https://doi.org/10.5194/egusphere-2022-131
Preprint. Discussion started: 26 April 2022

Evaluation of a long-term optimized management strategy for the improvement of cultivated soils in rainfed cereal cropland based on water retention curves

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Abstract. This study evaluates an optimized cropping system (including no-tillage, cover crops and organic amendments), as an alternative to conventional management for rainfed cereal cropping in a calcareous soil in a semi-arid Mediterranean climate zone in Navarre (Spain), based on the analysis of soil water retention curves (SWRC) and soil structure. In an agricultural area, plots were randomly selected on a soil unit (*Fluventic Haploxerept*), with contrasting managements: (a) *optimized system*; which includes no-tillage (18 years continuous) after conventional tillage, crop rotation, use of cover crops and occasional application of organic amendments, and (b) *conventional management*; which involves continuous conventional tillage (chisel plow), mineral fertilization, no cover crops and a lower diversity of crops in the rotation. Undisturbed soil samples from the soil surface (0-5 cm) and disturbed samples from the tilled layer (0-30 cm) were collected for both systems. The undisturbed samples were used to obtain the detalied SWRCs in the suction range 0 kPa to 110 kPa using a Hyprop® device. From these SWRCs, the Dexter S index was determined. Disturbed samples were used in the laboratory to assess soil structure by means of an aggregate-size fractionation. SWRCs showed significant differences between the two studied agricultural systems, corresponding to different pore size distributions. However, the S index did not show significant differences between the two cropping systems. In addition, the soil under conventional management showed greater macroporosity (gravitational water). As a result, the soil under the optimized system stored up to 10 % more water for the crop at the studied depth. Likewise, more stable macroaggregates were observed in the optimized system than in the conventional one, as well as more organic C storage, greater microbial activity, and biomass. Overall, these results reflect a better quality –or less degradation– of the soil after 18 years under the optimized system than its conventionally managed counterpart.

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1 Introduction

Soil degradation due to tillage and farming practices with little or no return of crop residues to the soil can manifest in different ways. Examples of these manifestations include decreased water infiltration and storage, compaction and poor aeration (Batey, 2009; Hu et al., 2021; Rabot et al., 2018). These symptoms are usually associated with a common cause: the deterioration of the natural structure of soils, which leads to changes in porosity and hydraulic properties (Kodesova et al., 2011; Pires et al., 2017). Therefore the structure of the soil, and many of its associated properties appear as diagnostic indicators in most agro-ecosystems (Rabot et al., 2018).

Conservation practices, which reduce or eliminate tillage (e.g., direct seeding, optimal maintenance of vegetation cover on the soil), are capable of preserving the structure of the soil and, consequently, its associated porosity (Bescansa et al., 2006; Islam and Reeder, 2014; Triplett and Dick, 2008).

In this sense, surface soil –as the interface with the atmosphere and inlet of rainwater– is the most critical zone in semiarid rainfed areas, where the optimization of the annual soil water balance is of the uttermost relevance for ensuring sustained and profitable crop yields.

Among the existing approaches to assess soil condition (Minasny and McBratney, 2018), Rabot et al. (2018) highlighted the interest of soil structure as an indicator of its performance, as well as the relevance of considering the organization, distribution, and stability of aggregates and the characterization of the pore network. There are different types of techniques to characterize the soil pore system (Pires et al., 2013; Taina et al., 2013; Pagliai et al., 2004). The analysis of soil water retention curves (SWRCs) is one of the most employed methods for characterizing soil pores. It enables an adequate characterization of the effective porous system (interconnected, functional pores), and is a relatively fast and low-cost methodology.

SWRCs are functions that relate the water content in the soil and the degree of retention/suction of moisture by the soil matrix. The degree of retention at low suctions is mainly associated with the porous system (size of pores) of the soil, and therefore SWRCs are a valuable tool to diagnose the physical condition of soils (Dexter, 2004a, b; Pires et al., 2017).

Starting from a completely saturated soil, the suction value for which desaturation begins is defined as the air-entry value. From this point, the water content in the soil decreases as suction increases, and an inflection is observed on the curve. The SWRC of most soils presents a J form, defined by the presence of the so-called air-entry region, in which the volumetric water content is maintained at saturation values even in suctions slightly over zero. This occurs due to occluded pores (not functional) (Kosugi et al., 2002). When there is no marked air-entry region, the SWRC adopts an S form. As such, in the case of fine-textured undisturbed soils, the SWRC usually presents the shape of an S (Kosugi et al., 2002).

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Following Brooks and Corey (1964), in J-shaped SWRC the best fit occurs with an exponential function. Nevertheless, for S-shaped SWRC, the fit with exponential functions is poor (Milly, 1987; van Genuchten and Nielsen, 1985), and it is recommended to employ sigmoidal-type functions such as the van Genuchten Equation (1980).

Dexter (2004a) proposed an S index to estimate the physical condition of soils (changes in soil structure, and therefore in porosity) based on the soil SWRC. This S index refers to the value of the slope at the inflection point of the SWRC (Dexter, 2004a, b). According to Dexter (2004a), this inflection point defines the limit between structural pores (in the range of low suction) and textural pores (in the range of high suction values).

The inflection point can be determined directly from the SWRC, and its precision depends on the number of measuring points (water content vs. suction) (Dexter, 2004a). Alternatively, experimental data could be disregarded, and the renowned van Genuchten equation (1980) can be assumed as a satisfactory adjustment function for data. The parameters of the equation can be then determined by pedotransfer functions, available in the scientific literature (Dexter, 2004a).

