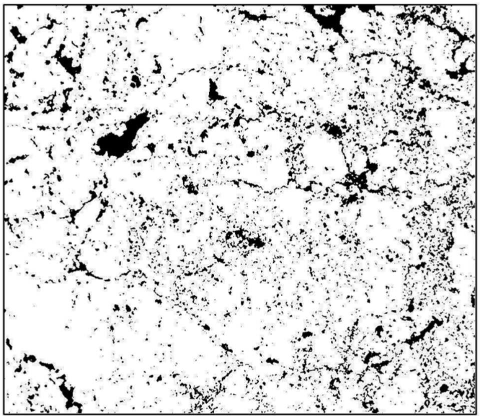


Figure 1. Porosity images (black color) from thin sections, vertically orientated from the soil surface, and for the different fertilizer treatments: Control (without slurry addition), dairy cattle slurry at a rate of 170 kg N ha^{-1} (170DCS) or 250 kg N ha^{-1} (250DCS). Image size was 42.0 mm long and 31.5 mm width.

Figura 1. Imágenes de porosidad del suelo (en negro) obtenidas a partir de láminas orientadas verticalmente desde la superficie del mismo y asociadas a diferentes tratamientos de fertilización: control (sin aporte de purín) y con aporte de purín de vaca lechera (DCS) aplicado a dosis de 170 kg N ha^{-1} (170DCS) o 250 kg N ha^{-1} (250DCS). El tamaño de cada imagen es de 42,0 mm de largo y 31,5 mm de ancho.

The application of DCS led to decreases in the solidity in pores with an AD greater than 100 μm; the circularity was also reduced but only above AD of 200 μm, while the roundness decreased in the pore range from 60 to 200 μm (table 4, page 256).

Finally, when DCS was applied, the aspect ratio (AR) increased in the AD pore range of 100-200 μm (table 4, page 256).

Table 4. Average values [a] of the pore shape descriptors for each fertilization treatment [b] and for the different ranges of apparent pore diameters.

Tabla 4. Medias [a] de los descriptores de la forma de los poros para los diferentes rangos de diámetro aparente (AD) de poros y para cada tratamiento de fertilización [b].

Pore-size (AD)/ Treatments	Shape pore descriptors			
60-100 µm	**Circularity**	**Solidity**	**Aspect ratio**	**Roundness**
Control	0.938	0.875	1.440	0.742A
170DCS	0.910	0.865	1.565	0.690B
250DCS	0.917	0.871	1.540	0.702AB
100-200 µm				
Control	0.797	0.860A	1.807B	0.618A
170DCS	0.752	0.842B	1.945A	0.577B
250DCS	0.758	0.847B	1.915A	0.587B
200-400 µm				
Control	0.595A	0.793A	2.053	0.548
170DCS	0.530B	0.751B	2.014	0.530
250DCS	0.542B	0.762B	2.072	0.543
>400 µm				
Control	0.348A	0.662A	2.243	0.512
170DCS	0.300B	0.617B	2.221	0.517
250DCS	0.293B	0.620B	2.113	0.532

[a] Mean values in columns followed by different letters are significantly different according to the LSD test at 0.05 probability level.

[b] Treatments: control (without N) and dairy cattle slurry fertilization (DCS); where numbers indicate the N applied rates of 170 or 250 kg N ha^{-1} $year^{-1}$.

[a] Valores medios en las columnas seguidos de diferentes letras son significativamente diferentes a un nivel de probabilidad de 0,05 con base a la prueba de mínima diferencia significativa.

[b] Tratamientos: control (sin aporte de N) y fertilización con purín bovino de leche (DCS) donde los números asociados indican las dosis de N aplicado, 170 o 250 kg N ha^{-1} $año^{-1}$.

Discussion

The significant increase of the porous area (>30 µm) in the 250DCS treatment (49% higher than 170DCS and the control, table 2, page 253) agree with the findings of Pagliai and Antisari (1993) about the increase in soil porosity percentage associated with high doses of pig slurry applications (300 m^3 ha^{-1}) in a maize crop. Mellek *et al.* (2010) when applying DCS (180 m^3 ha^{-1} $year^{-1}$) in a double-annual cropping system, attributed these porosity changes to the direct effects of the OM incorporation, among which were the improvement of the aggregation and the decrease of the soil bulk density, and their indirect effects among which were a higher root density that, after decomposition, increased the porous space.

