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Using Beerkan Procedure to Estimate Hydraulic Soil Properties under Long Term Agroecosystems Experiments

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Abstract: The BEST (Beerkan Estimation of Soil Transfer parameters) method was used to compare the hydraulic properties of the soils in two Long-term Agroecosystem Experiments (LTAEs) located at the FIELDLAB experimental site of the University of Perugia (central Italy). The LTAE "NewSmoca" consists of a biennial maize-durum wheat crop rotation under integrated low-input cropping systems with (i) inversion soil tillage (INT) or (ii) no-tillage (INT+) and (iii) under an organic cropping system with inversion soil tillage (ORG). ORG and INT+ involve the use of autumn-sown cover crops (before the maize cycle). Pure stand durum wheat was grown in INT and INT+, while a faba bean–wheat temporary intercropping was implemented in ORG. The LTAE "Crop Rotation" consists of different crop rotations and residue management, a continuous soft winter wheat and biennial rotations of soft winter wheat with maize or faba bean. Each rotation is combined with two modes of crop residue management: removal or burial. For INT+, despite the high-bulk density (>1.50 g/cm^3), we found that conductivity, sorptivity and available water are comparable to those of INT, probably due to a more structured and efficient micropore system. ORG soils show the highest conductivity, sorptivity and available water content values, probably due to the recent spring tillage occurring in the wheat inter-row with the faba bean incorporation into the soil. For LTAE Rotation, the residue burial seems to influence the capacity-based indicators positively. However, the differences in the removal treatment are minor, and this could be due to the inversion soil tillage, which limits the progressive accumulation of organic matter.

Keywords: hydraulic conductivity; BEST procedure; sorptivity; infiltration rate; bulk density; water retention; crop rotation; crop residuals; soil management; soft and durum wheat

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Citation: Vergni, L.; Tosi, G.; Bertuzzi, J.; Rossi, G.; Farneselli, M.; Tosti, G.; Tei, F.; Agnelli, A.; Todisco, F. Using Beerkan Procedure to Estimate Hydraulic Soil Properties under Long Term Agroecosystems Experiments. *Appl. Sci.* **2024**, *14*, 3817. https://doi.org/10.3390/app14093817

Academic Editor: Rafael López Núñez

Received: 4 April 2024
Revised: 24 April 2024
Accepted: 27 April 2024
Published: 30 April 2024

1. Introduction

Soil physical-hydraulic properties (SHPs), especially of the surface layers, have a relevant influence on many hydrological processes such as infiltration, water retention capacity, surface runoff, water erosion and recharge of aquifers [1]. Therefore, knowledge of the factors influencing the variability of SHP is crucial for the proper management of the soil and water resources from the field to the catchment scale. SHPs mainly depend on particle and pore size distribution and bulk density (ρ_d) [2]. These characteristics are, in turn, the result of intrinsic (natural) and extrinsic (anthropogenic) factors and the way they interact [3]. Intrinsic factors include texture, organic matter, carbonate content and mineralogy. Anthropogenic factors, limited to agroecosystems, include tillage, crop rotation, grazing and other specific practices such as the burial (or removal) of crop residues or the use of cover crops [4]. Tillage, which varies in its modality and frequency, is undoubtedly one of the most conditioning activities, not only for the direct alteration of the soil structure but also for its indirect effect on the carbon balance. High contents of soil organic carbon

(SOC), which are associated with the presence of stable aggregates, imply a reduction of ρ_d, higher values of saturated hydraulic conductivity (K_S) and improvements in soil water retention capacity [5].

Various studies have analysed SHP changes in soils subjected to different tillage methods [6–8]. In the short term, significant increases in K_S and porosity are found in conventionally tilled soils compared to those subjected to minimum tillage or untilled. On the other hand, differences in hydraulic properties tend to become insignificant a few months after the last tillage, even when comparing treatments such as conventional and untilled [6,9]. However, soils treated with minimum tillage or untilled are less prone than those treated with conventional tillage to surface crust formation [10] and can lead to progressive increases in SOC [11].

The practice of burying crop residues can lead to an improvement in soil structure and, thus, in SHP, according to two main mechanisms [12]; the increase in aggregate stability is due to the organic matter contributed by the residues and the reduction in ρ_d (residues being much less dense than the mineral component of the soil). The extent of these effects is primarily regulated by the type of crop rotation (i.e., type and number of different species involved in the rotation), which directly affects the quantity and quality of the residues buried and their decomposition rate. For example, Zhou et al. [13], in a study on the impact of management on mollisols of north-eastern China, show that the type of crop rotation influences SOC contents and aggregate stability and that continuous cropping (specifically maize) results in a lower accumulation of SOC and less stable soil aggregate compared to more variable cropping systems. Other factors, all interacting, that influence the effect of residues on SHP are soil characteristics, climate and the type of tillage. This complexity results in a still uncertain picture that requires further investigation under different experimental conditions [11,12].

In this work, the BEST (Beerkan Estimation of Soil Transfer parameters) method [14], was used for the hydraulic characterisation of clay-loam soils from some Long-term Agroecosystem Experiments (LTAEs) variable for crop rotations, residue management methods, tillage operations and agrochemical inputs. The BEST method is widely used [15] due to its simplicity, robustness, accuracy and versatility of application since it enables the estimate of soil hydraulic proprieties (water retention curve and hydraulic conductivity function) based on simple field infiltration measurements, information on the soil particle-size distribution and a few physical parameters. Specifically, the comparative analysis between different types of soil and crop management systems was based on the following parameters, all derived from the hydraulic characterisation obtained by the BEST method: saturated hydraulic conductivity (K_S), sorptivity (S), scale parameter of the Van Genuchten retention curve (h_g), two soil porosity indicators [i.e., the flow-weighted mean pore size (λ_m) and the numbers of pores per unit area (N_0)] and four capacity-based indicators [i.e., macroporosity (P_{MAC}), air capacity (A_C), relative filed capacity (R_{FC}) and plant available water content (AWC)] [16–18]. The main goal was to identify whether the different LTAEs considered have relevant roles in conditioning the soil's physical-hydraulic properties in the specific climatic and pedological conditions of the study area.

2. Materials and Methods

2.1. Study Area

Infiltration tests for the hydraulic characterisation of the soils took place at the experimental site FIELDLAB (42°57′22′′ N, 12°22′25′′ E) of the Department of Food, Agricultural and Environmental Sciences, University of Perugia. FIELDLAB is located in central Italy (Umbria region) and covers an entirely flat area of approximately 20 hectares. The climate is typically Mediterranean, with hot, dry summers and cold winters. The average annual precipitation is approximately 780 mm. According to the USDA Soil Taxonomy [19], the soils of the FIELDLAB can be classified as fine, mixed, mesic Typic Haplustept and belong mainly to the textural classes loam and clay-loam [20,21].

The plots considered in the present study are part of two LTAEs: "Rotation" and "NewSmoca" (Figure 1). Within the LTAE "Rotation", we selected 12 small plots (3.5 m × 7.0 m) that have been managed for more than 40 years with different cropping systems and crop residue management, continuous soft winter wheat, MoF; biennial rotations of soft winter wheat with maize, BiFM or faba bean, BiFV. These treatments are, in turn, combined with two methods of crop residue management, complete removal (plot with subscript "R") or their burial (plots with subscripts "B"), in both cases followed by surface ploughing. Further details of the Long-term Agroecosystem Experiment are available in Bonciarelli et al. [20].