The objective of this study was to assess the continuous application, throughout 18 years, of an optimized management system for the improvement of the soil physical condition, and the optimization of the soil water balance, in rainfed cereal agrosystems in semi-arid land. The comparison with conventional management was carried out for a cultivated soil characteristic of a semiarid rainfed cereal cropping area. To this end, the S index (Dexter, 2004a) was assessed, in comparison with the study of topsoil SWRCs and soil structure, as related to the size-distribution of stable macro- and microaggregates and their relation to organic C storage.

This study evaluates the long-term effects (throughout almost two decades) of optimized management on the study area, which was previously conventionally managemented. SWRC are analyzed for unaltered soil samples obtained with a specific equipment for soil water retention assessment in undisturbed soil samples. The results are compared with the same soil in conventional tillage conditions.

In addition, a study is developed on the size-distribution of water-stable aggregates, and the organic carbon stored therein, aiming to provide more information on the consequences of management on soil structure, and its relation to SWRCs.

2. Material and methods

2.1. Study zone and treatments

Agricultural fields under two contrasting agricultural management strategies on identical soil types (*Fluventic Haploxerepts* (Soil Survey Staff, 2014)), with loam texture at the upper soil horizon) and use (rainfed cereal cropping) were randomly selected in the municipality of Garinoain (Navarre) (42,59843° N, 1,64959° O).

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The physical-chemical analysis of soils (Table 1) –along with the visual inspection carried out in situ– showed high homogeneity of the soil at the study depths regarding the most relevant physical-chemical properties related to moisture retention, except for the content of organic C (which can be related to the change in management).

The contrasting managements strategies were: a) an *optimized system*, used for 18 consecutive years, which included direct seeding, an improved crop rotation including wheat (*Triticum aestivum L.*), barley (*Hordeum vulgare L.*), legumes (*Pisum sativum L.*, *Vicia faba L.* and others) and rapeseed (*Brassica napus L.)*, and the occasional use of cover crops and organic amendments (from now on referred to as 'optimized management' or OPM) and b) a *conventional management*, which employed conventional continuous (annual) tillage with a chisel plough down to 15 cm, mineral fertilization, without cover crops, and a less diverse crop rotation including mostly wheat and occasionally legumes and rapeseed (referred to as CM).

In CM, crop residues were not returned into the soil (both grain and straw were removed annually): only the non exported stubble and roots were therefore incorporated into the soil at 10-15 cm depth by vertical tillage.

In OPM, both grain and straw were also removed in the 11 first years of implementation, and only stubble remained on the surface of soil when direct seeding was implemented with minimal soil perturbation. Since then, and for the 7 remaining years, the procedure was slightly modified, and only grain was removed at harvest. Therefore chopped straw and stubble remained on the surface of the soil before direct seeding with no disruption of the soil surface.

To avoid the possible influence of the preceding crop, the two last crops of the rotation before sampling were the same (winter wheat (*Triticum aestivum L.)* and rapeseed (*Brassica napus L.*) in both systems.

Mineral fertilization (180 kg N·ha^{-1}, distributed in two coverers: 60 kg N·ha^{-1} and 120 kg N·ha^{-1}) was identical in both management practices. Organic fertilization was not used in any of the study treatments until the experiment year, in which an organic amendment was applied to the soil without disturbing the surface in the OPM treatment.

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Table 1. Physical-chemical properties of the topsoil (0-30 cm) in OPM and CM treatments. Mean ± standard deviation of the mean (n = 3).

Treatment	Optimized (OPM)	Conventional (CM)
Bulk density ($g \cdot cm^{-3}$)	1.26 ± 0.05	1.26 ± 0.15
pH	8.00 ± 0.05	8.01 ± 0.01
Organic C (%)	1.8 ± 0.10	1.5 ± 0.14
CE ($\mu S \cdot cm^{-1}$)	483.00 ± 5.66	795.00 ± 4.24
Carbonates (%)	31.64 ± 0.09	32.51 ± 0.14

2.2 Soil sampling and methodological approach

Soil sampling for both treatments (OPM and CM) was carried out in early Fall (after harvest and before soil preparation for seeding in CM), approximately four months after the last tillage for CM at three (n=3) randomly selected fields per treatment. Undisturbed cylindrical (8 cm diameter, 5 cm height) samples were collected from the first 5 cm of each sampling site.

Simultaneously, a second sampling procedure was carried out at 0-30 cm depth, in which disturbed samples were collected. The same three sampling locations were used for collecting three sub-samples per sampling point, which were then mixed to obtain a composite sample. Immediately after sampling, part of the composite soil was stored at 5 ºC for biological analysis, while the remainder was used to assess soil aggregation, as detailed below.

Determination of SWRCs. From the unaltered cylindrical samples, SWRC tracks were obtained in the laboratory with a Hyprop® device commercialized by METER (München, Germany) as described by Schindler et al. (2010). This device uses the Peters and Durner (2008) and Schindler (1980) simplified evaporation method. The procedure is based on the continuous measuring of hydric potential from two micro-tensiometers inserted into the saturated soil sample, while the moisture content of the sample is progressively reduced by evaporation. As the experiment advances, the sample loses water by evaporation, and the tensiometers record the variation of suction as a scale measures the weight change. The registries of suction and weight are automated and continuous. In this way, it is possible to obtain the relationship between the gravimetric and volumetric water content from measurements of weight and bulk density of the sample and its water content (Schindler et al., 2010).

