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Effects of No-Tillage and Conventional Tillage on Physical and Hydraulic Properties of Fine Textured Soils under Winter Wheat

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Abstract: The conversion from conventional tillage (CT) to no-tillage (NT) of the soil is often suggested for positive long-term effects on several physical and hydraulic soil properties. In fact, although shortly after the conversion a worsening of the soil may occur, this transition should evolve in a progressive improvement of soil properties. Therefore, investigations aiming at evaluating the effects of NT on porous media are advisable, since such information may be relevant to better address the farmers' choices to this specific soil conservation management strategy. In this investigation, innovative and standard methods were applied to compare CT and NT on two farms where the conversion took place 6 or 24 years ago, respectively. Regardless of the investigated farm, results showed negligible differences in cumulative infiltration or infiltration rate, soil sorptivity, saturated hydraulic conductivity, conductive pores size, or hydraulic conductivity functions. Since relatively small discrepancies were also highlighted in terms of bulk density or soil organic carbon, it was possible to conclude that NT did not have a negative impact on the main physical and hydraulic properties of investigated clay soils. However, a significantly higher number of small pores was detected under long-term NT compared to CT, so we concluded that the former soil was a more conductive pore system, i.e., consisting of numerous relatively smaller pores but continuous and better interconnected. Based on measured capacity-based indicators (macroporosity, air capacity, relative field capacity, plant available water capacity), NT always showed a more appropriate proportion of water and air in the soil.

Keywords: BEST-procedure; soil hydraulic conductivity; capacity-based soil indicators; conventional tillage; no-tillage; durum wheat

1. Introduction

No-tillage, zero tillage, and direct drilling or sod-seeding are terms to define a soil management system in which field crops are sown without any main soil tillage, determining a very limited disturbance of the soil (i.e., lower than 5 cm), which may arise by the passage of the drill coulters during sowing [1]. In this farming system, at least a third of the soil surface may remain covered with plant residues, but this soil surface can even reach 100% [2], thus promoting soil protection from water erosion [3,4] and potentially increasing both the organic matter content and the presence of microorganisms into the soil [5]. Moreover, conversion to no-tillage systems may improve soil physical properties [6] and increase the soil water retention in rainfed environments [7]. In addition, savings on operating costs and reductions in machinery emissions are expected [8].

Overall, no-tillage and sod-seeding is used nowadays, especially for cereal cultivation. Compared to the different areas where such techniques are quite common, i.e., America and Australia [2], in Europe (EU 27), minimum tillage and sod-seeding is only applied on 3.5 million hectares (Eurostat SAPM and FSS, 2010) which represent 3.5% of total arable land area. Italy follows this trend since, in mid-2013, the proportion between conventional tillage (CT) and no-tillage (NT) was respectively of about 5.2 and 0.6 million hectares [9]. Several reasons can be assumed for the reduced application of these agronomic techniques in Mediterranean environments, including: (i) the lack of policies encouraging their adoption, (ii) a prejudice by farmers, since detectable positive effects are often not immediately apparent as they can only be observed after that a new equilibrium in soil properties has been established, (iii) appropriate drilling equipment and great skill and expertise are needed [10]. Regarding the second point, literature references suggest that the success of this option basically depends on the water availability for the crop; for example, comparable wheat yields between soil management strategies (CT≈NT) may be obtained under dry climates, while greater differences (CT»NT) can occur under humid climates [11]. In fact, exceptions have been identified with reference to specific soils, i.e., Vertisols, that is to say fertile structured soils and with a good water holding capacity, for which the shift from CT to NT can be less problematic and some level of economically acceptable yields even during dry periods can be reached [12,13]. Consequently, as fine textured soils are quite common in several cereal-growing areas (i.e., Southern Italy), conversion to NT may be considered a viable solution as compared to less suited soils [14]. The mentioned trend could be reversed as, starting from 2014, more and more farmers in Italy are making a conversion from CT to NT, taking advantage of the benefits of public funding for rural development (PSR 2014–2020), such that an increase of more than twice the NT area is expected over the next few years [15,16]. Consequently, as durum wheat is the main cereal crop in Italy, with a cultivated area of about 1.2–1.3 Mha (ISTAT, 2017), an increased focus on the effects of conversion from CT to NT on soil physical and hydraulic properties is desirable [1,2].

A relevant topic discussed in the literature concerns the transition time from CT to NT after which soil properties and crop yields begin to benefit from an expected higher complexity of the soil system [1,17,18]. A summary of long-term NT impact on physical and hydraulic soil properties was reported by Strudley et al. [19], and a recent review by Chandrasekhar et al. [20] discussed the modeling approaches to study the soil porosity in the transition from CT to NT. In particular, shortly after the conversion to NT and up to about 4–5 years, a worsening in soil properties, i.e., an increase in dry bulk density and a corresponding decrease in soil porosity or in hydraulic conductivity, can occur [2,19] regardless on the soil type [2]. However, this relatively short transition should evolve in a progressive improvement of soil structure, stabilization of the organic carbon content and/or of its improvement, i.e., in more complex fractions, also thanks to the increase of the microflora and the microfauna into the soil [1,2]. References also suggest that a period of about a decade may be considered the reasonable minimum time-frame for reaching a steady-state, namely characterized by an enhanced soil physical quality and stabilized production levels [1,11,19,21]. Reichert et al. [22], investigating the impact of conventional tillage on soils previously under no-tillage, suggested a temporal schematization of soil reconsolidation and soil aggregate creation processes, which can be divided into four phases: initial (1.5 years), intermediary (3.5 years), transitional (5 years), and stabilized (14 years) conditions. Regarding the impact on crop production, a global meta-analysis by Pittelkow et al. [11] has suggested that yields in the first 1–2 years following NT implementation declined for all crops except oilseeds and cotton, but matched CT yields after 3–10 years, except for maize and wheat in humid climates. Johnston and Poulton [23] suggested that research on this topic should be conducted investigating long-term experiments in order to assess the environmental sustainability and profitability when it works at full capacity. Long-term experiments, although expensive, can represent ideal laboratories to elucidate, for a given agro-environment, the impact of NT on soil physical and hydraulic properties [24–26]. Therefore, as the time elapsed in the conversion from CT to NT may be a crucial factor to evaluate the impact of alternative soil management strategies on soil properties, it is desirable to establish comparisons selecting farms under transition or farms where it is plausible to hypothesize that steady conditions of soil properties were reached, with farms in which the conventional tillage of the soil is adopted.

The assessment of NT impact on the soil obviously also depends on the specific evaluated soil property, soil texture, agro-environment, and their interaction [1,19,26]. Chang and Lindwall [27], for example, suggest that after 8 years on a loam soil in Canada, soil bulk density did not differ among crop rotations, and after 10 years of NT with continuous winter wheat, soil bulk density was higher than under CT. Conversely, an initial increase in bulk density near the surface of NT soils was showed by Vogeler et al. [21], but after 6 years a decline to values equal to or even less than that after ploughing were detected. Contrasting results were reported also in terms of hydrodynamic soil properties. Liepic et al. [28], for example, reported a reduction of about 60% of the cumulative infiltration under long-term NT as compared to CT, while Azooz and Arshad [29] showed that long-term NT generally increased ponded infiltration rates under initial dry, near field capacity and field capacity, but not under near saturated soil conditions.

The general conclusions drawn from the examined literature suggest that, if a trend exists, NT increases the aggregate stability and the pores' connectivity, generating inconsistent responses in total porosity and soil bulk density compared to CT; this corresponds to a very likely increase in the saturated or near-saturated hydraulic conductivity of NT soil management [19]. Therefore, suggested advances in this research area should be addressed to dispel existing doubts in order to: (i) fill the gap of knowledge for specific agro-environments, (ii) provide information of NT under long-term experiments to quantify pros and cons compared to CT, (iii) obtain improvements in the soil hydraulic characterization accuracy, by applying parametric estimation methods that allow both to evaluate soil properties changes and to obtain input data for agro-environmental simulation purposes. However, to our knowledge, a lack of information exists for Mediterranean agro-environments of Italy, as only few investigations were carried out in orchards [30] or for irrigated vegetable crops [31], and no reference has assessed the impact of NT on hydrostatic and hydrodynamic soil properties under rainfed wheat cultivation.