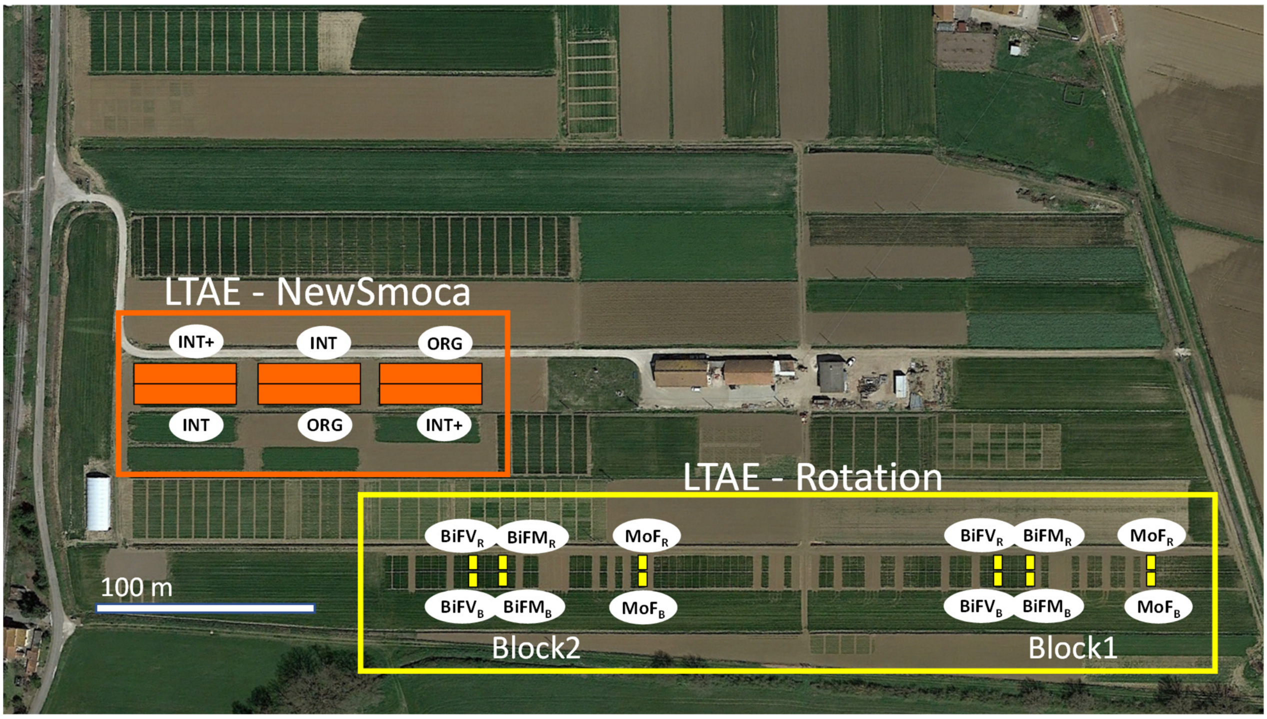

Figure 1. Maps showing the position of the plots considered in each Long-term Agroecosystem Experiment (LTAE). The acronyms indicate different soil, crop or residue management (see the text for detailed descriptions).

Within the LTAE "NewSmoca" (Figure 1), established in 2013, we selected 6 large (i.e., field-scale) plots (12 m × 45 m). In this LTAE, since 2018, a biannual crop rotation grain maize–durum wheat was applied to three cropping systems (with two replicates each): (i) integrated conventional no-tillage with direct drilling of the crops (INT+), (ii) organic with inversion soil tillage (ORG) and (iii) integrated conventional with inversion tillage (INT). Durum wheat was grown as a sole crop in INT and INT+ (single rows 0.15 m and 0.19 m apart, respectively). While in ORG, durum wheat was temporarily intercropped (TIC, [21]) with faba beans (*Vicia faba* L. var. minor Beck. cv Scuro di Torrelama) in alternate rows, 0.45 m apart with faba beans sown in the middle of the wheat inter-row space. At the beginning of wheat heading, the faba bean's biomass was incorporated into the wheat inter-row space by split rotary hoeing [21]. Sowing density was 400 kernels m^{-2} for wheat (in all systems) and 90 seeds m^{-2} for faba beans (in ORG). In ORG and INT+, grain maize was preceded by an autumn-sown cover crop of hairy vetch (Vicia villosa Roth) and triticale (×*Triticosecale* Wittm.) in a mixture (triticale at 25% + hairy vetch at 75% of their ordinary full sowing rates, i.e., 400 and 200 seeds m^{-2}, respectively), while, in INT, the soil was left bare and weed-free (by mechanical control). Cover crop termination was carried out traditionally in ORG; the aboveground biomass of the mixture was mowed, finely chopped (0.02–0.1 m) and immediately incorporated into the soil (0.2 m depth) by a rotary cultivator equipped with tines and a back-roller. In INT+, the cover crop biomass was roll-crimped and left on the soil surface as dead mulch.

2.2. Methods for Soil Hydraulic Characterisation

2.2.1. BEST Procedure and Derived Soil Hydraulic and Porosity Parameters

The hydraulic characterisation of the soil in the plots under consideration was conducted using the BEST method, which allows the parameters of the retention and hydraulic conductivity curves to be estimated based on infiltration tests and data on soil texture, ρ_d bulk density [ML^{-3}] and water content [14]. The BEST method involves performing infiltration tests with a near-zero hydraulic head and can be considered a simplified version of the results obtainable with a tension infiltrometer by imposing zero tension.

The basic assumption is that the water retention and hydraulic conductivity functions can be represented using van Genuchten's [22] model with Bourdine's [23] condition and that of Brooks and Corey [24], respectively:

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[1 + \left(\frac{h}{h_g}\right)^n\right]^{-m} \tag{1}$$

$$m = 1 - \frac{2}{n} \tag{2}$$

$$\frac{K(\theta)}{K_s} = \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^\eta \tag{3}$$

$$\eta = \frac{2}{m \cdot n} + 2 + p \tag{4}$$

where θ is the volumetric soil water content [L^3L^{-3}], θ_r is the residual soil water content (assumed to be zero) [L^3L^{-3}], θ_s is the saturated soil volumetric water content [L^3L^{-3}], h is the soil water pressure head [L], h_g is the van Genuchten scale parameter representing the inflexion point of the water retention curve [L], K is the soil hydraulic conductivity [LT^{-1}], K_s is the saturated soil hydraulic conductivity [LT^{-1}] and m, n (>2) and η are shape parameters. Additionally, p is a tortuosity parameter set equal to 1 following the Burdine relation.

Specifically, m, n and η are shape parameters depending on soil texture and are typically estimated from particle size distribution (PSD) with pedotransfer functions. θ_r, θ_s, h_g and K_s are scale parameters that depend on the structure of the porous medium and are estimated by a three-dimensional (3D) field infiltration experiment at zero water pressure head, using the approximations of the quasi-exact implicit infiltration model for transient [Equation (5) and (6)] and steady states [Equation (7) and (8)] proposed by Haverkamp et al. [25]:

$$I(t) = S\sqrt{t} + \left(AS^2 + BK_s\right)t \tag{5}$$

$$i(t) = \frac{S}{2\sqrt{t}} + \left(AS^2 + BK_s\right) \tag{6}$$

$$I_s(t) = \left(AS^2 + K_s\right)t + C\frac{S^2}{K_s} \tag{7}$$

$$i_s = AS^2 + K_s \tag{8}$$

where I is the 3D cumulative infiltration [L], i the infiltration rate [LT^{-1}], I_S is the asymptotic model for I for large times [L] and i_s the steady-state infiltration rate [LT^{-1}], S the sorptivity [$LT^{-0.5}$], t is the time [T] and A (L^{-1}), B and C are constants that can be expressed using the Brooks and Corey relationship.

The infiltration tests last until steady-state conditions are reached. Therefore, different algorithms can be used to estimate K_s and S. Some of these, such as those known as BEST-slope [14] and BEST-intercept [26], are based on fitting the model to the transient phase of the infiltration process. Others, such as BEST-steady [27], are based solely on experimental data describing cumulative infiltration in steady-state conditions. Details on the different algorithms and the most suitable conditions for their application can be found in Angulo-Jaramillo et al. [15].