To this end, after the evaporation experiment concluded, the samples were dried in an oven at 105 ºC for 24 h to determine the dry weight and the soil bulk density, for the subsequent evaluation of the results using the Hyprop-Fit (version: 4.2.2.0) software (Pertassek et al., 2015).

2.3 Determination of the S index

The S index was determined as described by Dexter (2004a). This index represents the value of the slope of the SWRC at the inflection point when the curve is expressed as the natural logarithm of suction (in hPa) versus the gravimetric moisture content, θg (kg·kg^{-1}) (Dexter, 2004a, b). It is assumed that, as S increases, structural pores are more abundant and, therefore, there are better conditions for water flow and storage in the soil (Dexter, 2004a).

The value of S was calculated in two different ways: i) from a sigmoidal function fitted to experimental data (Eq. 1) and ii) from the adjusted parameters of the van Genuchten (1980) function (Dexter, 2004a):

$$y = \frac{a}{1 + e^{-\left(\frac{x - x_0}{b}\right)}} \quad (1)$$

Where *y* is the logarithm of suction (hPa), *x* is the gravimetric moisture (kg·kg^{-1}), and *a*, *b*, x_0 are parameters of the equation. The Hyprop® device, besides determining SWRC, provides values for soil unsaturated hydraulic conductivity (SUHC) at different water contents. From these SUHC it is possible to estimate the moisture content of the soil at field capacity –i.e., once gravitational water is drained– which corresponds to the inflection point of the SWRC (Fontanet, 2014).

Finally, the soil pores size-distribution was estimated from the equivalent radius obtained from the suction values of SWRCs, by Jurin's law (1718).

$$h = \frac{2\, T \cos\theta}{\rho\, g\, r} \quad (2)$$

where *h* is the height of the liquid (m), *T* is the surface tension (N·m^{-1}), θ is the contact angle of the liquid, ρ is the density of the liquid (kg·m^{-3}), *g* is the gravitational acceleration (m·s^{-2}), and *r* is the equivalent radius of the pores (m) retaining water at a potential equivalent to *h* (m).

2.4 Indicators of soil structure

Aggregates size-fractionation. Firstly, field-moist soil samples were gently passed through a 5 mm sieve, without forcing the aggregates, and left to dry naturally. Then 50 g were collected from each soil sample and subjected to humidification with deionized water vapor until saturation.

Water-stable aggregates fractionation followed the step-wise protocol described by Oliveira et al. (2019) (Fig. 1), as follows.

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Firstly, each moist soil sample was sequentially sieved (250 µm and 50 µm) to obtain three aggregate fraction sizes (Elliot, 1986) macroaggregates (Magg, > 250 µm), microaggregates (magg, 50-250 µm) and the silt and clay fraction ((s+c), < 50 µm) (Fig. 1). To this end, initially, 50 g of saturated soil sample were spread over a 250 µm sieve. The soil was then submerged in deionized water for approximately 30 seconds, and then manually sieved by moving the sieve upwards and downwards 15 times in a distance of 1.5 cm during 30 seconds. The sieved material was then placed on a 50 µm sieve, submerged again for 30 seconds in deionized water, and the manual sifting was repeated. The sieved material was then transferred to a 500 mL centrifuge bottle, and centrifuged at x 13000 *g* for 10 minutes to recover the silt and clay fraction. The aggregates retained by the sieves (> 250 µm and 50-250 µm) were gathered and dried in an oven at 50 ºC along with the fraction < 50 µm, and stored at ambient temperature for subsequent analysis.

The second step consisted in the fractionation of the > 250 µm fraction (Magg, Fig. 1) in other three new fractions: coarse particulate organic matter > 250 µm (cPOM + sand), micro-aggregates within macroaggregates (mMagg, 50-250 µm) and particles < 50 µm within macroaggregates (M(s+c)) (Fig.1). To this end, an ad hoc device adapted from Six et al. (2002), which consists of a block formed by a 250 µm sieve located above a 50 µm sieve, was employed. This block was placed on an agitator. Ten g of Magg (> 250 µm) and 50 glass beads (4 mm in diameter) were poured on the 250 µm sieve. The block was horizontally agitated for approximately 2 minutes at 125 rpm while deionized water was poured until Magg disaggregated completely. The material retained in the 250 µm and 50 µm sieves corresponded to the fractions of > 250 µm (cPOM + sand), and mMagg (50-250 µm), respectively. Similar to the first step, the M(s+c) fraction was recovered by centrifugation. The three fractions were dried at 50 ºC and stored at ambient temperature.

Figure 1. Scheme of the experimental protocol carried out for water-stable aggregates size-fractionation, as adapted from Oliveira et al. (2019).

2.5 Statistical analysis

Three (n=3) replicates of each study treatment (OPM and CM) were used in the statistical analysis. A one-factor analysis of variance (ANOVA) with significance level $p < 0.05$ was performed for the different indicators to examine the significant influence of OPM. All statistical treatments were performed using IBM SPSS Statistics 27.0 (SPSS Inc., 2021).

3. Results and discussion

3.1 Analysis of the SWRCs

A clear difference between the SWRCs of the two treatments assessed was observed: the variability between treatments was remarkably superior to the one existing between the replicates of the same treatment (Fig. 2).