The Beerkan Estimation of Soil Transfer (BEST) parameters procedure [32] is an attractive, easy, robust, and inexpensive way for a parametric soil hydraulic characterization [33,34]; namely, it allows for the simultaneous determination of both the water retention curve, i.e. the relationship between volumetric water content, θ, and pressure head, h, and the hydraulic conductivity function, i.e. the relationship between the soil hydraulic conductivity, K, and θ (or h) [32]. Because of its simplicity, accuracy, and versatility of application (i.e., a standard or simplified application of the experimental procedure can be chosen), in fact, BEST was adopted in various agronomic-forest or -environmental investigations to compare, for example, different land uses [35,36], to assess the physical quality of Brazilian [37], Sicilian [38], or Burundian [33] soils, to investigate the effect of forest restoration on soil hydraulic conductivity [39] or to establish the role of soil sealing in water infiltration [40,41]. To date, the experimental procedure has received increasing attention and about eighty theoretical or applicative manuscripts were published, as reported on the Scopus database. Application of the BEST-procedure, for example, recently allowed the direct measurement of basic hydrodynamic soil properties, i.e., saturated hydraulic conductivity and soil sorptivity, and to estimate water dynamic based indicators, i.e., flow-weighted mean pore size and the corresponding number of hydraulically active pores of agricultural [42,43] and marginal [36] soils. Consequently, as the methodology allows one to obtain a high number of accurate measurements in a relatively short time, it allows one to minimize the spatial and temporal variability of the investigated soil properties. Moreover, since it is expected that alternative soil management strategies, such as CT or NT, can impact sorptivity [44], structure [45], and hydrostatic and hydrodynamic soil properties [46], BEST has proven to be a technique to accurately evaluate the impact of agronomic treatments on the physical and hydraulic properties of cultivated soils. However, since the considered soil management strategy could also affect the optimal balance between water and air in the soil, the water retention curve has been experimentally determined in the lab, and some capacity-based indicators (e.g., macroporosity, air capacity, relative field capacity, plant available water capacity) were estimated to evaluate the impact of MT and NT on soil water conservation [36].

The general objective of this investigation was to assess the impact of alternative soil management strategies on physical and hydraulic properties of fine textured soils, applying field and lab procedures, to help fill a gap of information on this topic for Mediterranean environments. In particular, two private farms located in Puglia (southern Italy), in which the long-term NT for durum wheat was established from a different time frame, six or twenty-four years, were selected and compared to CT. To achieve these goals, basic physical and hydraulic properties of the soil, i.e., texture, bulk density, total organic carbon, cumulative infiltration or infiltration rate, saturated hydraulic conductivity and sorptivity, and soil water retention curve were directly measured; two indicators of soil porosity were estimated to account for the hydrodynamic soil properties (flow-weighted mean pore size and number of hydraulically active pores), and four capacity-based indicators (macroporosity, air capacity, relative field capacity, and plant available water capacity) were considered as hydrostatic soil properties.

2. Materials and Methods

2.1. Experimental Sites

Selected experimental sites were two private farms located in central (Giglio farm, Gravina in Puglia, 40°52′57.1″N, 16°22′31.4″E) and north (Casone farm, Candela, 41°08′04.8″N, 15°31′56.0″E) Apulia, southern Italy (Figure 1). Hereafter, the two farms investigated will be identified as Gravina and Candela. Two alternative soil management strategies for durum wheat cultivation were considered in this investigation, namely conventional tillage, CT and no-tillage, NT. Two surface areas of approximately 2.6–5.3 and 5.5–8.2 ha, were respectively selected in Gravina and Candela farms (Figure 1). In Gravina, the NT management plot was repeated for approximately 24 years while in CT plot the monoculture of wheat had been carried out for 28 years. Protein pea fallow has preceded durum wheat cultivation on NT. Therefore, NT run under conservative agriculture, as it respects the principles of direct sowing, residuals on the surface and crop rotation. As an example, Figure 1 shows some views of fields at the Gravina site. At Candela farm, the transition was relatively more recent as NT practice had been implemented from 6 years, and a biennial crop rotation, "cereals (barley or durum wheat)—field bean" was established. Additional information on the main cultivation practices carried out in the investigated farms were reported in Table S1.

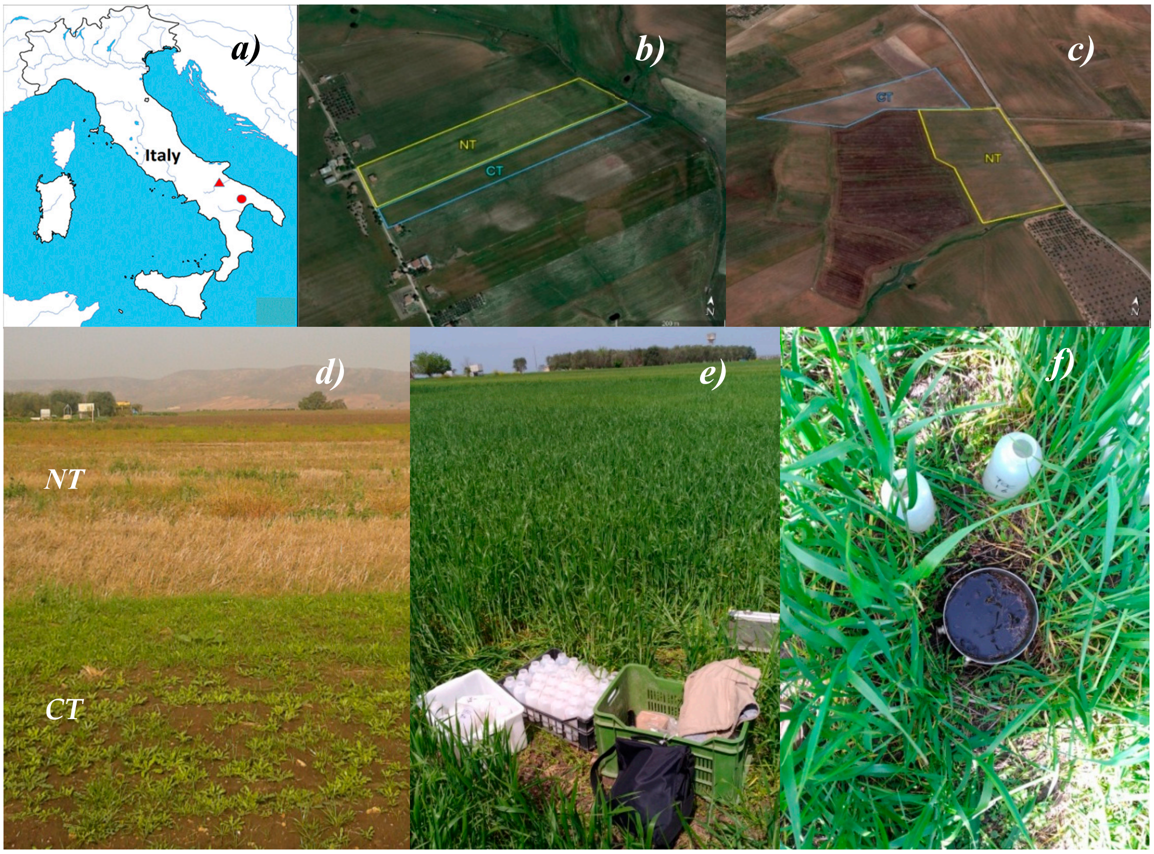

Figure 1. Geographical location of the studied sites (**a**) of Gravina (**b**) and Candela (**c**) (point and triangle respectively on the map); view of Gravina site (early November) under no-tillage, NT and conventional tillage, CT (**d**); view of the field site in April (**e**) and detail of the cylinder used for Beerkan tests (**f**) under NT in Gravina.

2.2. Soil Sampling and Measurements

Eleven to thirteen BEST experiments were randomly carried out in the spring season (between the end of April and the beginning of May, at heading-flowering stages) of 2017 to obtain soil hydraulic characterization (i.e., saturated hydraulic conductivity, K_s and the hydraulic conductivity function) of each experimental area (i.e., CT and NT of Gravina and Candela sites). In particular, as is common for BEST application, a falling head infiltration experiment of Beerkan type was carried out at each sampling point using a metal ring with a cutting edge. In detail, Beerkan tests were performed using a 15-cm-inner diameter cylinder, inserted to a depth of about 1 cm to avoid lateral loss of ponded water [32]; a known volume of water (200 mL) was repeatedly poured into the cylinder, establishing a height of water of 1.1 cm, and the time needed for complete infiltration was logged. The procedure was repeated for a total of 15 water volumes, and experimental cumulative infiltration, I(t), and infiltration rate q(t), were thus deduced.