Then, the scale parameter of the water retention curve, h_g, can be estimated as:

$$h_g = -\frac{S^2}{c_p(\theta_s - \theta_i)[1 - (\theta_i/\theta_s)^\eta]K_s} \tag{9}$$

where θ_i is the initial soil water content $[L^3L^{-3}]$ and c_p is a coefficient depending on n, m, and η, according to Lassabatère et al. [14]. Scale parameter h_g is used also to estimate the capillary length α_h (L) [28] as:

$$\alpha_h = -h_g \tag{10}$$

From α_h, and according to the following relationship from Mubarak et al. [29], it is possible to calculate the flow-weighted mean pore size λ_m (L):

$$\lambda_m = \frac{\sigma_w}{\rho_w g \alpha_h} \tag{11}$$

where σ_w is the water surface tension $[MT^{-2}]$, ρ_w is the water density $[ML^{-3}]$ and g denotes the gravitational acceleration $[LT^{-2}]$.

The λ_m parameter represents the mean dimension of pores contributing to the infiltration process. It can be considered an indicator of the contribution of the capillary component to the total flow. The higher λ_m, the greater the contribution of gravity compared to capillary forces in the infiltration process [17].

Once λ_m has been estimated, it is possible to calculate the corresponding number of hydraulically active pores per unit area, N_0 (L^{-2}), having a mean size equal to λ_m, according to Watson and Luxmoore [30]:

$$N_0 = \frac{8\mu K_s}{\rho_w g \pi \lambda_m} \tag{12}$$

where μ is the dynamic viscosity of water $[ML^{-1}T^{-1}]$.

2.2.2. Soil Capacity-Based Indicators

Four capacity-based indicators were selected to obtain a more specific evaluation of the soil's physical quality, which are as follows: macroporosity P_{MAC}, air capacity A_C, relative field capacity R_{FC} and plant available water capacity AWC. The definitions of these four indicators and some generalised ranges and critical limits from the literature [17,31] are given below.

Macroporosity, P_{MAC} (L^3L^{-3}), is defined as:

$$P_{MAC} = \theta_s - \theta_m \tag{13}$$

where $0 \leq P_{MAC} \leq \theta_s$ and θ_m is the saturated volumetric water content of the soil matrix exclusive of macropores $[L^3L^{-3}]$ (i.e., for h = −0.1 m).

The P_{MAC} parameter, which defines the volume of soil macropores, is related to the ability of the soil to drain excess water quickly. Optimal values for P_{MAC} are between 0.05 and 0.10, while $P_{MAC} \leq 0.04$ is the lower critical limit typical of soils degraded by compaction.

Air capacity, A_C (L^3L^{-3}), of undisturbed field soil is defined by White [32] as:

$$A_C = \theta_s - \theta_{FC} \tag{14}$$

where $0 \leq A_C \leq \theta_s$ and θ_{FC} is the field capacity soil water content $[L^3L^{-3}]$ (i.e., for h = −1 m).

Optimal values of A_C for reducing aeration deficits in the root zone are between 0.10 and 0.26 (for sandy-loam to clay-loam soils $A_C \geq 0.14$), while values lower than 0.10 often decrease plant growth and promote root diseases.

Plant-available water capacity, AWC (L^3L^{-3}), indicates the water content that can be stored in the soil available to plant roots. AWC is traditionally defined as [32]:

$$AWC = \theta_{FC} - \theta_{WP} \tag{15}$$

where $0 \leq AWC \leq \theta_{FC}$ and θ_{WP} is the water content at the permanent wilting point [L^3L^{-3}] (i.e., for h = −153 m).

AWC values higher than 0.2 are considered optimal, while AWC < 0.10 is considered "poor" for root growth and function.

Relative field capacity, R_{FC} (dimensionless), is defined by:

$$R_{FC} = \frac{\theta_{FC}}{\theta_s} = 1 - \frac{A_C}{\theta_s} \tag{16}$$

with $0 \leq R_{FC} \leq 1$. R_{FC} indicates the soil's ability to store water and air relative to the soil's total pore volume (as represented by θ_s).

Optimal R_{FC} values, ensuring the ideal balance between root-zone soil water and soil air capacity are between 0.6 and 0.7. Values lower than 0.6 indicate "water-limited" soil due to insufficient soil water, while greater R_{FC} values indicate insufficient soil air ("aeration-limited" soil).

The volumetric water contents, θ_s, θ_m, θ_{FC} and θ_{WP}, required for the estimation of the indicator were obtained from the soil water retention curves derived from the BEST method for the corresponding h values.

2.2.3. Experimental Procedures

The workflow diagram of the experimental procedures and the corresponding results are shown in Figure 2. For each infiltration test, we collected one disturbed sample (from the first 15 cm) and six undisturbed samples of approximately 100 cm^3, three from a depth of 0–5 cm and three from a depth of 5–10 cm.

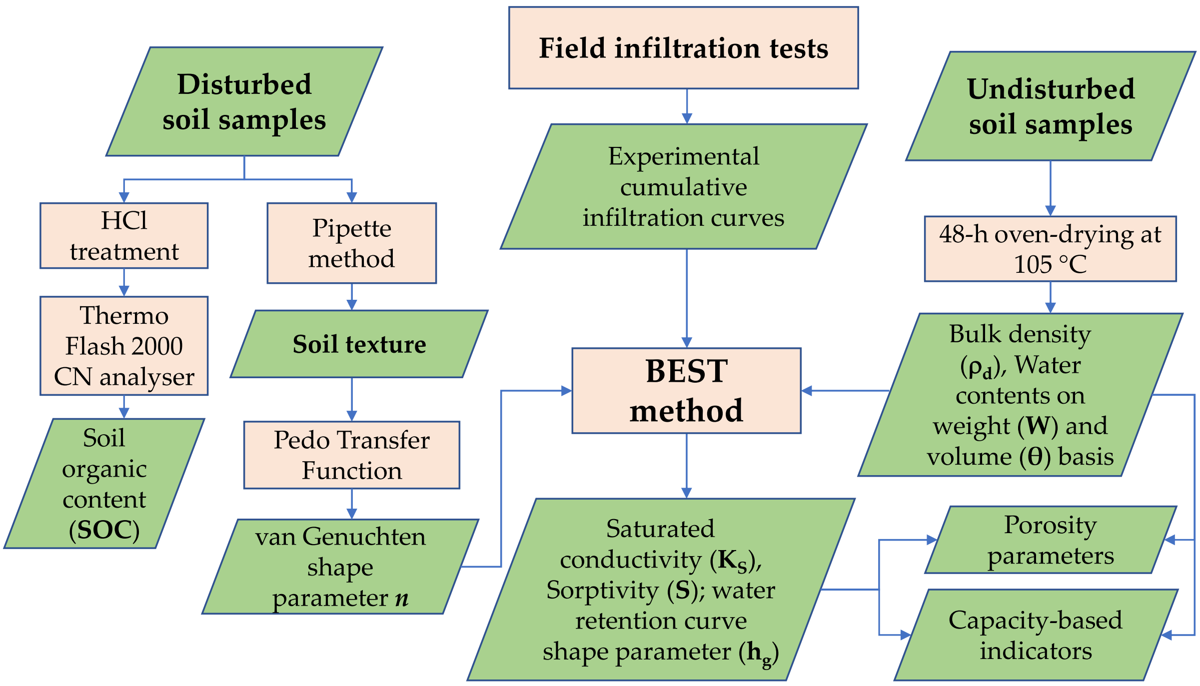

Figure 2. Workflow diagram of the experimental procedures.

The disturbed samples were used for texture determination using the pipette method [33] and SOC content using a Thermo Flash 2000 CN analyser (Thermo Fisher Scientific, Waltham, MA, USA) after treatment with HCl to remove the inorganic C. After oven drying for 48 h at 105 °C, the undisturbed soil samples allowed for the determination of the bulk density ρ_d (g cm^{-3}) and the initial volumetric water content by weight W_i (g g^{-1}). The initial volumetric water content θ_i was obtained as $\theta_i = W_i \cdot \rho_d$. The volumetric water content at saturation θ_S was computed as $(1 - \rho_d)/2.65$, where the value 2.65 g cm^{-3} is the assumed density of the soil particles. In the BEST method, the residual volumetric water content θ_r is supposed to be zero. When applying the BEST procedure for each sampling point, the averages θ_i and bulk density of the values measured at the two depths (0–5 cm; 5–10 cm) were used.