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Figure 2. Soil water retention curves for each replicate (n= 3) for the two treatments (optimized management (OPM) vs. Conventional management (CM).

The saturation water content in both treatments was similar ($p > 0.05$), which indicates that there was no significant compaction (and therefore, reduction of the total porous space) because of management for the studied depth. This is consistent with the observation of soil in both treatments presenting the same bulk density (Table 1). In both treatments, a relevant presence of occluded or nonfunctional pores was not observed (the air-entry region was negligible, Fig. 2).

In relation to the shape of the SWRCs, both corresponded to the S type (Kosugi et al., 2002).

Nonetheless, the specific water capacity (change in the moisture content per unit of suction; $d\theta/d\Psi$, as defined by Hillel (1998)) in the suction range between saturation (0 kPa) and near field capacity (10.5±0.56 kPa) was significantly higher for CM ($d\theta/d\Psi = 1.89 \pm 0.32$) than for OPM ($d\theta/d\Psi = 0.34 \pm 0.05$). However, when suction was greater than 10 kPa, the value of specific water capacity tended to be similar for both treatments, with no significant differences ($p > 0.05$) above 32 kPa ($d\theta/d\Psi = 0.10 \pm 0.01$) (Fig. 2). This means that the soil under CM presented a higher population of macropores (gravitational water) (see section 3.3) than OPM. As macropores drain quickly at low suctions, when these macropores become empty, the volume of soil capable of storing capillary/available water is then reduced. Consequently, up to 100 kPa, the soil under OPM stored a higher amount of water (ca. 10-15 %) per unit of volume than under CM (Fig. 2).

3.2 S index

van Genuchten Approximation. Despite the different behavior of the SWRCs observed for both treatments (Fig. 2), the S index (Dexter, 2004a, b) did not reflect those differences ($p > 0.05$) (Table 2).

Table 2. S index values and contents of water (θ) and suction (Ψ) corresponding to the inflection point, obtained with the van Genuchten equation. Mean ± standard deviation of the mean (n=3).

Treatment	S index	Inflection point	
		θ (%)	Ψ (kPa)
Optimized (OPM)	0.035 ± 0.002	33.80 ± 0.98	23.85 ± 6.70
Conventional (CM)	0.035 ± 0.007	31.66 ± 0.55	6.22 ± 2.15

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In this sense, it must be observed that the water content corresponding to the inflection point of both treatments was close to moisture at field capacity. This agrees with the results of Dexter and Bird (2001), who affirmed that the water content related to the inflection point is optimal for tillage and was herein considered as close to field capacity.

Approximation with a sigmoidal equation adjusted to experimental data. In the sigmoidal equation, as with van Genuchten, no differences were observed between optimized management and conventional management ($p > 0.05$) (Table 3). In addition, the sigmoidal equation proposed herein presented a dispersion of S values one order of magnitude higher than when calculated from the van Genuchten's equation for both treatments (Tables 2 and 3). In spite of this, it should be noted that the modeled SWRCs closely matched the experimental data.

Table 3. S index values and contents of water (θ) and suction (Ψ) corresponding to the inflection point, obtained with the sigmoidal equation adjusted to experimental data. Mean ± standard deviation of the mean (n=3).

Treatment	S index	Inflection point	
		θ (%)	Ψ (kPa)
Optimized (OPM)	0.040 ± 0.016	36.53 ± 0.98	6.97 ± 6.70
Conventional (CM)	0.057 ± 0.012	29.57 ± 0.81	9.53 ± 2.15

The S value for the two study treatments reflected good soil physical quality ($0.035 < S \leq 0.050$) for the van Genuchten equation (Table 2) and *very good* (≥ 0.050) for the sigmoidal equation (Table 3) (Bacher et al., 2019; Dexter, 2004b; Reynolds et al., 2009).

Overall, it can be concluded from these observations that the S index, whichever method used for ist determination, did not show sensitivity to soil management under the conditions of the present investigation. This is in line with the observations of Alonso et al. (2022), who recently reported overall *good* S values in silt loam and sandy loam soils subjected to moldboard plowing, deep loosening and minimum tillage managements. In contrast, this diagnosis did not hold for other soil physical quality indicators studied (Alonso et al., 2022).

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This lack of differences can be explained, at least partially, by the fact that Dexter (2004a) related the S index to changes in both bulk density and soil type, whereas in our study the texture of the two study treatments was very similar (Table S1), and there were no significant differences in bulk density ($p > 0.05$, Table 1).

3.3 Analysis of the pores size-distribution

Fig. 3 depicts the accumulated frequency of pore diameter (mean of the three replicates) for the study soil under OPM and CM, and the classification of pore sizes according to the Soil Science Society of America (Weil and Brady, 2017).

Figure 3. Accumulated frequency of pore sizes (mean of three replicates) of the soil under the two studied treatments (OPM and CM), and pore size classification (Weil and Brady, 2017). Note: X-axis in logarithmical scale.

For both treatments, the percentage of mesopores (equivalent diameter between 30 and 80 µm) was similar (5.6±0.7 in OPM and 8.0±1.3 in CM) ($p > 0.05$). The mesopores (Fig. 3) are associated with water retention after free drainage, with a suction that enables easy extraction by plants (readily accessible water), transmitting water by capillarity to the radicular zone (Weil and Brady, 2017). It is therefore considered that the population of mesopores partially reflects the physical quality of a cultivated soil, and it can therefore be inferred that OPM did not produce remarkable changes in the soil structure associated to this pore-size range compared to CM.