For each infiltration point, two undisturbed soil cores (0.05 m in height by 0.05 m in diameter) were collected at the 0 to 0.05 m and 0.05 to 0.10 m depths near the cylinder (e.g., <10 cm) to determine the soil water content at the beginning of an infiltration experiment, θ_i, and the soil dry bulk density, *BD*. Following a procedure commonly used for BEST application, a unique value of both θ_i and *BD* was determined for each sampling point by averaging the values measured at the two depths [36,40,47]. A disturbed soil sample (0–0.10 m depth) was collected at each sampling point to determine both the soil particle size distribution (*PSD*) and the total organic carbon (*TOC*) content. The clay, silt, and sand percentages were determined according to the USDA standards [48]. The *TOC* content was quantified through dry combustion using a TOC Vario Select analyzer (Elementar, Germany), which conducts a catalytic combustion by high temperatures in an air environment [49].

For each soil management strategy (CT and NT) and farm (Gravina and Candela) considered in this investigation, from seven to eleven undisturbed soil cores (8 cm-inner-diameter by 5 cm-height) were randomly collected at the 0 to 0.10 m depth to determine some soil water retention values at high pressure heads ($h \geq -100$ cm); a corresponding number of disturbed soil samples were also collected to determine other water retention curve values at low pressure heads ($h \leq -330$ cm). In detail, volumetric water retention, θ, data were determined on each undisturbed soil core by a hanging water column apparatus for pressure head, h, values ranging from -5 to -100 cm, and on repacked soil cores by pressure plate method for h values ranging from -330 to $-15{,}300$ cm [50]. Finally, the soil water retention function was obtained fitting the experimental data with the van Genuchten [51] model, as it is common in the parameterization procedures [50].

At the end of the crop season, each farmer provided the total grain yields (q ha^{-1}) obtained in the fields under CT and NT. Additional measurements on the crop growth, i.e., leaf area index (*LAI*) and aboveground biomass, were also carried out once at Gravina site at the end of stem elongation stage. LAI was directly measured by LAI-2000 Plant Canopy Analyzer (Li-Cor).

2.3. Application of BEST Procedure and Estimation of Soil Porosity Indicators

The BEST procedure [32] was applied in order to estimate the hydraulic conductivity function, i.e., the relationship between the hydraulic conductivity, K, and the volumetric soil water content, θ. according to the Brooks and Corey [52] model:

$$\frac{K(\theta)}{K_s} = \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{\eta} \tag{1a}$$

$$\text{with } \eta = \frac{2}{mn} + 2 + p \tag{1b}$$

where θ [L^3·L^{-3}] is the volumetric soil water content; K [L T^{-1}] is the soil hydraulic conductivity; n (>2), m, and η are shape parameters; p is a tortuosity parameter set equal to 1 following Burdine's condition [53]; field saturated soil water content, θ_s [L^3·L^{-3}], residual soil water content, θ_r [L^3·L^{-3}], and field saturated hydraulic conductivity, K_s [L T^{-1}], are scale parameters. In BEST, θ_r is assumed to be zero. Both shape and scale parameters must be estimated.

The texture-dependent shape parameters of the model were estimated from the particle-size analysis and *BD* assuming a shape similarity between the *PSD* and the water retention curve [54], while structure dependent scale parameters are estimated by a three-dimensional (3D) field infiltration experiment at zero pressure head, using the two-term transient infiltration equation by Haverkamp et al. [55]. A simplified approach was adopted in this investigation in order to apply the BEST-procedure in the simplest way possible (as the choices made below about the infiltration constants). In detail, basic soil texture fractions, i.e., sand, sa (%, USDA classification) and clay, cl (%) content were used to estimate n parameter, using a specifically developed pedotransfer function, PTF, by Minasny and McBratney [56]:

$$n = 2.18 + 0.11[48.087 - 44.954S(x_1) - 1.023S(x_2) - 3.896S(x_3)] \tag{2a}$$

where:

$$x_1 = 24.547 - 0.238sa - 0.082cl \tag{2b}$$

$$x_2 = -3.569 + 0.081sa \tag{2c}$$

$$x_3 = 0.694 - 0.024sa + 0.048cl \tag{2d}$$

$$S(x) = \frac{1}{1 + \exp(-x)} \tag{2e}$$

Generally θ_s is estimated from BD, assuming a soil particle density of 2.65 g cm^{-3} [34,57], while K_s and the soil sorptivity, S, are estimated by fitting the explicit three-dimensional infiltration model proposed by Haverkamp et al. [55] to the transient cumulative infiltration data.

Structure-dependent scale parameters were estimated by a falling head infiltration experiment of Beerkan type. In detail, the 3D cumulative infiltration, I (L), and the infiltration rate, i (L T^{-1}), can be approached by the following explicit transient (Equations (6a) and (6b)) and steady-state (Equations (6c) and (6d)) expansions [32,55]:

$$I(t) = S\sqrt{t} + \left(AS^2 + BK_s\right)t \tag{3a}$$

$$i(t)\frac{S}{2\sqrt{t}} + \left(AS^2 + BK_s\right) \tag{3b}$$

$$I_{+\infty}(t) = \left(AS^2 + K_s\right)t + C\frac{S^2}{K_s} \tag{3c}$$

$$i_s = AS^2 + K_s \tag{3d}$$

where i_s (L T^{-1}) is the steady-state infiltration rate, A (L^{-1}), B and C are constants defined taking into account initial conditions as [55]:

$$A = \frac{\gamma}{r(\theta_s - \theta_i)} \tag{4a}$$

$$B = \frac{2-\beta}{3}\left[1 - \left(\frac{\theta_i}{\theta_s}\right)^{\eta}\right] + \left(\frac{\theta_i}{\theta_s}\right)^{\eta} \tag{4b}$$

$$C = \frac{1}{2\left[1 - \left(\frac{\theta_i}{\theta_s}\right)^{\eta}\right](1-\beta)} \ln\left(\frac{1}{\beta}\right) \tag{4c}$$

where r (L) is the radius of the disk source, γ and β are the infiltration constants [55].

Finally, the retention curve scale parameter, h_g, was estimated by the relationship:

$$h_g = -\frac{S^2}{c_p(\theta_s - \theta_i)\left[1 - (\theta_i/\theta_s)^{\eta}\right]K_s} \tag{5}$$

where θ_i [L^3 L^{-3}] is the soil water content at the time of sampling, and c_p is a coefficient dependent on n, m, and h according to Lassabatère et al. [32] (Equation (6b)).

Three alternative algorithms, i.e., BEST-slope [32], BEST-intercept [58], and BEST-steady [59] were applied in this investigation, differing only in the way the infiltration model is fitted to the experimental data [59]. However, in accordance with the reasoning given in the data analysis section, only one of the applied algorithms was selected for comparison purposes (CT vs. NT). Finally, the infiltration constants, β and γ, were fixed at the reference values of literature (β = 0.6 and γ = 0.75) [32]. An updated version of the workbook by Di Prima et al. [60] that considers all the available algorithms was used to analyse the experimental cumulative infiltrations, $I(t)$, by the three BEST-algorithms.

Two soil water dynamic based indicators were considered in this investigation to compare alternative soil management strategies (CT and NT), namely the flow-weighted mean pore size λ_m [L] and the number of hydraulically active pores per unit area $C_{\lambda m}$ [L^{-2}] [36,42,43].

The flow-weighted mean pore size λ_m was calculated by the following relationship according to Mubarak et al. [42]:

$$\lambda_m = \frac{\sigma_w}{\rho_w g \alpha h} \tag{6}$$

where σ_w [M T^{-2}] is the surface tension of water, ρ_w [M L^{-3}] is the density of water, g [L T^{-2}] is the acceleration due to gravity, and αh [L] is the capillary length, calculated from the scale parameter h_g as $\alpha h = -h_g$ [43,54].

The value of $C_{\lambda m}$ was calculated according to Watson and Luxmoore [61]:

$$C_{\lambda m} = \frac{8\mu K_s}{\rho_w g \pi {\lambda_m}^4} \tag{7}$$

where μ [M $L^{-1}T^{-1}$] stands for the dynamic viscosity of water.

With regard to the aforementioned indicators, it may be useful to underline that λ_m represents the pore size that contributes to water infiltration under ponding condition, thus providing an estimation of the relative importance of gravity and capillary forces on the total flow; consequently, $C_{\lambda m}$ provides an estimation of the number of soil pores, for unit of area, having a mean size equal to λ_m [46].