The infiltration experiments were carried out following the guidelines given in the literature [15]. The positions to perform the tests were chosen randomly, avoiding the portions of soil with evident compaction due to the passage of agricultural machinery. At each position, the aerial apparatus of the vegetation was cut at ground level without altering the soil structure. Then, a metal cylinder 16.3 cm in diameter was inserted approximately 1 cm into the soil to avoid lateral losses. The test consisted of pouring constant volumes of water ($\approx 1.465 \times 10^{-4}$ m^3) from time t = 0, waiting each time for complete infiltration and noting the required time. The poured volume determined a negligible hydraulic head ($\approx$ 0.7 cm), in accordance with the basic assumptions of the BEST method. Generally, steady-state conditions are reached using 8 to 15 water volumes depending on soil conditions [15]. Given the possible difficulties in detecting the steady state during field tests, it was decided always to pour at least 15 volumes (i.e., 105 mm) and to identify in post-processing the time when the steady state conditions occurred. In most cases, this ensured the achievement of near-stationary conditions, identified by negligible variations in the infiltration times of the 2–3 consecutive water inputs. The measures were used to derive the I(t) curves. The infiltration test was replicated at least five times for each plot shown in Figure 1. The positions for repetitions were chosen around the first test, spacing them at least 1 m apart. Therefore, 30 tests were performed for LTAE NewSmoca and 60 tests for LTAE Rotation, with at least 10 infiltration tests for each treatment (Figure 1).

The experimental cumulative infiltration curve I(t) was analysed using three different algorithms, BEST Slope, BEST Intercept and BEST Steady.

The hydraulic parameters obtained from replicated infiltration tests were averaged to obtain characteristic values for the plot based on a specific algorithm. In most cases, to obtain a more robust characterisations [15], the parameters derived from the three algorithms were also averaged in turn. Sometimes, due to the poor fit of some of the algorithms, the corresponding parameters were not considered when calculating the average hydraulic parameters of each plot.

All infiltration tests were conducted in a limited time interval (between the last decade of July and the first week of August 2023) without precipitation. Furthermore, the previous crop was always soft or durum wheat harvested a few days ago (around the beginning of July). The different plots were, therefore, very homogeneous regarding soil water content, type of vegetation and distance from the last tillage. This made it possible to reduce the introduction of disturbance factors (i.e., not linked to the type of management) capable of influencing the hydraulic characterisation of the soils.

3. Results

3.1. Soil Texture and Organic Content

From the analyses of the disturbed soil samples, the particle-size distributions of the superficial horizons (Ap) of each plot considered in the study were obtained (Figure 3). The soil texture shows moderate variability, which is reduced within the same LTAE.

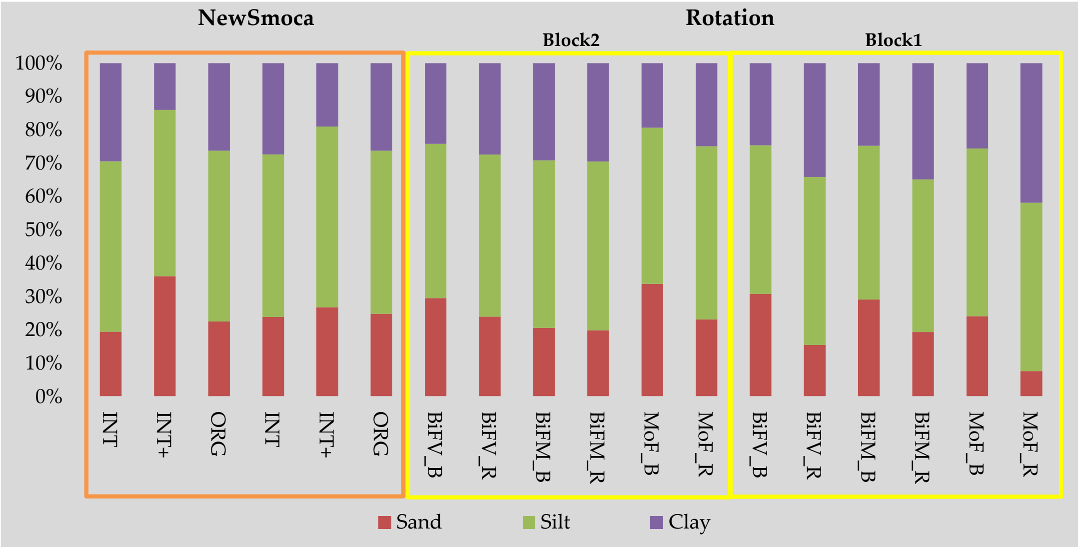

Figure 3. Mean percentages of sand, silt and clay particles for the plot considered in each Long-term Agroecosystem Experiment (LTAE). The plots correspond to those in Figure 1 in order from left to right. The acronyms indicate different soil, crop or residue management (see the text for detailed descriptions).

Organic carbon contents, SOC (%), were also obtained from the same samplings. Table 1 shows the mean values and standard deviations of the SOC in the different treatments. It can be observed that the values are mainly lower than 1%, with only slight differences among treatments. The only exception is the INT+ treatment, which shows significantly higher values than all the others.

Table 1. Mean and standard deviation (sd) of the Soil Organic Content (SOC, %) in the soil samples collected from the Ap horizon in the plots under different treatments in the considered Long-term Agroecosystem Experiment (LTAE).

LTAE	Treatment	SOC (Mean) (%)	SOC (sd) (%)
NewSmoca	INT+	2.09	0.38
NewSmoca	INT	0.74	0.01
NewSmoca	ORG	0.80	0.03
Rotation	BiFV_R	0.84	0.08
Rotation	BiFM_R	0.77	0.06
Rotation	MoF_R	0.95	0.12
Rotation	BiFV_B	0.98	0.03
Rotation	BiFM_B	0.81	0.14
Rotation	MoF_B	0.98	0.07

3.2. Physical Properties

First, we analysed the variability of physical soil parameters W_i, ρ_d and θ_i in the different LTAEs.

Regarding the LTAE NewSmoca plots, Figure 4 shows the average values of the three physical parameters for the sampling depths of 0–5 cm and 5–10 cm, respectively. The histograms also show the error bars in terms of confidence intervals and the letters associated with Tukey's 5% significance test (equal letter indicates non-significant differences), applied after a one-way ANOVA. The greatest variability is found in the first 5 cm layer. In particular, the INT+ treatment denotes significantly higher moisture and bulk density values than the other two. These, in turn, are very similar in water content, but the bulk density is lower for the organic treatment. In the 5–10 cm layer, no significant differences in moisture content are found, while the differences in bulk density are confirmed, albeit less markedly than in the surface layer.