Similarly, the population of smaller pores (micropores, with equivalent diameter between 5 and 30 µm) did not present significant differences for both treatments (15.5±1.1 % in OPM and 16.4±2.3 % in CM, Fig. 3) ($p > 0.05$), which confirmed the textural homogeneity of the soil in both treatments, as this porosity is more associated with its texture than structure (Pagliai et al., 2004).

On the contrary, the proportion of pores with equivalent diameters > 80 µm (macropores) differed between treatments ($p < 0.05$). For CM, macropores represented 27.7±4.8 % of total porosity and only 11.6±2.3 % for OPM. As such, in CM, the population of pores with equivalent diameter 500-1000 µm and > 1000 µm represented 5.5±1.3 % and 4.4±2.2 %, respectively. For OPM, the population of pores larger than 500 µm –considered mainly as fissures (Pagliai et al., 2004)¬ was 2.8±1.3 %, with no apparent presence of pores larger than 1000 µm (< 1.3±0.7 %). This explains the fast desorption rate at low suction values (high specific water capacity) observed in CM compared with OPM (Fig. 2). This can be understood if the soil consolidated after its disaggregation by tillage (which was carried out four months before sampling), maintaining a significant presence of macropores (> 500 µm) formed as a consequence of tillage. It is likely that, the presence of these pores induced by tillage would have been more remarkable right after tillage (a few days after), leading to a more pronounced difference in specific water capacity values between both treatments.

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Pires et al. (2017) evaluated the effect of tillage and direct seeding on the structure of an Oxisol through the analysis of SWRCs and micromorphological assessments. From their results, it can be observed (see Fig. 1 and 2, Pires et al., 2017) that the soil under conventional tillage reduced its water content (starting from saturation) by 15 % when a suction of approximately 20 cm was applied. For the soil under direct seeding, the decrease was only of 5 %. For the depth range 10-30 cm, the changes in moisture content with suction were similar for both treatments.In addition, in the soil under direct seeding pores within the size range 50-500 µm –responsible for draining excess water (Greenland and Pereira, 1977)– occupied 39 % of the total porous space, while for tilled soil the percentage was slightly over 60 %.

In agronomic and climatic conditions closer to the soil studied here, Pagliai et al. (1984) studied the size distribution of size and shape of soils in a clay loamy vertic soil under conventional tillage and direct seeding, using micromorphological image analysis of soil thin sections. The size-distribution of pore was more regular in the soil under direct seeding than under conventional tillage. For direct seeding, 7 % of the total pores identified (=145) were macropores (500-1000 µm), occupying 25 % of the porous space (image area). For conventional tillage, in turn, the bias was considerable: 22 % of total pores (=45) corresponded to macropores (500-1000 µm and >1000 µm), occupying approximately 85 % of the porous space (Fig. 1, Pagliai et al., 1984).

3.4 Analysis of the size-distribution of stable aggregate

Mass losses during fractionation accounted for 3.6±0.2 % of the initial samples, with no differences between treatments (data not shown), which means that the differences found (Fig. 4) can be considered as a response to the studied treatments.

For both treatments, the percentage of aggregated soil was 92.2±0.3 %, as the (s+c) fraction presented 5.8±0.4 % of the initial mass (Fig. 4). However, clear differences were observed in the size-distribution of aggregates ($p < 0.05$). Considering only the aggregated soil mass (i.e., excluding the non-aggregated (s+c) fraction), the soil under OPM had 75.9±2.6 % of stable macroaggregates (Magg, > 250 µm); while this percentage was of 57.5±2.1 % for CM.

In relation to cPOM and magg, although both included an undetermined percentage of sand particles, the similar texture of the soil for both treatments (Table S1) allows to consider that the greater amount of cPOM and mMagg observed in OPM in comparison to CM (where M(s+c) represented a greater proportion of total Magg mass) (Fig. 4) were a consequence of management in the study site.

The preponderance of Magg under OPM reflects better soil condition (or lower degradation) than under CM, in terms of aggregates stability. As conceptualized in the hierarchical model of soil aggregation (Angers et al., 1997; Beare et al., 1994; Golchin et al., 1994; Oades, 1984; Six et al., 1999, 2004; Tisdall and Oades, 1982), while magg are formed and stabilized mostly by the action of persistent agents (e.g., cationic complexes, humidified organic matter), Magg result from the union of these microaggregates among themselves by the action of transitory agglutinating agents (hyphae and mycorrhizae, microbial

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and vegetable derivatives. According to this hierarchical vision of soil aggregation, these agglutinating agents are, in turn, widely conditioned by soil management: the formation of (macro) aggregates is thus favored by the lower degree of soil disturbance by tillage, higher inputs of crop (organic) residues in the soil organic matter pool, and the punctual organic amendments used in OPM (Jastrow, 1996; Lehmann and Kleber, 2015; Six et al., 2004; Tisdall and Oades, 1982). This observation is supported by the higher proportion of cPOM (Fig. 4) and total organic C (Table 1) found under OPM.

In addition, complementary analyses (Supplement 2) revealed higher microbial activity and microbial biomass C under OPM compared to CM, supporting a relationship between soil biological activity and aggregation in the studied soil (Six et al., 2002).