2.4. Capacitive-Based Indicators

For each soil water retention curve determined in the lab, four capacity-based indicators were estimated, and the impact of CT and NT on soil water conservation was assessed with reference to the optimal values of literature [50,62]. In detail, estimated soil water retention values corresponding to soil pressure head, h = 0, 10, 100, and 15,300 cm were used to calculate the macroporosity (P_{mac}), air capacity (AC), relative field capacity (RFC), and plant available water capacity ($PAWC$), as summarized in Table 1. Therefore, the impact of soil management strategy was established as the difference between mean measured and optimal values (Table 1).

Table 1. Selected capacity-based indicators and corresponding optimal ranges or critical limits according to Reynolds et al. [62] and Castellini et al. [50].

Soil Physical Indicator	Reference Value	Mean Optimal Value
Macroporosity, P_{mac} (cm^3 cm^{-3}) $P_{mac} = \theta_s - \theta_m$	$0.04 \le P_{mac} \le 0.10$ optimal $P_{mac} < 0.04$ aeration limited soil $P_{mac} > 0.10$ water limited soil	$P_{mac} = 0.07$
Air capacity, AC (cm^3 cm^{-3}) $AC = \theta_s - \theta_{FC}$	$0.10 \le AC \le 0.26$ optimal $AC < 0.10$ aeration limited soil $AC > 0.26$ water limited soil	$AC = 0.18$
Relative field capacity, RFC (dimensionless) $RFC = \frac{\theta_{FC}}{\theta_s} = \left[1 - \left(\frac{AC}{\theta_s}\right)\right] = \left(\frac{PAWC+\theta_{PWP}}{\theta_s}\right)$	$0.6 \le RFC \le 0.7$ optimal $RFC < 0.6$ water limited soil $RFC > 0.7$ aeration limited soil	$RFC = 0.65$
Plant available water capacity, $PAWC$ (cm^3 cm^{-3}) $PAWC = \theta_{FC} - \theta_{PWP}$	$PAWC \ge 0.20$ ideal $0.15 \le PAWC < 0.20$ good $0.10 \le PAWC < 0.15$ limited $PAWC < 0.10$ poor	$PAWC = 0.20$

θ_s = saturated soil water content; θ_m = water content of the soil matrix (h = –10 cm); θ_{FC} = soil water content at the field capacity (h = –100 cm); θ_{PWP} = soil water content at the permanent wilting point (h = $-$15,300 cm).

2.5. Data Analysis

For each variable considered in this investigation (cl, si, sa, θ_i, θ_s, BD, TOC, h_g, S, K_s, λ_m, $C_{\lambda m}$, P_{mac}, AC, RFC, $PAWC$), a given dataset was summarized by calculating the mean and the associated coefficient of variation (CV). Arithmetic means were calculated for cl, si, sa, θ_i, θ_s, BD, TOC, λ_m, $C_{\lambda m}$, P_{mac}, AC, RFC, $PAWC$, since they were assumed to be normally distributed, as commonly suggested in the literature [36,62], while h_g and soil variables directly linked to the infiltration experiment, S and K_s, were assumed to be logarithmically distributed [63,64], and geometric means and associated CVs were calculated using the appropriate lognormal equations [65,66].

The impact of alternative soil management strategies on soil properties, i.e. CT and NT, was assessed in terms of cumulative infiltration and infiltration rate ($I(t)$ and $q(t)$), because it is expected that such different soil management can have a significant influence on the hydrodynamic properties of the soil. For the aforementioned soil systems, BD and TOC were considered to give account of possible effects on soil compaction or soil structure, respectively. Parameters directly obtained by

BEST (i.e., scale parameter, soil sorptivity, and saturated hydraulic conductivity, h_g, S, K_s) or those estimated from BEST (dimension and number of hydraulically active pores, λ_m and $C_{\lambda m}$) were also considered because the former represent fundamental hydraulic properties, and the latter are useful indicators for comparison purposes [41,67]. The hydraulic functions, that is, the hydraulic conductivity function, $K(\theta)$, and the water retention curve, $\theta(h)$, were respectively estimated or measured to show any differences in the saturated/unsaturated soil domain. Finally, capacity-based indicators (P_{mac}, AC, RFC, $PAWC$) were selected to assess the optimal balance between air and water into the soil [50].

Regarding the BEST application, we would like to point out that -intercept or -steady provide the same h_g estimation [34] and, consequently, a unique λ_m value for these algorithms can be obtained, whilst different estimations of S and K_s values can be obtained, according to the applied BEST-algorithm. Therefore, the impact of BEST-algorithms on S and K_s estimations was evaluated, but only one was selected to compare soil management strategies. For this purpose, as BEST-algorithms mainly consider the transient or the steady-state phase of the infiltration process [59], an analysis of the cumulative infiltration curves was carried out to establish the possible non-attainment of steady flow. Then, the equilibration time, t_s, namely, the time needed to reach steady-state conditions, the infiltrated depth at the equilibration time, $I(t_s)$, and the total duration, for the infiltration runs were determined and used to select the most appropriate algorithm for comparison purposes (CT vs. NT). Specifically, the t_s value was determined according to Angulo-Jaramillo et al. [68] as the first value for which:

$$\frac{\left|I(t) - I_{reg}(t)\right|}{I(t)} \cdot 100 \leq E \tag{8}$$

where $I(t)$ is the cumulative infiltration during time t, $I_{reg}(t)$ is the cumulative infiltration estimated from the regression analysis of the $I(t)$ vs. t plot, while E is the criterion for establishing the onset of linearity. Equation (8) is applied starting from $t = 0$ and progressively excluding the first data points until a value of $E \leq 2\%$ was reached [68].

Finally, the statistical significance between CT and NT or between soil properties was performed according to a two-tailed t-test ($P = 0.05$).

3. Results

3.1. Basic Soil Properties

According to the USDA classification, the texture of the upper layers of the soil (0–10 cm) was always clay in Candela (i.e., both for CT and NT) while it was both clay-loam or clay in Gravina site, depending on the soil management (CT or NT, respectively) (Table 2). Therefore, if compared to CT, the long-term NT showed an increase in the clay and sand fractions of the upper layer of Gravina soil. TOC, BD, θ_s, and θ_i, values of investigated soils were reported in Table 3. In detail, similar TOC values were generally detected, except for Candela where CT showed significantly lower values. Significantly higher values of BD were observed only under NT of Gravina as they were 1.15 times higher than CT, while no significant differences were detected in Candela. Since in BEST the saturated soil water content, θ_s, is estimated from the value of BD, significantly lower values of θ_s were also detected in the former case on the no-tillage plot (Table 3). Finally, relatively comparable θ_i values were detected in Candela, while higher differences between soil management strategies were detected in Gravina (Table 3). The impact of θ_i values on soil hydraulic characterization is reported in the following section.

Table 2. Clay (*cl*), silt (*si*), and sand (*sa*) contents (0–0.1-m depth) according to the USDA classification for sites (Gravina and Candela) and soil managements (conventional tillage, CT and no-tillage, NT) considered.

Site (Soil Management)	cl (%)	si (%)	sa (%)	USDA
Gravina (CT)	34.9	34.7	30.4	clay-loam
Gravina (NT)	42.9	21.5	35.5	clay
Candela (CT)	50.3	21.8	27.8	clay
Candela (NT)	55.0	24.5	20.5	clay

Table 3. Mean and associated coefficient of variation (CV, in parenthesis) of initial and saturated volumetric soil water content, θ_i and θ_s (cm^3/cm^3), bulk density, *BD* (g/cm^3), and total organic carbon, *TOC* (%).

	TOC	*BD*	θ_s	θ_i
Gravina CT	1.518 a (7.6)	1.1396 a (9.7)	0.5699 a (9.7)	0.1781 a * (9.3)
Gravina NT	1.614 a (13.5)	1.3007 b (7.4)	0.5092 b (7.4)	0.2156 a (13.8)
Candela CT	1.248 a (4.7)	1.2876 a (16.2)	0.5141 a (16.2)	0.2489 a (23.3)
Candela NT	1.514 b (14.1)	1.3299 a (15.0)	0.4982 a (15.0)	0.2807 a (26.1)

* For a given experimental site (i.e., Gravina or Candela), mean values followed by the same letter are not significantly different according to a two-tailed *t*-test (P = 0.05).