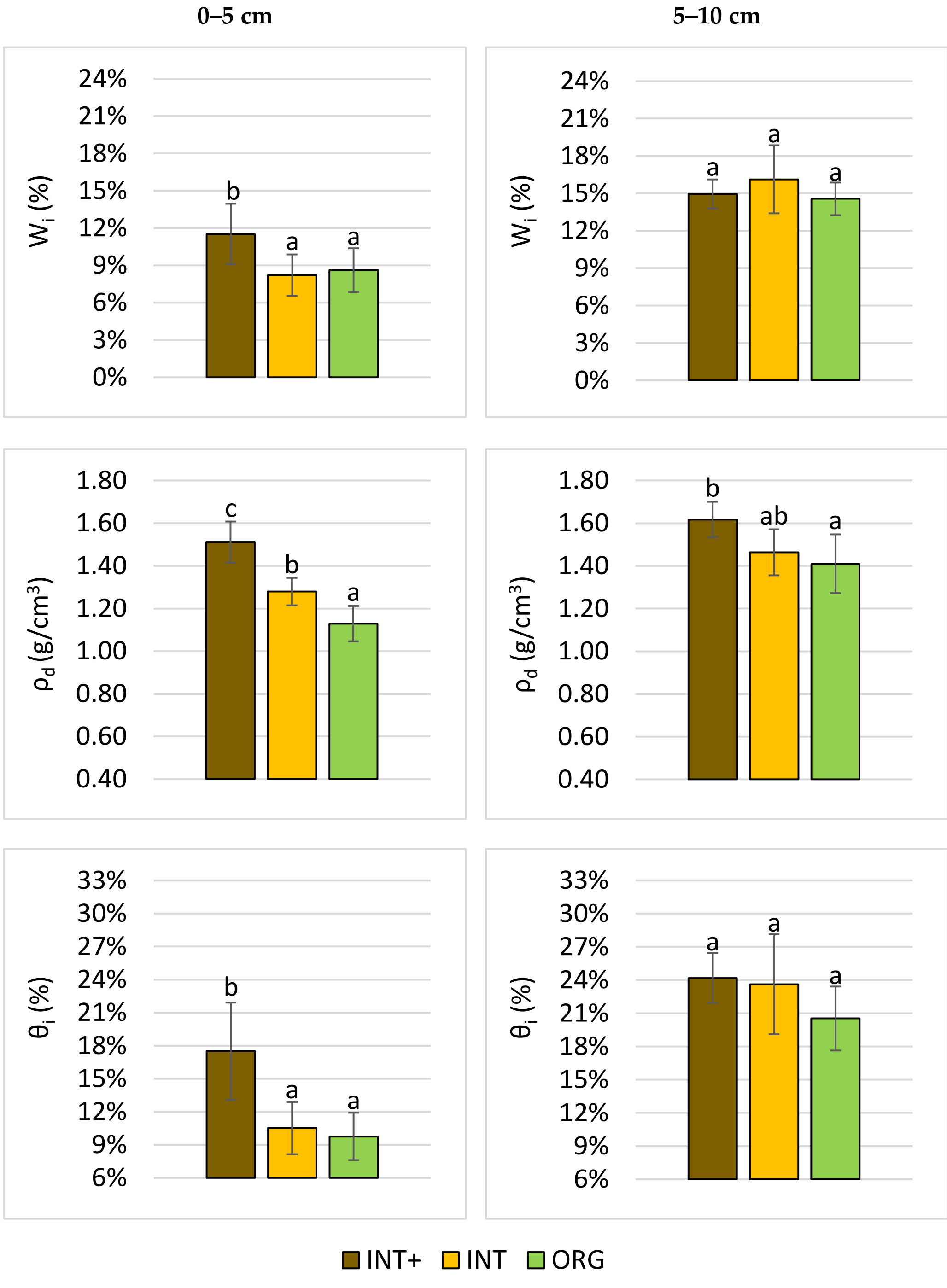

Figure 4. Mean values and error bars (95% confidence interval of the mean) of soil physical properties W_i, ρ_d and θ_i deriving from the samples collected in the 0–5 cm and 5–10 cm soil layers of the LTAE NewSmoca. Different letters are significantly different means according to a one-way ANOVA and Tukey's test (0.05 significance level). The abbreviations INT+, INT and ORG indicate different soil and crop management practices (details are given in the text).

For the LTAE Rotation, the analysis was performed by a two-way ANOVA considering the factors Rotation Type (RT, 3-level factor: MoF, BiFM, BiFV), Residual Management (RM, 2-level factor: buried, B; removed, R) and their interaction.

Figure 5 shows the mean values and the corresponding 95% confidence intervals of W_i, ρ_d and θ_i for each RT-RM combination.

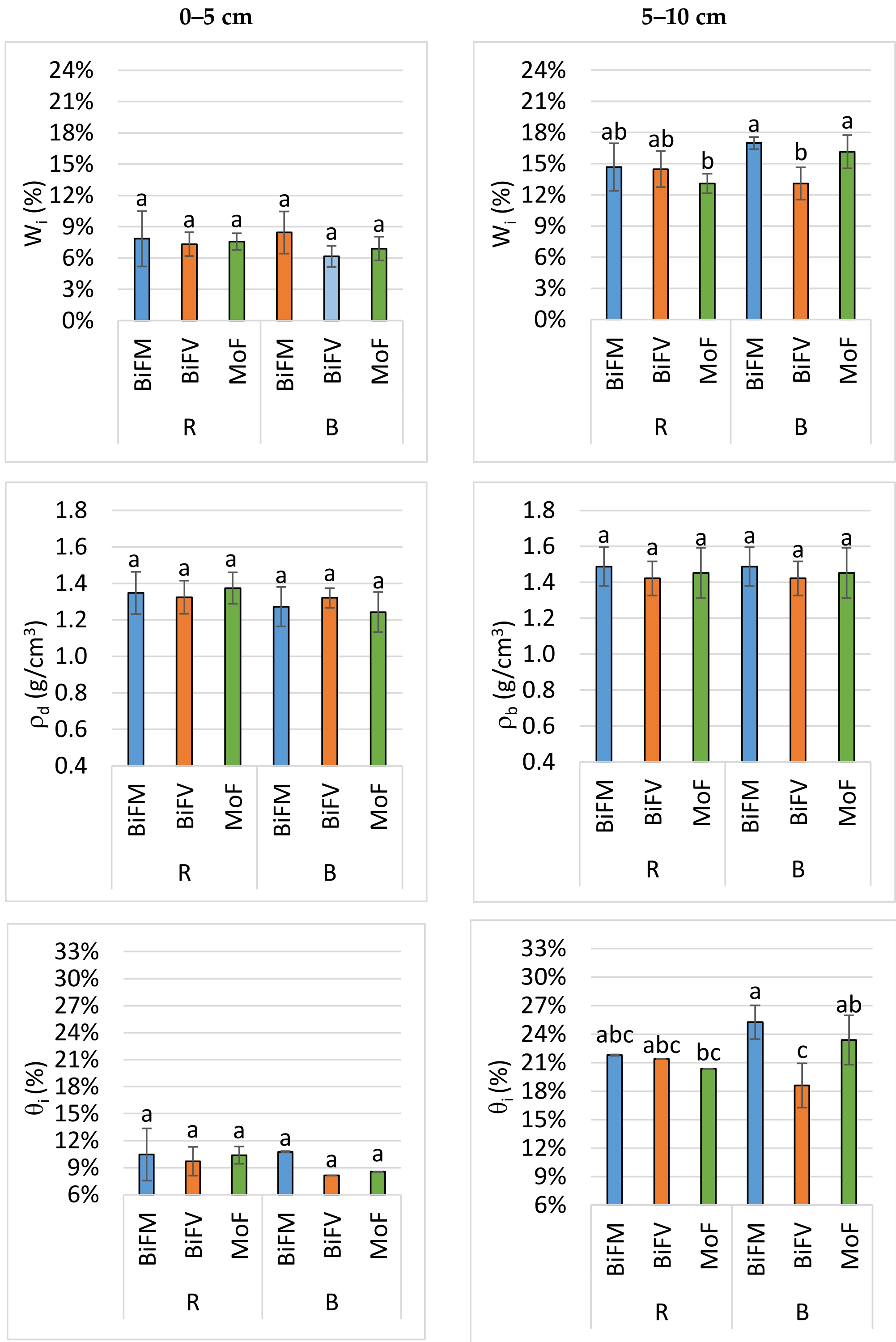

Figure 5. Mean values and error bars (95% confidence interval of the mean) of soil physical properties W_i, ρ_d and θ_i of soil samples collected in the layers 0–5 cm and 5–10 cm of the LTAE Rotation. Different letters are significantly different means according to a two-way ANOVA and Tukey's test (0.05 significance level). The abbreviations BiFM, BiFV and MoF indicate different crop rotations (details are given in the text). The letters R and B indicate the removed and buried crop residuals, respectively.