Figure 4. Size-distribution of stable aggregates and individual particles in the soil under OPM (a) and CM (b) Magg: Macroaggregates; magg: microaggregates; mMagg: microaggragates within macroaggregates. s+c: silt+clay fraction; cPOM: coarse particulate organic matter >250 μm and sand particles.

4. Conclusions

From the analysis of detailed SWRCs, it was possible to carry out a complete characterization of the porous space of a typical cultivated topsoil (0-5 cm) from a semi-arid area in the region of Navarre (N Spain), after 18 years of application of an optimized soil management strategy, combining no tillage with crop rotations and organic amendments, and for the same soil under conventional tillage.

The proportion of macropores/fissures (gravitational water) was remarkably higher with conventional management. Consequently, the soil submitted to the optimized management strategy stored up to 10 % more capillary/available water. This difference seems specially relevant for rainfed agriculture at a *xeric* regime area where water is the most limiting factor for crops growth, such as the study zone.

Direct seeding and the associated practices combined in the optimized management strategy promoted also a better structure of the soil, reflected in the proportion and size of water-stable (macro)aggregates, very likely due to the increased accumulation of agglutinating agents (vegetable and microbial derivatives). In addition, it is likely that the vegetable cover maintained in this management can also preserve the integrity of aggregates from the action of erosive agents.

It is noteworthy that, despite these clear differences observed in soil structure and water retention, the S index (Dexter, 2004a, b) did not reveal significant differences between treatments. This was so because the inflection point in the SWRCs that defines the value of S, was located approximately within the range of suctions/water content where the value of specific moisture capacity for both treatments was similar.

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It is therefore recommended to evaluate other mathematical indices with a more integrative focus on the water retention curve to assess the changes in soil porosity and water retention induced by management in soils like the one studied here.

The relevance of soil water retention and infiltration at the soil surface in rainfed systems in semi-arid land make these results highly relevant, although similar experiments at deeper soil layers are needed for a complete assessment of the optimized management studied here.

In summary, our results suggest that this type of system that includes, among other techniques, the suppression of tillage, crop rotations, and the application of organic amendments, is providing good results from the viewpoint of the physical quality of the soil. This can be translated into higher soil sustainability in Mediterranean agrosystems. However the optimized management analyzed herein is not currently a widespread practice in the region, which illustrates the need for an adequate assessment and dissemination to overcome the reluctance of farmers and other potential barriers to the adoption of this type of systems.

Data availability. The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author contribution. RG and IV conceptualized and supervised the paper. LA designed the experiments and AA carried them out. RG, MC and AA visualized the project, did the formal analysis, and conducted the investigation with IV, who also collected the resources. AA prepared the manuscript with contributions from all co-authors.

Competing interests. The contact author has declared that neither herself nor her co-authors have any competing interest.

Financial support. This study was developed within the framework of project 011-1365-2020-000075 CropStick: sentinel of salts, pH, nitrogen and nutrients, and deep percolation, financed by the Government of Navarre.

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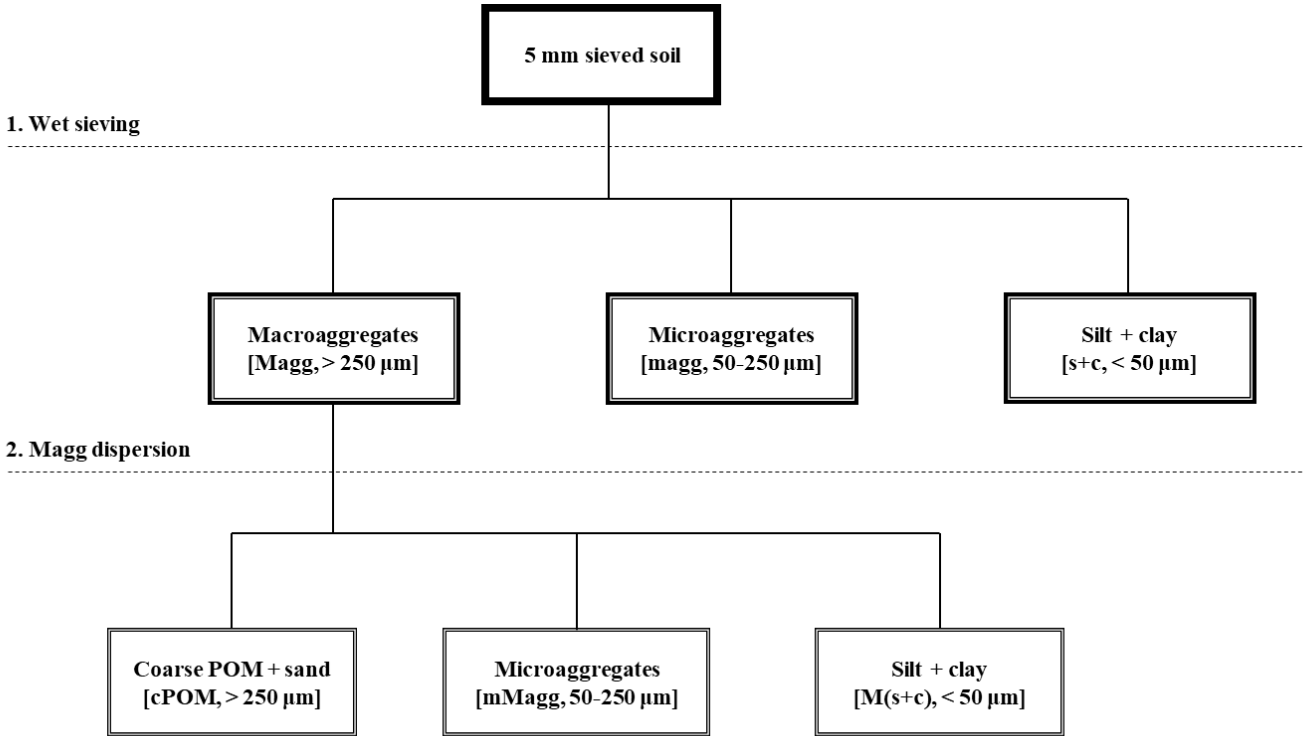

Figure 1. Scheme of the experimental protocol carried out for water-stable aggregates size-fractionation, as adapted from Oliveira et al. (2019).