3.2. Comparison and Choice among BEST-Algorithms

The volumetric soil water content at the time of experiments, θ_i, has exceeded the suggested condition by Lassabatere et al. [32] according to which BEST experiments should be carried out in relatively dry soil conditions (i.e., $\theta_i \leq 0.25\ \theta_s$); this soil condition should ensure a greater success rate to obtain, using all the available BEST-algorithms (slope, intercept and steady), physically plausible estimates of soil hydraulic properties (i.e., positive values of K_s and S) [59]. Relatively high θ_i values, in fact, strongly affected Candela sites results, as relatively low percentages of success were obtained using BEST-slope under CT (1/12; 8% of success) and under NT (27%); relatively higher success rates however were obtained with the same algorithm at Gravina where BEST-slope provided about 67% and 69% of successes for CT and NT, respectively. This success deficit of BEST-slope was not completely surprising as several references of literature suggest such a response and Castellini et al. [36], for example, recently discussed this topic for most of the available investigations. On the contrary, since the other two BEST-algorithms, i.e. intercept and steady, always provided analyzable results in 100% of considered cases, they were considered to establish a comparison between conventional and alternative soil management strategies (CT vs. NT).

Table 4 shows the comparison results of S and K_s carried out by the alternative BEST-algorithms. Application of -intercept or -steady showed differences for each considered variable since discrepancies by a factor of 1.1–1.3 for S and 1.2–1.7 for K_s, were detected. According to a paired two-tailed t-test (p = 0.05), the differences between BEST-algorithms were always significant (Table 4). Results of this investigation are in line with the main references of literature. Bagarello et al. [59], for example, using a large sample size (N = 401), detected lower values of S and K_s, using BEST-steady as compared to BEST-intercept; observed K_s discrepancies between algorithms were at most equal to a factor of 1.5 (1.1 as a mean), and can be considered practically negligible for many agronomic applications [67,69]. Consequently, an analysis of the cumulative infiltration curves was made to verify if the steady flow conditions were always reached during field experiments, and it was used as a criterion for choosing the most suitable calculation algorithm, and to compare selected soil treatments.

Table 4. Geometric mean (GM) and associated coefficient of variation (CV%) of soil sorptivity (S) and saturated hydraulic conductivity (K_s) obtained for each BEST-algorithm (Intercept and Steady), experimental site (Gravina and Candela) and soil management (conventional tillage, CT and no-tillage, NT).

Variable	S **(mm s^{-1})**				K_s **(mm h^{-1})**			
Algorithm	**Intercept**		**Steady**		**Intercept**		**Steady**	
Statistic	GM	CV	GM	CV	GM	CV	GM	CV
Gravina CT	1.429 aA	38.3	1.277 bA	35.7	96.932 aA	53.8	77.496 bA	53.7
Gravina NT	1.589 aA	53.7	1.460 bA	53.5	136.112 aA	113.0	114.945 bA	115.4
Candela CT	2.759 aA	41.9	2.130 bA	44.7	230.167 aA	104.5	137.105 bA	121.3
Candela NT	2.771 aA	31.2	2.299 bA	32.4	297.889 aA	85.6	205.223 bA	100.4

* For a given variable (S, K_s) and combination (i.e., experimental site–soil management), mean values of BEST-algorithm followed by the same lowercase letter are not significantly different according to a paired two-tailed t-test (P = 0.05). For a given variable and BEST-algorithm, mean values of the different combinations (i.e., Gravina, CT vs. NT) followed by the same capital letter are not significantly different according to a *two tailed* t-test (P = 0.05).

Cumulative infiltrations showed the expected shapes with a concave part (concavity downwards) corresponding to the transient state and a linear part at the end of the curves related to the steady-state (Figure 2). Relatively flat cumulative infiltrations, i.e., relatively lower infiltration rates, were generally observed in Gravina more than in Candela (Figure 2a,b), showing for the former site relatively higher total time of experiments (i.e., infiltration experiments that lasted up to 2.5 h). However, a visual inspection of $I(t)$ relationships suggests no substantial difference between soil management strategies. This finding was also showed in terms of infiltration rates (Figure 2c,d); for a given infiltration time, differences in mean values of infiltration rate between sites did not exceed an order of magnitude.

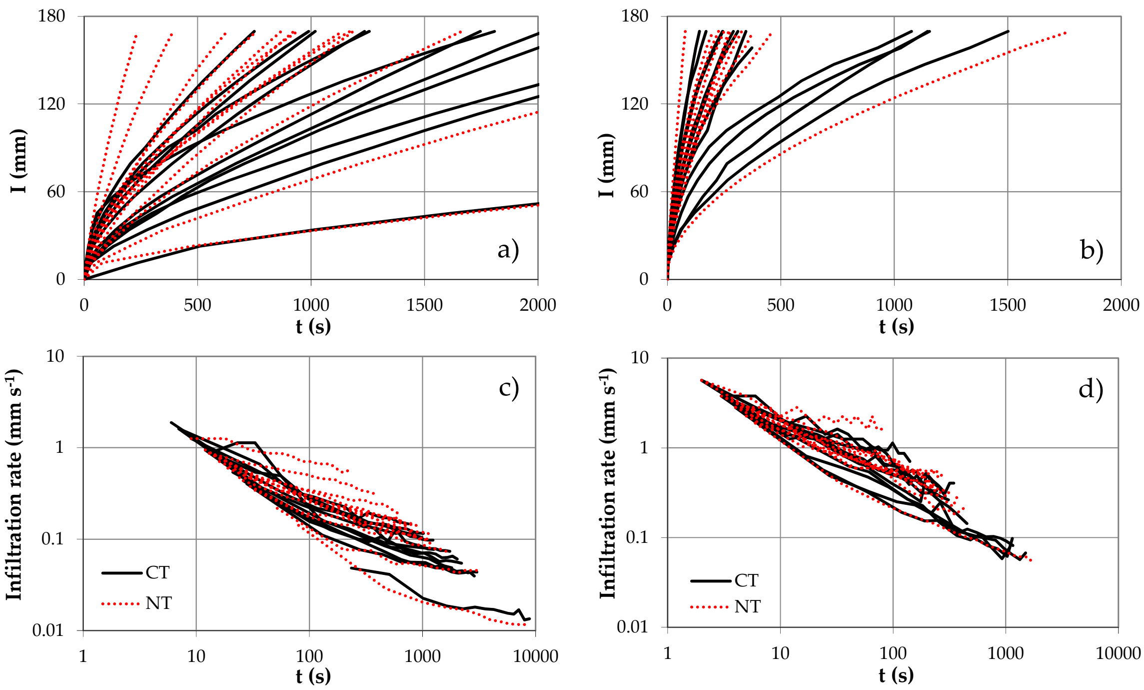

Figure 2. Cumulative infiltrations (**a**,**b**) and infiltration rates (**c**,**d**) at the study sites, Gravina (on the left) and Candela (on the right), under conventional tillage (CT) and no-tillage (NT). Note that $I(t)$ relationship of Gravina was truncated at t = 2000 s; lost information can be assumed from Table 4.

Table 5 summarizes the results of steady-state flow analysis. Equilibration time, t_s, i.e. the time needed to reach steady-state conditions or, similarly, the duration of the transient phase, was different among soils ranging by two orders of magnitude (from a minimum of 65 s to a maximum of 6415 s). In particular, for a given site, higher mean t_s values were obtained under CT rather than NT, with differences that were equal to a factor of 1.6 or 1.3, respectively, for Gravina or Candela. The infiltrated depth at the equilibration time was 70% of the total infiltrated depth (I_{tot} = 170 mm) for Gravina and 80% of I_{tot} for Candela (Table 5). This suggests that clear steady-state conditions were always reached before the end of infiltration experiments, and both BEST-intercept and BEST-steady could be used considering the last data points, according to the specific infiltration curve. Consequently, as steady-state conditions were clearly highlighted, the comparison between soil management in terms of S, K_s, and $C_{\lambda m}$, and in terms of h_g and λ_m, will be referred only to the BEST-steady algorithm.

Table 5. Minimum (Min), maximum (Max), mean, and coefficient of variation (CV%), of the equilibration time, t_s (s), infiltrated depth at the equilibration time, $I(t_s)$ (mm), and total duration, t_{end} (s) for the infiltration runs.