For the 0–5 cm layer, the analysis indicates a significant effect (p-value = 0.03) of the Residual Management factor on ρ_d, which exhibits a mean value lower in the buried than in the removed treatment (1.28 vs. 1.35 g/cm^3). No significant effects are associated with Rotation Type, nor with the RT-RM interaction. For the 5–10 cm horizon, the situation is more complex. Regarding W_i, the two-way ANOVA indicates significant effects for Rotation Type (p-value = 0.007), Residual Management factor (p-value = 0.01) and their interaction (p-value = 0.002). For ρ_d, the ANOVA does not reveal any significant effect. For θ_i, the result is very similar to that found for W_i, even if in this case the Rotation Type factor is not significant (p-value = 0.15).

3.3. Results from BEST Procedure

3.3.1. Experimental Cumulative Infiltration and Infiltration Rate

The initial moisture conditions of the topmost soil layer (0–5 cm) met the condition required by the BEST procedure (i.e., $\theta_i < 0.25\ \theta_S$) [14] in most cases (80 per cent of samples). This allowed the correct application of the method and the possibility of observing the transient phase of the infiltration process in sufficient detail, although the moisture of the subsurface layer (5–10 cm) often did not meet the same condition.

The dynamics of the cumulative infiltration and infiltration rate of each infiltration experiment are shown in Figure 6. In several cases, near-stationary conditions were reached before pouring the 15 volumes.

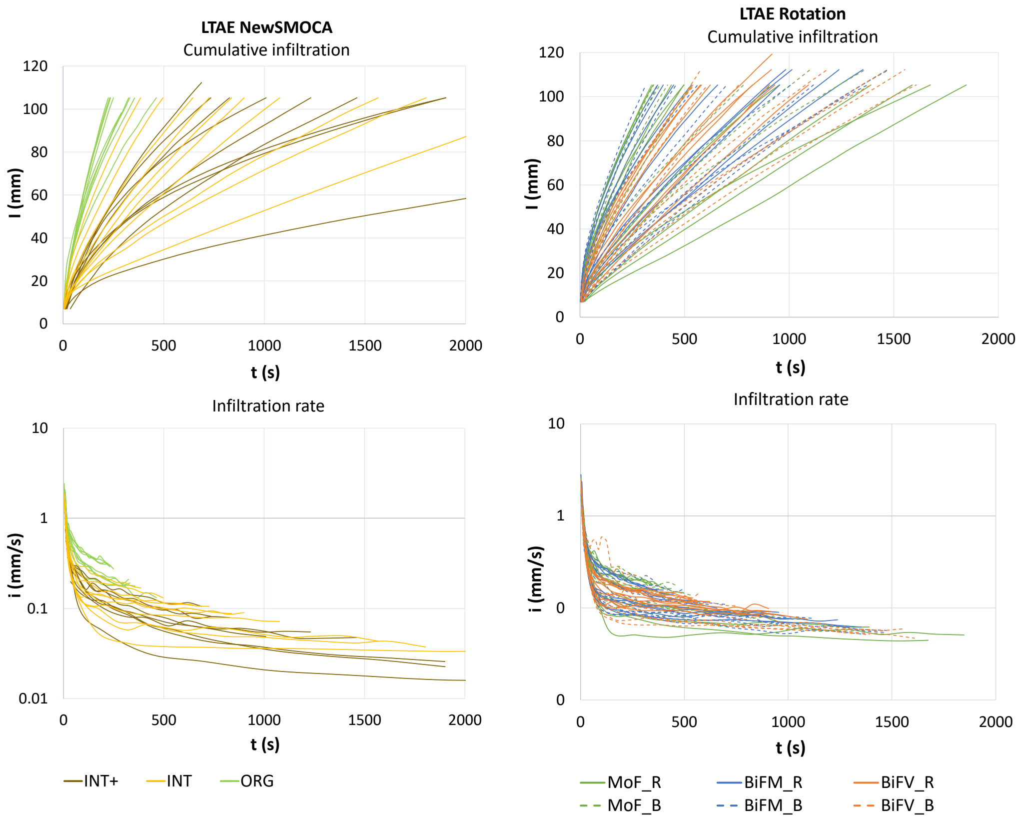

Figure 6. Cumulative infiltration I (mm) and infiltration rate i (mm/s) for the experiments carried out in the LTAE NewSmoca (30 curves) and Rotation (60 curves). For graphical reasons, the durations of two experiments in the plots INT e INT+ appear truncated at 2000 s in the figure showing the cumulative infiltration. Their effective durations are 2536 and 5327 s, respectively.

Regarding LTAE NewSmoca, the ORG plots present higher infiltration rates than the INT and INT+ ones (which are quite similar). In LTAE Rotation, there is a less broad range of variation compared to that of LTAE NewSmoca, but more specific considerations on the effect of rotation or residual management cannot be deduced from Figure 6.

The cumulative infiltration curves obtained for LTAE NewSmoca exhibited an excessive concavity in several cases. This phenomenon usually indicates progressive soil sealing throughout the test, attributed to the disturbance caused by the manual pouring volumes of water [15,34]. Under these conditions, as pointed out by Di Prima et al. [34], the BEST-Slope and BEST-Intercept algorithms cannot be used, while the BEST-Steady algorithm can still give some useful indications of the values of K_s and S. However, these are anomalous conditions for correctly applying the BEST method. Therefore, the results must be considered cautiously. In the present work, which has mainly comparative purposes, this uncertainty was considered tolerable to obtain rough indications of the differences between the different Long-term Agroecosystem Experiments. Furthermore, in order not to introduce inhomogeneities in the results, all the infiltration curves obtained in the NewSmoca LTAE were processed with the BEST-Steady algorithm alone, even in those cases where the other algorithms provided a satisfactory fitting to the experimental infiltration curves.

Instead, for the plots considered in the LTAE Rotation, a satisfactory fit of the theoretical models of the BEST method to the experimental cumulative infiltration curves was generally attained with any algorithm. Therefore, the hydraulic parameters characterising the plots were obtained by averaging the estimates provided by all three algorithms.

3.3.2. Soil Hydraulic and Porosity Parameters

The hydraulic and porosity parameters obtained for the soils subjected to the different LTAE NewSmoca treatments were analysed with a one-way ANOVA and Tukey's test (Table 2).

Table 2. Mean values of hydraulic parameters and capacity indicators for the treatments considered with each Long-term Agroecosystem Experiment. The same letter indicates no significant differences according to Tukey's test at the 5% significance level within the same LTAE. K_S: saturated hydraulic conductivity; S: sorptivity; h_g scale parameter of the water retention curve; λ_m: flow-weighted mean pore size; N_0: number of soil pores having a mean size λ_m; P_{MAC}: macroporosity; A_C: air capacity; R_{FC}: relative field capacity; AWC: plant available water content. The treatment acronyms are defined in the text.