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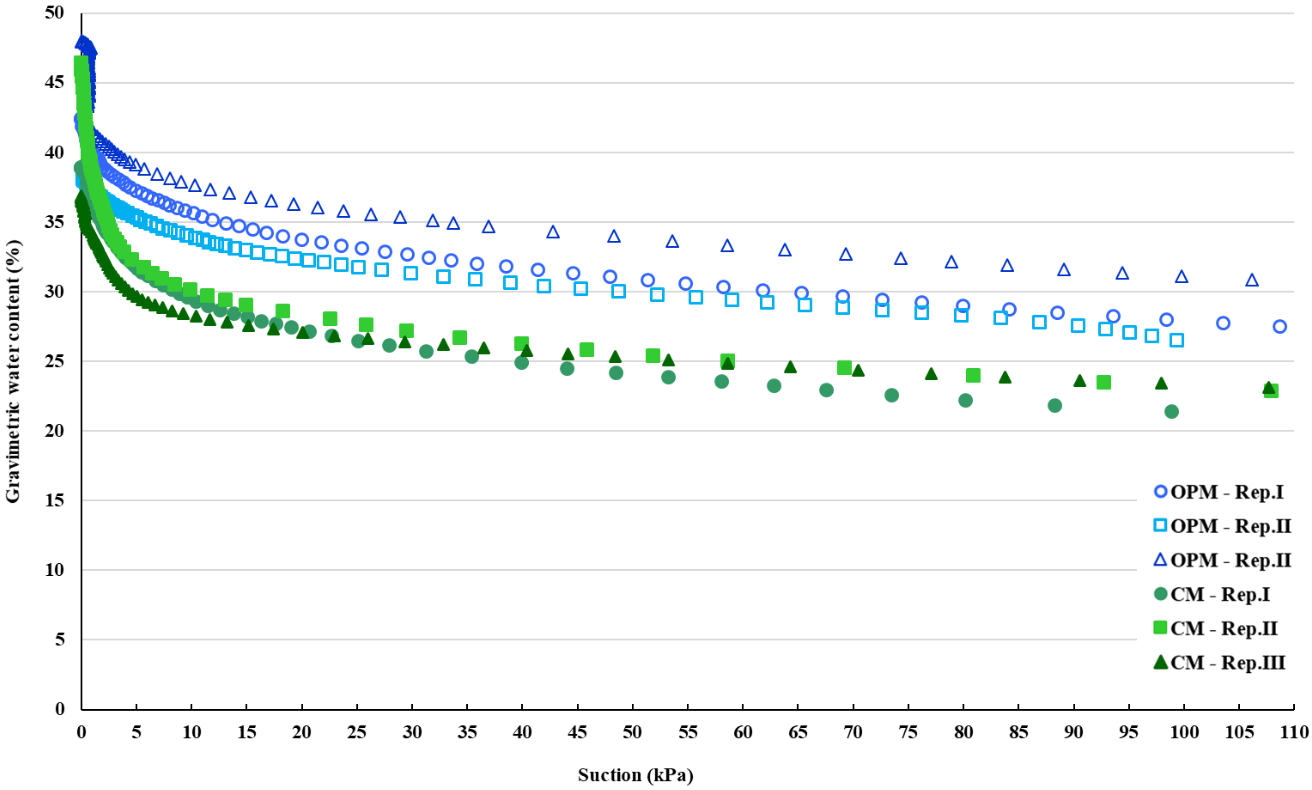

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Figure 2. Soil water retention curves for each replicate (n= 3) for the two treatments (optimized management (OPM) vs. Conventional management (CM).