Variable	Site	Statistics			
		Min	**Max**	**Mean**	**CV%**
t_s	Gravina CT	458	6415	1417	113.9
	Gravina NT	153	3962	868	111.0
	Candela CT	87	811	345	76.9
	Candela NT	65	1182	259	119.3
$I(t_s)$	Gravina CT	102	136	119	7.6
	Gravina NT	68	136	118	17.8
	Candela CT	102	147	133	9.7
	Candela NT	102	147	132	10.4
t_{end}	Gravina CT	750	8795	2311	93.8
	Gravina NT	234	8750	1683	133.6
	Candela CT	141	1501	590	81.8
	Candela NT	79	1775	414	111.6

3.3. Comparison between CT and NT

Comparison between CT and NT showed relatively low differences between the soil management strategies, since a general equivalence in terms of hydrodynamic soil properties was detected. In fact, according to the results discussed before and regardless of the site considered, no significant difference between CT and NT was detected in terms of S (differences not higher than a factor of 1.1) and K_s (factor of 1.5) (Table 4). This finding suggests that, despite the substantial differences between farms about the time elapsed in the conversion from CT to NT (six to twenty-four years), hydrodynamic soil properties under CT and NT were comparable both in Candela and Gravina. The negligible differences between the soil management strategies are clearly shown in Figure 3 since, neglecting some points of the mean cumulative water infiltration curve (that is, the first or last two-three data points) for which sorptivity or some discrepancies in the mean flows may have occurred, a ratio of Δt-CT/Δt-NT practically equal to one was observed for more than half (up to about the ninth applied water volume) of the infiltration process. Therefore, detected differences between Δt-CT and Δt-NT were also expressive of a substantial equivalence of the compared soil management strategies over infiltration time.

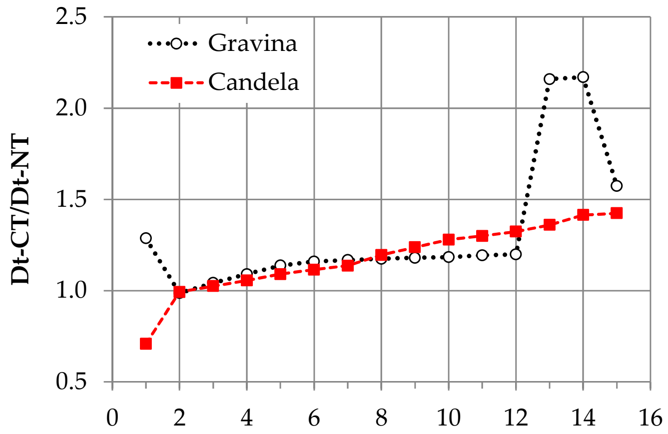

Figure 3. Ratio between the mean infiltration time for water infiltration in CT and NT during the Beerkan runs against the number of the applied volumes of water.

Figure 4 shows the interquartile range of the water retention curve scale parameter, h_g, of the flow-weighted mean pore size, λ_m and of the number of hydraulically active pores, $C_{\lambda m}$. Lower mean values of h_g (higher in absolute value) were generally detected at Candela than Gravina (173–155 mm and 79–98 mm, respectively). For a given soil management strategy, Candela showed a higher variation range by a factor of 1.5–1.8 as compared with Gravina. These findings support bulk density values, on average higher in Candela than in Gravina. However, for a given site, no significant differences were detected between CT and NT (Figure 4). Accordingly, the flow-weighted mean pores size, λ_m, was higher in Gravina (0.097–0.077 mm) than in Candela (0.044–0.052 mm), respectively under CT and NT, but no statistical significance between treatments was detected (Figure 4). Differences significantly higher were instead detected in terms of $C_{\lambda m}$ in Gravina, since NT showed a higher number of hydraulically active pores (by a factor of 3.1) as compared to CT (Figure 4). This result is quite surprising as, although the expected inverse relationship between λ_m and $C_{\lambda m}$ was detected, i.e., few pores larger or many smaller ones, a long-term undisturbed soil would have let suppose the first condition, as reported for marginal soils with natural vegetation [46]. However, $C_{\lambda m}$ depends on both λ_m and K_s and, although discrepancies in soil texture classes were detected (i.e., higher percentages of clay and sand fractions were detected under NT), results of this investigation suggests that a long-term no-tilled soil with relatively small pores, but more numerous and probably well-connected, may be more conductive as compared to CT; this can mitigate the increase of bulk density in long-term no-tilled soils. On the other hand, Candela showed only negligible differences on number of conductive pores, and NT findings do not seem to be all consistent with each other (i.e., larger pore size corresponded to a larger number of conductive pores, or higher BD values did not determine higher values of h_g; the latter was also extremely variable under NT). However, although no statistical significance was found for the mentioned soil properties, observed inconsistencies probably can be considered as a signal that soil conservation practices, repeated for a relatively short time of six years, do not allow to detect clear relationships between soil properties. Moreover, even when soil data of two farms were poled together to give account only for the effect of soil management (Gravina + Candela), the comparison in terms of both λ_m and $C_{\lambda m}$ provided consistent findings, since CT and NT were not different according to a two-tailed *t*-test (Figure 5), and the expected decreasing relationship between these two variables was verified. As a consequence, we are inclined to suppose that a soil compaction under Candela-CT may have occurred, as evidenced by the relatively low variability (and concomitant extreme outlier) of λ_m (Figure 4). This reasoning finds support in a similar soil behavior showed by Souza et al. [43], since an increasing relationship between λ_m and $C_{\lambda m}$ was detected due to the formation of superficial crust that locally may have reduced the size of conductive pores, as compared to non-crusted soils.

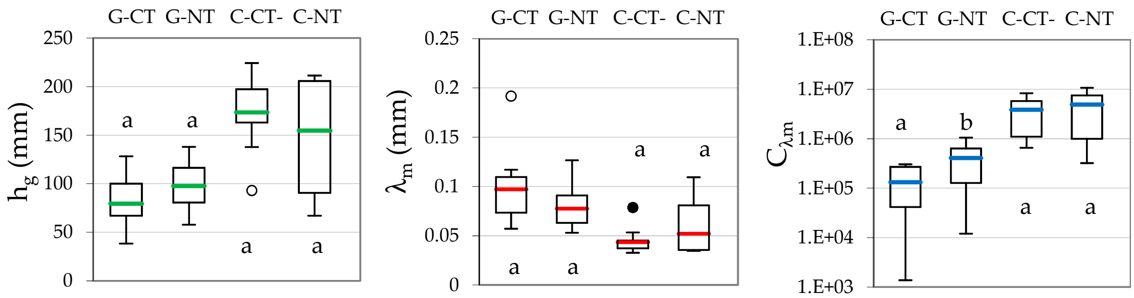

Figure 4. Mean values and interquartile range (min, max, 1st and 3rd quartile) of retention curve scale parameter, h_g (in absolute value), flow-weighted mean pore size, λ_m, and number of hydraulically active pores per unit area ($C_{\lambda m}$) obtained with BEST-steady. Open circles represent outliers (closed circles extreme outliers). For a given site, Gravina and Candela (G and C), soil management strategies (CT or NT) followed by the same letter are not significantly different according to a two-tailed *t*-test (p = 0.05).

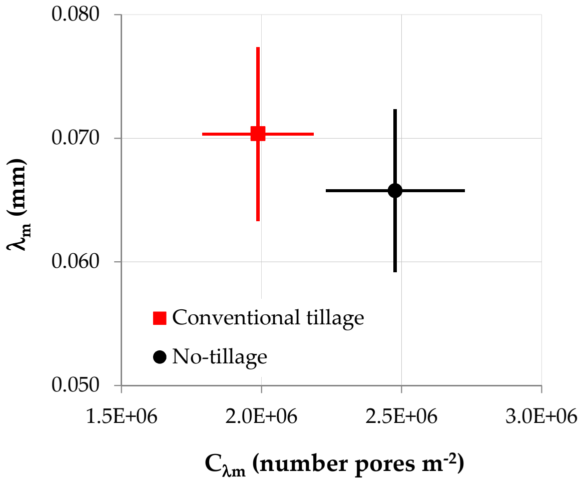

Figure 5. Comparison between of CT and NT in terms of mean values of flow-weighted mean pore size, λ_m, and number of hydraulically active pores per unit area, $C_{\lambda m}$ (i.e., Gravina + Candela dataset). Bars represent ± 10% deviation on the mean values.

The comparison in terms of hydraulic functions is reported in Figure 6. For two selected θ values (i.e., 0.4 and 0.7), differences in the $K(\theta)$ values between the soil management strategies were within an order of magnitude. Accordingly, similar results for shape parameters of BEST were detected (m = 0.05 − 0.06, n = 2.11 − 2.13, and η = 21 − 19, respectively for Candela and Gravina). In particular, higher K differences were generally detected for Gravina (i.e., differences by a factor of 2.9–10.3 at θ = 0.4 and 0.7, respectively) than Candela (3.2–4.3). However, slightly higher differences were detected in the former case close to water saturation as compared to unsaturated ones, suggesting a more efficient conductive system under relatively higher moisture conditions (Figure 6).