LTAE	Treatment	K_S (mm/s)	S (mm/s$^{0.5}$)	h_g (mm)	λ_m (mm)	N_0	P_{MAC}	A_C	R_{FC}	AWC
NewSmoca	INT+	0.02 ^{a}	0.93 ^{a}	−138.6 ^{a}	0.06 ^{a}	4.5×10^5 ^{a}	2% ^{a}	13% ^{a}	69% ^{a}	17% ^{a}
NewSmoca	INT	0.04 ^{a}	1.31 ^{a}	−57.7 ^{b}	0.13 ^{b}	4.2×10^4 ^{ab}	5% ^{b}	17% ^{b}	64% ^{b}	17% ^{a}
NewSmoca	ORG	0.10 ^{b}	2.34 ^{b}	−66.8 ^{b}	0.11 ^{b}	1.4×10^5 ^{b}	5% ^{b}	19% ^{b}	64% ^{b}	19% ^{b}
Rotation	BiFV_R	0.05 ^{a}	1.59 ^{a}	−68.7 ^{a}	0.12 ^{a}	1.4×10^5 ^{a}	4% ^{a}	15% ^{a}	67% ^{a}	16% ^{a}
Rotation	BiFM_R	0.05 ^{a}	1.49 ^{a}	−58.5 ^{a}	0.13 ^{a}	5.3×10^4 ^{a}	5% ^{a}	16% ^{a}	65% ^{ab}	16% ^{b}
Rotation	MoF_R	0.05 ^{a}	1.50 ^{a}	−60.9 ^{a}	0.15 ^{a}	1.2×10^5 ^{a}	5% ^{a}	15% ^{a}	66% ^{abc}	15% ^{b}
Rotation	BiFV_B	0.05 ^{a}	1.54 ^{a}	−72.8 ^{a}	0.11 ^{a}	1.8×10^5 ^{a}	4% ^{a}	17% ^{ab}	65% ^{abc}	17% ^{bc}
Rotation	BiFM_B	0.04 ^{a}	1.39 ^{a}	−55.8 ^{a}	0.14 ^{a}	4.3×10^4 ^{a}	6% ^{a}	19% ^{b}	61% ^{bc}	17% ^{cd}
Rotation	MoF_B	0.06 ^{a}	1.78 ^{a}	−69.8 ^{a}	0.11 ^{a}	1.1×10^5 ^{a}	5% ^{a}	19% ^{b}	62% ^{c}	18% ^{d}

For all hydraulic parameters (K_S, S, h_g, λ_m, N_0), we found significant effects due to the soil management treatment with *p*-values of 1.2×10^{-5}, 1.2×10^{-8}, 1.6×10^{-5}, 4.3×10^{-7} and 8×10^{-3}, respectively. For K_S and S, the differences are attributable to the ORG treatment, which, for both parameters, shows significantly higher values compared to INT and INT+, which do not present significant differences. Considering scale parameter h_g, the significant differences are attributable to the INT+ treatment, which has a decidedly lower value than that found for INT and ORG. The same consideration holds for λ_m and N_0, which are significantly different (lower and higher, respectively) in the INT+ treatment compared to the other two treatments.

In the case of the LTAE Rotation, a two-way ANOVA was conducted to analyse the effect of Rotation Type and Residual Management factors and their interaction on the estimated porosity and hydraulic parameters. The analysis revealed a moderate significance of the RT factor on K_S, S, h_g and N_0 with *p*-values of 0.02 for all variables. Beyond these statistical differences, the actual differences are often negligible (Table 2). To deepen the analysis, considering the layout of the plots in the LTAE Rotations (Figure 1), an additional element of variability was considered by dividing the plots into Block 1 and Block 2 (Figure 1). In this case, the ANOVA indicated a significant effect of the "Block" factor on all the hydraulic parameters, with *p*-values ranging between 10^{-4} and 10^{-16}. In particular, the mean values of S, K_s, h_g, λ_m and N_0 for Block 1 are, respectively, 0.07 mm/s, 1.9 mm/s$^{0.5}$, −73 mm, 0.10 mm and 187,325, while for Block 2 they are 0.035 mm/s, 1.2 mm/s$^{0.5}$, −56 mm, 0.14 mm, and 33,983.

3.3.3. Capacity-Based Indicators

The same statistical methods described in the previous paragraph were also used to evaluate the differences in the capacity indicators. For the LTAE NewSmoca, the one-way ANOVA showed significant differences among treatments for all the capacity-based indicators with *p*-values of 10^{-7} order (P_{MAC}, $A_{C,}$ and AWC) and 10^{-3} for R_{FC}. The significant differences are mainly attributable to the INT+ treatment with P_{MAC} and A_C values lower than those of the other two treatments and a higher R_{FC} value. In terms of AWC, however, the INT+ and INT treatments show similar values, significantly lower than those estimated for ORG. In any case, all parameters are within the ranges considered good or optimal, except for P_{MAC} for the INT+ treatment, which indicates aeration-limited soil.

For LTAE Rotation, the results obtained from the two-way ANOVA are more complex than those obtained for the hydraulic and porosity parameters. The Residual Management factor is highly significant for parameters A_C, R_{FC} and AWC with *p*-values of 1.7×10^{-7}, 9×10^{-5} and 2.5×10^{-12}, respectively. In particular, it can be observed (Table 2) that the burial (B) treatments have generally higher values of A_C and AWC and lower values of R_{FC} than removal (R) treatments. The Rotation Type factor appears much less significant, for which *p*-values of 0.02, 0.01 and 0.01 were found for P_{MAC}, A_C and R_{FC}, respectively. In this case, the reason is to be found in the BiFV treatment, which presents mean values that are lower for P_{MAC} and A_C and higher for R_{FC}. The interaction RT-RM is significant only for AWC with a *p*-value of 1.3×10^{-5}. As for the hydraulic and porosity parameters, a significant effect of the block on all the capacity parameters was also detected.

4. Discussion

A first consideration related to the LTAE NewSmoca concerns the higher K_S and S values obtained for the ORG treatment compared to INT and INT+ (Table 2). The first explanation has to be found in the fact that the ORG treatment involves a surface tillage (i.e., about 20 cm depth) in early spring for the incorporation into the soil of the faba bean biomass intercropped with wheat. The effect of such recent tillage would justify the relatively high values of both K_S and S, which agrees with previous studies [35,36]. The lowest values of ρ_d observed for ORG (Figure 3) further support this interpretation. In addition to this short-term factor, the ORG treatment could be affected by a long-term effect due to the use of cover crops and the progressive increase in SOC expected in this type of soil management [37]. As Blanco-Canqui et al. [7] pointed out, some factors, such as conventional inversion soil tillage, could counteract this type of impact and the progressive accumulation of SOC. The SOC values detected in the AP1 horizon of the ORG plots indicate values only 0.1 percentage points higher than the INT plots, decidedly modest to affect the SHP significantly [11]. Concerning the capacity-based indicators, the ORG treatment showed similar or better values than the other two, particularly regarding AWC (Table 2). Unfortunately, it is impossible to establish the extent to which these differences depend on the more recent tillage, the use of cover crops or even modest differences in texture (Figure 3).

Other interesting observations arise from the comparison between INT and INT+. The most evident effect of the no-tillage treatment (i.e., INT+) is the significant increase in ρ_d, which causes a slight worsening of some parameters, particularly those related to air exchange such as P_{MAC}, A_C and R_{FC} (Table 2). However, consistent with previous studies (e.g., Castellini et al. [8]), no-tillage does not appear to lead to relevant changes in most SHPs compared to conventionally tilled treatment INT. On the contrary, parameters λ_m and N_0 (respectively lower and higher in INT+ than in INT) indicate for the INT+ treatment the presence of a more structured soil, with numerous relatively smaller pores but likely continuous and better interconnected. This result denotes improved structural stability, resulting from the synergetic action of no-tillage and progressive SOC accumulation in the shallow soil layer, typical of this soil management strategy [38,39]. Indeed, SOC analyses in the AP1 horizon (Table 1) indicate 1.4 percentage point higher values in the INT+ treatment than in INT. The fact that similar AWC values were estimated for the INT and INT+ treatments (Table 2) is consistent with the previous interpretation. It appears even more relevant considering that the soil textural conditions of the INT+ plots (slightly more sandy and less clayey than the INT plots, Figure 3) would have led to lower AWC values.

In conclusion, the INT+ soil, despite the deterioration of some physical parameters such as ρ_d, thanks to the enhanced microporosity, shows SHP comparable with those found for the conventional treatment (INT).

With regard to the LTAE Rotation, some significant differences were found in the physical parameters. In particular, the bulk density ρ_d in the first 5 cm in soils where residue burial is approximately 0.07 g/cm^3 lower than in soils with residue removal, consistent with what is expected from this practice. Although statistically significant, the difference appears to be of little relevance in influencing the hydraulic behaviour of the soil. Moreover, in the lower layers (5–10 cm), no significant differences in terms of ρ_d can be detected. As far as water content is concerned, there are also no particularly marked differences in the different combinations of Rotation Type and Residual Management. The statistically significant differences found for W_i and θ_i in layers 5–10 cm, are not easy to interpret and, again, do not seem so relevant in practical terms. The statistical significance is likely the result of the modest variability in the samples taken at this depth. These subtle differences in physical characteristics are consistent with the fact that the BEST-derived hydraulic and porosity parameters appear barely influenced by the different crop rotations or residue management.