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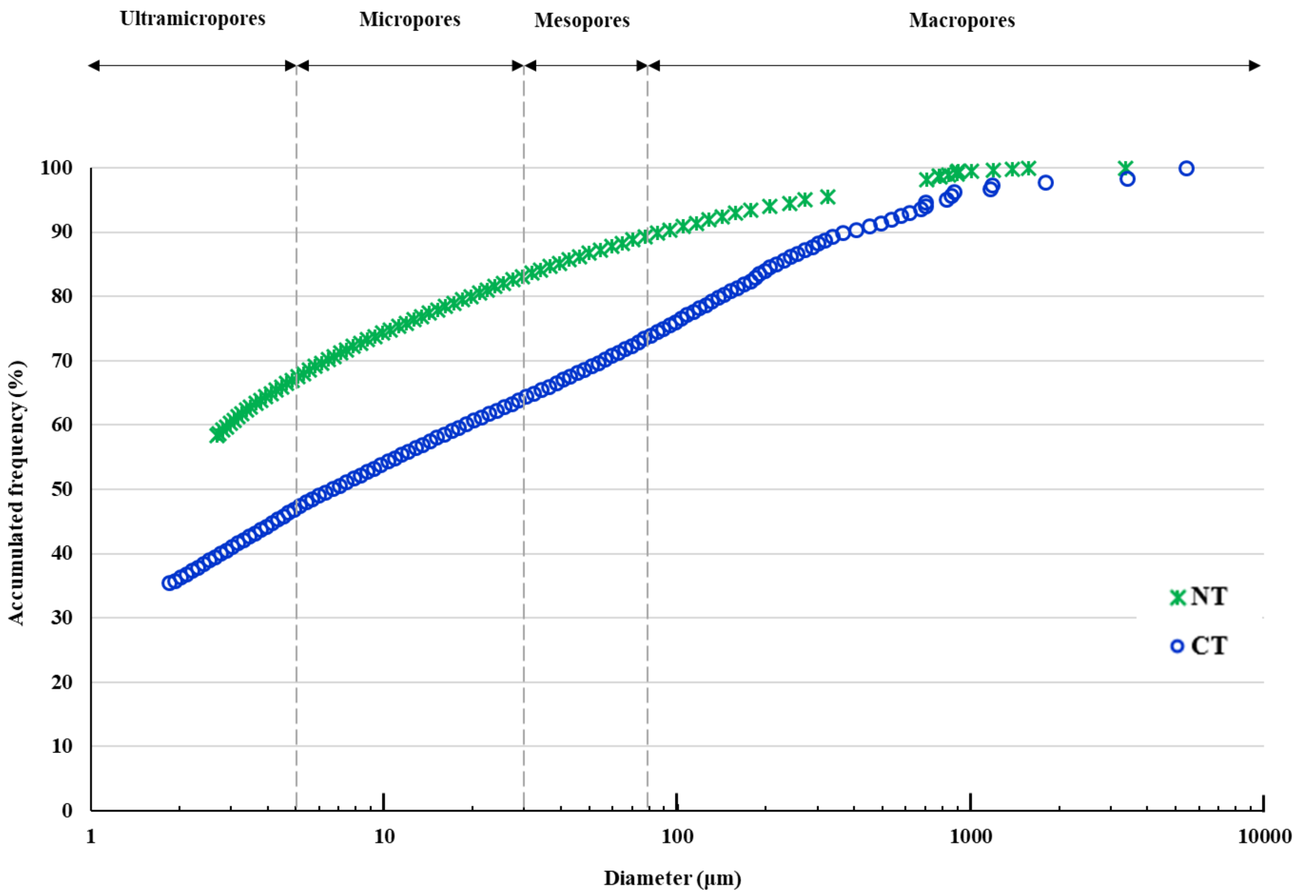

Figure 3. Accumulated frequency of pore sizes (mean of three replicates) of the soil under the two studied treatments (OPM and CM), and pore size classification (Weil and Brady, 2017). Note: X-axis in logarithmical scale.

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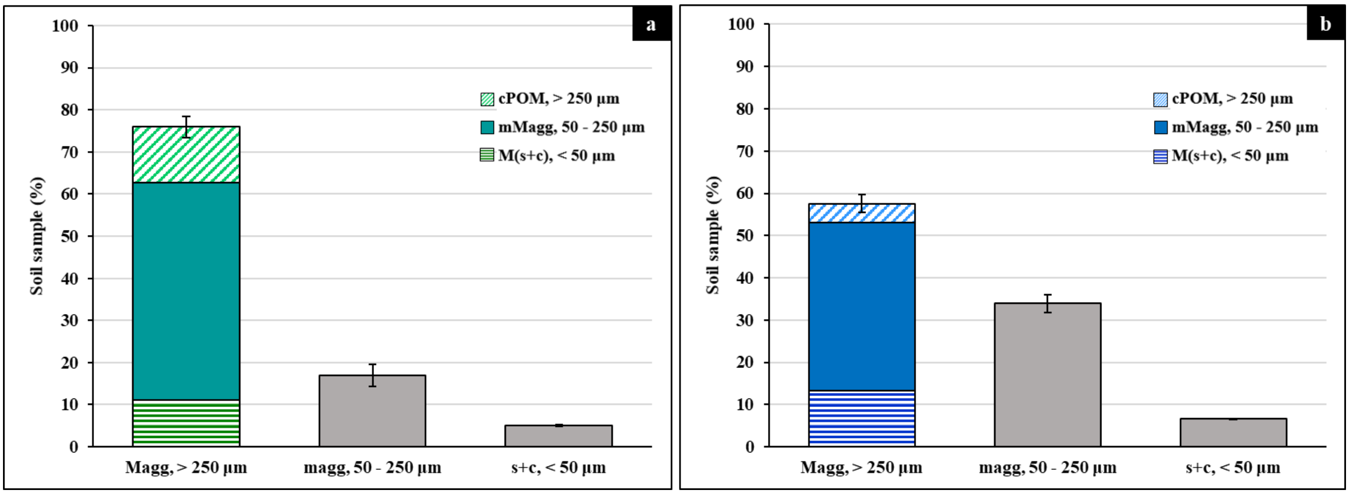

Figure 4. Size-distribution of stable aggregates and individual particles in the soil under OPM (a) and CM (b) Magg: Macroaggregates; magg: microaggregates; mMagg: microaggragates within macroaggregates. s+c: silt+clay fraction; cPOM: coarse particulate organic matter >250 µm and sand particles.