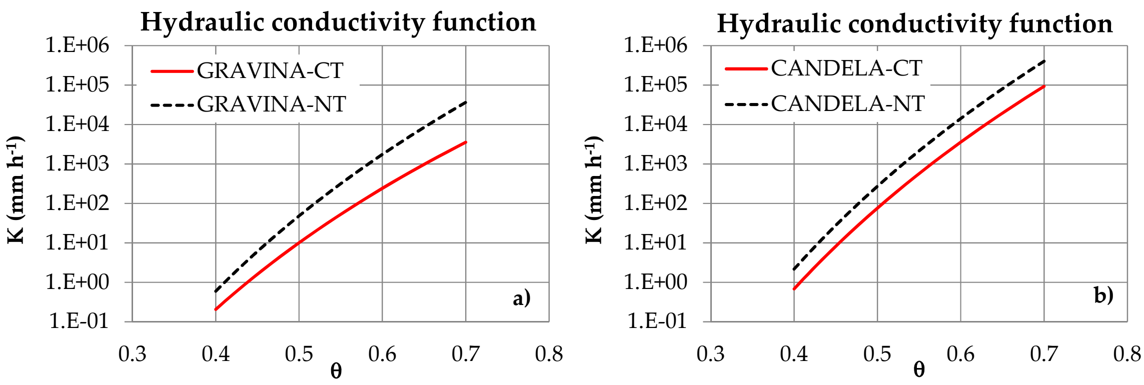

Figure 6. Hydraulic conductivity functions obtained with BEST-steady at Gravina (**a**) and Candela (**b**) sites.

The comparison between CT and NT based on measured soil water retention is depicted in Figure 7. In general, measured soil water retention data showed a relatively low variability as coefficients of variation (CVs) of θ values ranged from about 15–20% to 2–3%, decreasing as the potential decreases (i.e., −5 to −15,300 cm). As shown, noticeable differences in soil water retention were detected only in the Candela site, as relatively low differences were detected between CT and NT in Gravina only close to water saturation (e.g., 0.06 cm^3 cm^{-3} at h = −5 cm) (Figure 7). In other words, the water retention curve of Candela-CT highlighted the typical features of a tilled soil, namely: (i) relatively lower bulk density value, and (ii) relatively low value of the pressure head at the inflection point (i.e., 10 cm against 25–26 cm for the remaining ones). This behavior is adequately represented in Figure 8, where the comparison among pore size distributions clearly shows a higher modal diameter for Candela-CT (298 μm) as compared to other sites (about 115 μm); for Candela-CT, this resulted in lower degrees of saturation at the inflection point of the water retention curve [62], by 4% as compared to Candela-NT, or by 15%–29% as compared to Gravina-CT or Gravina-NT. Therefore, as compared to hydrodynamic soil properties, a more evident impact of soil management strategy (CT or NT) can be quantified in terms of capacity-based indicators.

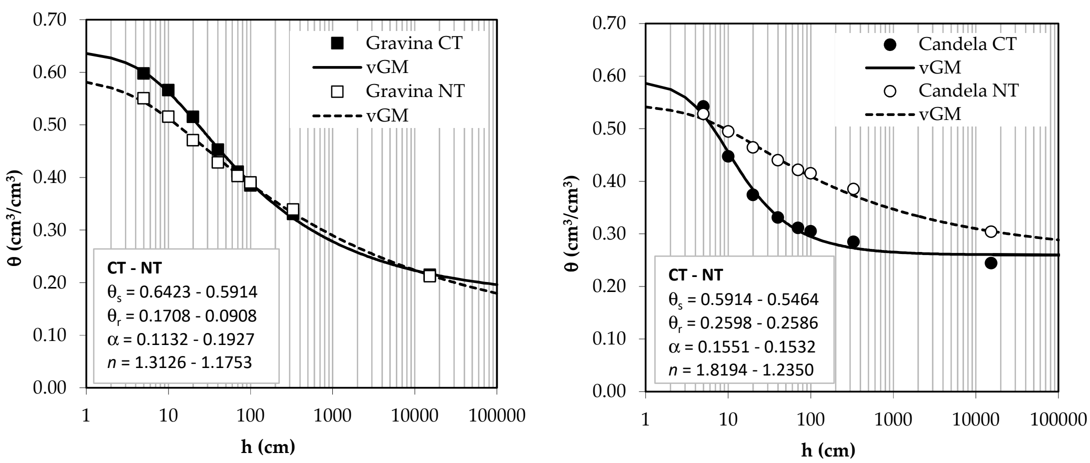

Figure 7. Measured (points) and modelled (lines) soil water retention data (van Genuchten model, vGM) for conventional tillage (CT) and no-tillage (NT) of Gravina (on the left) and Candela (on the right) sites. Parameters of vGM (θ_s, θ_r, α, and n) are also reported (α = 1/cm).

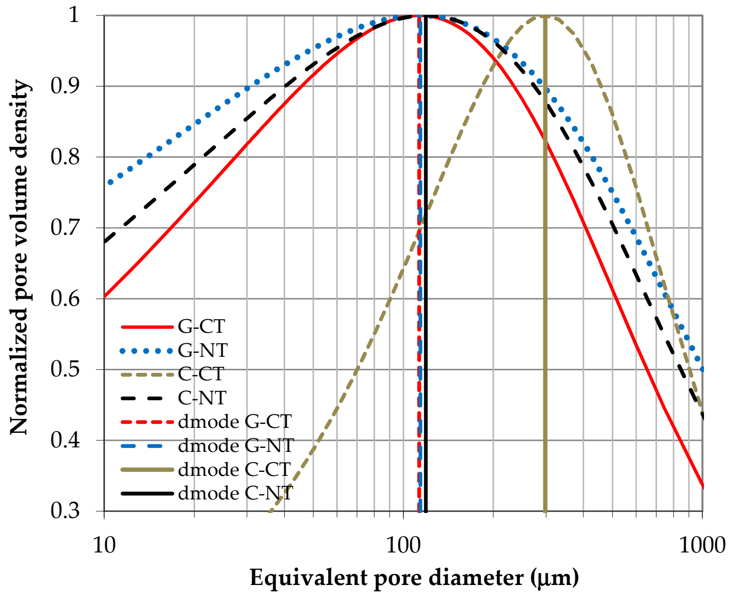

Figure 8. Normalized pore volume distributions and the corresponding modal diameters (d_{mod}) of the four site–soil management combinations (G, Gravina; C, Candela; CT, conventional tillage; NT, no-tillage), calculated according to Reynolds et al. [62].

In accordance with the literature assessing optimal physical conditions of agricultural soils (Table 1), a better soil physical quality was observed for Gravina rather than for Candela, since optimal values of macroporosity, air capacity, and relative field capacity, as well as good levels of plant available water, were always detected both under CT and NT (Table 6). Conversely, the Candela site showed some discrepancies between soil management as nonoptimal soil conditions were always detected under CT, while optimal values of macroporosity or of air capacity were detected under NT. As summarized by *RFC*, opposite conditions generally were identified between CT and NT, as too porous (*RFC* < 0.6) or too compact (*RFC* > 0.7) soil conditions were detected in the former and in the latter treatment of Candela site, respectively (Table 6). For a given soil management strategy, CT or NT, the impact of the time that has elapsed since the conversion to NT on capacity-based indicators (24 and 6 years, for respectively for Gravina and Candela) was shown in Figure 9. For a given soil indicator (i.e., P_{mac}, *AC*, *RFC*, *PAWC*), lower discrepancies between CT and NT than optimal mean values were always detected under the long-term conversion of Gravina (Figure 9). For this site, moreover, no-tillage showed always results closer to the optimum (in terms of AC and RFC), or virtually equivalent (P_{mac} and *PAWC*), as compared to conventional tillage, reinforcing the hypothesis that sufficiently long periods of time positively affects the soil physical properties' stabilization.

Table 6. Mean values of capacity-based indicators measured at Gravina (G) and Candela (C) sites under conventional tillage (CT) and no-tillage (NT).

Site-Soil Management	P_{mac}	AC	RFC	PAWC
G-CT	0.080	0.253	0.606	0.173
G-NT	0.079	0.204	0.655	0.173
	=	=	=	=
C-CT	**0.136**	**0.297**	**0.498**	**0.035**
C-NT	0.049	0.137	**0.749**	**0.104**
	≠	≠	=	=

P_{mac} = macroporosity ($cm^3\ cm^{-3}$); *AC* = air capacity ($cm^3\ cm^{-3}$); *RFC* = relative field capacity (-); plant available water capacity = *PAWC* ($cm^3\ cm^{-3}$). The symbols indicate that, for a given comparison, soil indicators provided an equal (=) or a different (≠) evaluation if compared to the reference values of Table 1; non-optimal values were highlighted in bold.