The most relevant differences in the hydraulic and porosity parameters were found in the spatial comparison (i.e., Block 1 vs. Block 2), consistent with the moderate textural differences found in the two blocks (Figure 3). In particular, the plots in Block 1 had average sand and clay values of 21% and 31%, respectively, as opposed to Block 2, for which the same fractions were 25% and 25%. These textural differences are evidently the main driver of the BEST-derived soil hydraulic and porosity parameters.

The result obtained for the capacity-based indicators is more interesting. In this case, besides the effect of different textures between the blocks, the influence of the Residual Management factor appears equally relevant. In particular, the plots with residue burial perform better than those with residue removal in terms of P_{MAC}, A_C and R_{FC}. This result agrees with what is expected under these residue management practices [5,11]. However, this contrasts with the fact that the SOC values in the burial treatment are higher than in the removal treatment by just 0.1 percentage points. Despite the long-term experimentation, the reason for this limited increase is, as already commented previously, the probable contrasting effect of the conventional inversion soil tillage.

From our findings, the introduction of cover crops in a cropping system with soil in-version tillage (i.e., ORG) or with soil conservation management (i.e., INT+) appears to be a practice of paramount importance for improving soil health, but the best results are only achieved when soil conservation practices are applied. Even with proper crop residue management (i.e., RM burial in LTAE "rotation"), the SOC increases in the long term and the improvement of several soil quality parameters (e.g., λ_m and N_0) cannot be achieved. Therefore, the combination of cover crops with conservation tillage represents a win-win solution that can bring together environmental and productive performances towards true agricultural sustainability. However, there is still a long way to go in scientific research on the site-specific management of no-tillage-cover crop systems and their relationship with soil water dynamics, especially in the Mediterranean environment.

5. Conclusions

In this work, the BEST method was applied for the hydraulic characterisation of the soils of two Long-term Agroecosystem Experiments in a typical Mediterranean environment with predominantly loamy soils. Treatments differed in various aspects, such as residue management, crop rotations, tillage type, use of cover crops and agrochemicals.

The method has proven to be ideal for obtaining the parameters of the soil retention and hydraulic conductivity curves under field conditions in a relatively simple and expeditious manner. From the BEST-derived retention curve, capacity-based indicators were derived to assess the availability of air and water in the soil. Information on pore characteristics (size and number) was also obtained using established equations.

The BEST method demonstrated good sensitivity, which allowed us to detect the most relevant differences between soil and crop management strategies. The hydraulic parameters obtained in some soil treatments could be affected by some uncertainty due to possible sealing phenomena that occurred in some infiltration tests. However, comparing the estimates obtained from these particular infiltration curves and those with more regular behaviour showed no substantial differences. In the future, it is advisable to adopt automated procedures, such as those illustrated by Concialdi et al. [40], to reduce the experimental effort and attenuate surface disturbance phenomena due to manual operations.

In general, no-tillage led to a high compaction of the surface soil layers. However, probably thanks to the cover crop practice, this loss of porosity was compensated by forming a stable structure with high microporosity, resulting in hydraulic properties similar to those estimated for the soils under conventional tillage. Soils under organic farming showed the highest conductivity, sorptivity and available water content values. However, it is unclear to what extent this is due to more recent tillage, soil texture differences or practices favourable to increasing organic matter (e.g., cover crops and biomass incorporation).

Burying crop residues determined minor differences in hydraulic properties compared to soils where residues were removed. This could depend on the fact that this type of residue management was combined with conventional inversion soil tillage, which does not allow for a relevant accumulation of organic matter.

More clarity can be gained with further experimental activities to increase the size of the data sets and the robustness of the statistical analyses. In this context, it will be fruitful to adopt experimental designs that allow the study of the effect of soil and crop management techniques on hydraulic properties as far as possible while minimising the influence of other factors (mainly soil texture). The study was also based on data collected over a limited period. The literature (e.g., [12]) shows how soil hydraulic properties can change within a few weeks of the last tillage or residue burial. Future research should, therefore, aim to increase the sampling frequency. This is a difficult challenge given the time and effort usually required to obtain the hydraulic characterisation of soils. In this context, rapid and reliable methods such as BEST are undoubtedly worth investing in.

Author Contributions: Conceptualisation, L.V., G.T. (Grazia Tosi), F.T. (Francesca Todisco) and J.B.; methodology, L.V., G.T. (Grazia Tosi), F.T. (Francesca Todisco) and J.B.; validation, L.V., G.T. (Grazia Tosi), F.T. (Francesca Todisco), J.B. and G.R.; formal analysis, L.V., G.T. (Grazia Tosi), F.T. (Francesca Todisco), J.B. and G.R.; investigation, L.V., G.T. (Grazia Tosi) and G.R.; resources, M.F., G.T. (Giacomo Tosti), A.A. and F.T. (Francesco Tei); data curation, L.V., G.T. (Grazia Tosi) and G.R.; writing—original draft preparation, L.V., G.T. (Grazia Tosi), F.T. (Francesca Todisco) and J.B.; writing—review and editing, L.V., G.T. (Grazia Tosi), F.T. (Francesca Todisco), J.B., G.R., M.F., G.T. (Giacomo Tosti), A.A. and F.T. (Francesco Tei); supervision, L.V., G.T. (Grazia Tosi), F.T. (Francesca Todisco) and J.B.; project administration, A.A., F.T. (Francesca Todisco) and F.T.; funding acquisition, F.T. (Francesca Todisco), F.T. (Francesco Tei) and G.T. (Giacomo Tosti). All authors have read and agreed to the published version of the manuscript.

Funding: This study received funding from (i) the European Union-Next-GenerationEU-National Recovery and Resilience Plan (NRRP)–MISSION 4 COMPONENT 2, INVESTIMENT N. 1.1, CALL PRIN 2022 D.D. 104 02-02-2022–(Soil Conservation for sustainable AgricuLture in the framework of the European green deal-SCALE) CUP N. J53D23010340006; (ii) the European Union-Next-GenerationEU-National Recovery and Resilience Plan (NRRP)–MISSION 4 COMPONENT 2, INVESTIMENT N. 1.1, CALL PRIN 2022 D.D. 104 02-02-2022–(Small reservoIrs restoration: Green blu-infrastructures to enHance rural area resilience To clImate chaNGe-SIGHTING) CUP N. F53D23002270008f; (iii) the European Union-Next-GenerationEU-National Recovery and Resilience Plan (NRRP)–MISSION 4 COMPONENT 2 INVESTIMENT N. 1.4—D.D. 1032 17 June 2022, Agritech National Research Center-CN00000022.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

B	Residual burial followed by surface ploughing
BEST	Beerkan Estimation of Soil Transfer parameters
BiFM	Biennial rotations of soft winter wheat with maize
BiFV	Biennial rotations of soft winter wheat with faba bean
INT	Integrated conventional with inversion soil tillage
INT+	Integrated conventional no-tillage with direct drilling of the crops
LTAE "Crop Rotation"	Different crop rotations and residue management: continuous soft winter wheat and biennial rotations of soft winter wheat with maize or faba bean.
LTAE "NewSmoca"	Biennial maize-durum wheat crop rotation under integrated low input cropping systems
LTAEs	Long-term Agroecosystem Experiments
MoF	Continuous soft winter wheat
ORG	Organic cropping system with inversion soil tillage
PSD	Particle size distribution
R	Residual complete removal followed by surface ploughing
RM	Residual management
RT	Rotation type
SHP	Soil physical-hydraulic properties
SOC	Soil organic carbon

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