The OM soil addition from slurries is low when compared with other solid organic wastes (8, 21), so the 170DCS did not supply enough OM to make an improvement in soil porosity detectable. However, a porosity increase (>30 μm) was detected at the higher dose of 250DCS (table 2, page 253). This increase is advantageous for the soil-water-plant relationship, and for the maintenance of a good soil structure. In addition, in soil superficial layers (first 0.05 m), it could reduce superficial compaction (27, 37) and assure the different soil services such as gaseous exchange (1).

Our results emphasize that the pore range between 60 and 400 μm is sensitive to the fertilizer type and rate applied, and therefore this range could be introduced as an indicator of physical soil quality.

In addition, at the 250DCS rate, the porosity increase was distributed among different ranges, which enhances the different functionality of pores (41), both in water storage (30-60 and 60-100 μm, table 2, page 253), and in the water and air fluxes, as a guarantee of their improved supply to roots and microorganisms (12, 41).

Finally, the increment in the pore range between 100 and 400 μm (table 2, page 253) is important to avoid any constraint in root development and growth (25, 41), since the root hairs usually have diameters between 0.1 and 0.3 mm.

The porosity linked to AD >400 μm increases gradually, from the control, with the rate of DCS applied (table 2, page 253).

In a broad sense, these pores usually result from soil fauna activity, mainly earthworm activity (40, 41).

The incorporation of organic fertilizers such as DCS stimulates microbial activity (7, 15, 45) and increases macrofauna which changes the soil surface layer, increasing the presence of large pores (11, 18). Thus, it results in structural improvement. In contrast, its decrease, as shown in the control (>400 μm, table 2, page 253), can be related to compaction problems (18) and lower soil faunal activity. The large pores (>400 μm) in the 250DCS treatment do not correspond to cracks, which are commonly associated with low levels of soil OM contributions (5).

Changes in pore shapes were observed, regardless of the DCS applied rate (table 4, page 256). Dairy cattle slurry increased the elongation (AR, 100-200 μm, Circularity, 200-400 μm and >400 μm, table 4, page 256), angularity and roughness (R, 100-200 μm; S, 200-400 μm and >400 μm, table 4, page 256) of pores. These changes could result in an increase in soil water holding capacity, leading to better water management efficiency, as well as facilitating the soil penetration by roots (15, 22, 27, 44). This fact is of particular relevance in intensive systems, with a substantial machinery traffic because that annually doubles or triples when compared with a single annual crop. Also, when the soil is wet, the elongated pores with rough and irregular walls are more difficult to seal than the circular and smooth ones. Thus, in the face of activities favouring disaggregation (transit of machinery, impact of raindrops or irrigation), they would not be totally closed, *i.e.* the circulation of fluids would not be compromised (24, 29).

Our results support the option of considering, in intensive systems, the application of 250 kg N ha^{-1} (split into winter and summer crops) of organic origin (through contributions of DCS) to improve soil physical fertility. Our findings reinforce the positive evaluation of this rate, from the agronomic point of view, reported by other authors (32, 33) in similar agricultural systems.

Conclusions

In a coarse loam soil, when an intensive production system is introduced, the DCS rate equivalent to 250 kg N ha^{-1} (split into winter and summer crops) increased porosity (AD greater than 30 μm) up to 26%. This figure almost doubled with respect to the one (14%) found at the lower rate of 170 kg N ha^{-1}; the latter did not differ from the control. Slurries, independently of the rate and compared with the control, mainly increased the presence of pores with an AD greater than 400 μm. This fact acts as a warning of the potential existence of compaction problems when OM is not applied. In addition, changes in the pore shape by DCS (roughness and elongation increases) would favour water retention, which is important in winter rainfed crops. These results confirm that in a double cropping programme, the application of DCS at an equivalent rate of to 250 kg N ha^{-1} could prevent compaction (increases macroporosity) despite the intensity of machinery traffic, while it helps to slow down the potential drainage of infiltrated water by increasing the tortuosity of the pores.

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