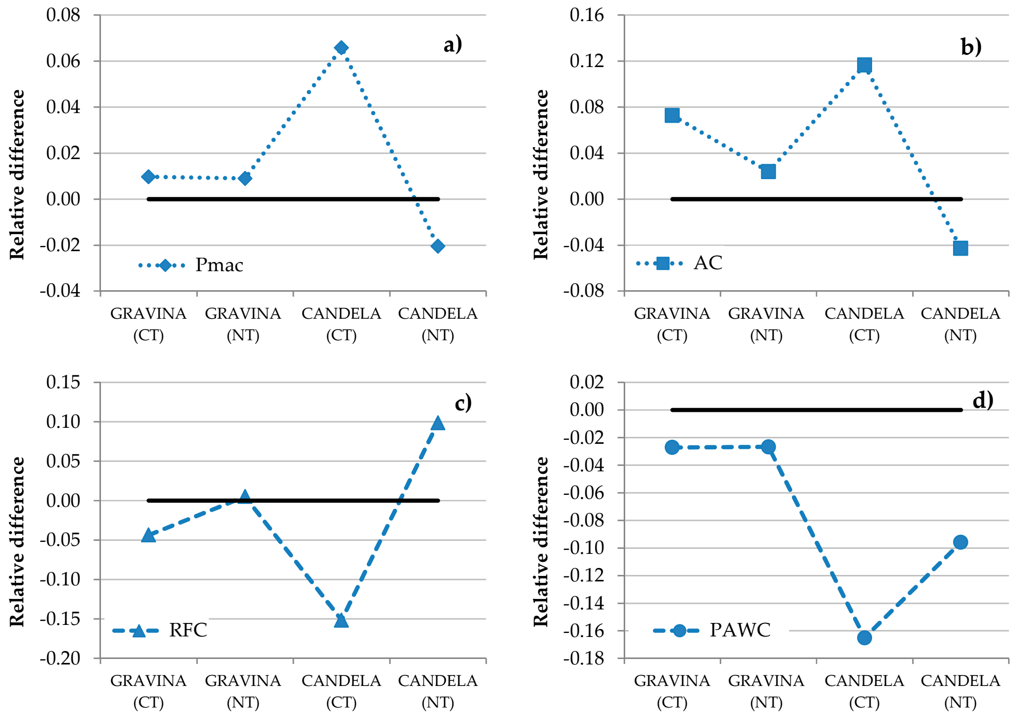

Figure 9. Relative differences between measured mean values and optimal mean values for macroporosity (**a**), air capacity (**b**), relative field capacity (**c**) and plant available water capacity (**d**), according to the Table 1.

LAI and biomass were higher under CT than NT at Gravina by a factor of 1.2 (Figure 10), but observed differences were not statistically significant. Therefore, lower grain yields by 10% were obtained under NT (3.0–2.7 t ha^{-1}, respectively for CT and NT). No information was reported for Candela as some crop damages were observed after germination due to extreme weather conditions; this resulted in noncomparable plant densities between the alternative soil management strategies.

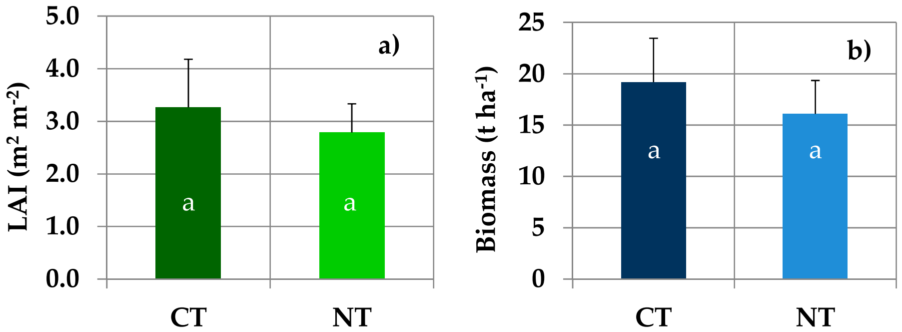

Figure 10. Leaf area index (LAI) (**a**) and fresh biomass (**b**) measured at Gravina site. Bars represent standard deviations. For each diagram, values followed by the same letter are not significantly different according to a two-tailed *t*-test (p = 0.05).

4. Discussion

Although the literature suggests that seasonal changes in soil physical properties may be caused by several physical factors, for example, the arrangement of soil particles, pore system configuration and compaction due to raindrop impact [40,70,71], and contrasting results may be summed according to selected investigation (among others, [70–73]), findings basically agree that soil tillage represents the main factor that can sharply reduce soil density and increase hydrodynamic properties [70]. The main effects of CT on soil physical properties run out during an annual or two-year crop cycle [70–73], as soil is gradually compacted due to natural reconsolidation by gravity and raindrop impact [70,74,75]. However, cases where the above-mentioned natural stabilization of soil properties are not uncommon as a natural soil compaction was reported even at the end of an annual growth cycle [67,73]. Past this time, if a soil is no longer tilled, the literature agrees that the above-mentioned natural stabilization of soil properties may occur after about five to six years [17,76].

In this investigation, the relative short/long term impact (i.e., six or twenty-four years) of selected soil management, CT or NT, was evaluated mainly in terms of soil bulk density, hydrodynamic soil properties, soil hydraulic conductivity functions, and capacity-based indicators, and discussed with reference to the literature. Contrasting results of NT effects on *BD* (i.e., NT≈CT or NT»CT) were generally reported in the literature [21,27] as several main factors (soil texture, organic matter, climatic environment, and agronomy) are involved in the soil reconsolidation processes. Similar conclusions were drawn by [77] for fine-textured soils (i.e., clay loam or silty clay loam) in a Mediterranean environment very similar to those considered in this investigation (i.e. northern Apulia), because both significant (by a factor of 1.22) and negligible (1.03) differences between NT and CT were observed. Our results showed that only long-term NT resulted in a significant increase in *BD*, but, according to the literature guidelines to establish acceptable levels of soil compaction (i.e., $BD \leq 1.30$ g cm^{-3}) above which yield loss could occur due to inadequate soil aeration [62], our results also demonstrate that 24 years of continuous no-tillage has not degraded the soil and acceptable levels of soil density remain. Therefore, according to Soane et al. [1], soil bulk density may be recommended as the main, and easily determinable, soil parameter to detect soil physical deterioration due to a continuous no-tillage.

Infiltration rate or hydraulic conductivity of NT soils is sometimes, but not always, found to be appreciably higher than in ploughed soils [1]. Vogeler et al. [21] detected higher K_s values under NT rather than CT in a German soil, while no differences were reported under unsaturated conditions by Moret and Arrúe [71]. Villarreal et al. [44], comparing CT and NT for a crop rotation including maize and soybean for the last 15 years, detected higher values of S under CT (a factor within the range 1.1–2.4) or variable differences on K_s depending on the sampling time, namely higher under CT before seeding or six leaf stage (a factor of 2.4–1.4, respectively), or higher under NT between the six-leaf stage and physiological maturity (a factor of 1.8–1.9). Also, even minor mean differences were observed in terms of soil porosity (total, macro, meso, or microporosity) [44]. Although this investigation represents a knowledge contribution for a Mediterranean agro-environment for which a lack of information exists, it provides specific information of short- and long-term effects of NT practice on hydrodynamic and hydrostatic soil properties. Although a seasonal variability in soil properties cannot be excluded a priori, since literature suggests prudence on this, the general result obtained in this study was a null effect of long-term NT on hydrodynamic soil properties. At least four main results can be summarized for the investigated fine textured-soils: (i) long-term no-tillage significantly increased *BD* but this does not result in a reduction in soil permeability; (ii) short-term (six years) no-tillage did not result in significant changes in selected soil properties, possibly because this was a transition phase; (iii) although short-term and long-term NT systems showed similar hydrodynamic soil properties, they highlighted different characteristics of the conductive pore system; (iv) a more conductive pores network, i.e., consisting of relatively smaller pores that are more numerous and probably better interconnected, has been identified under long-term NT compared to CT. Conversely, application of capacity-based indicators revealed differences between treatments suggesting that, when well-managed, NT systems can give rise to an optimal balance between the liquid and gaseous phases of the soil.

Overall, the literature suggests that a different NT response on grain yield reduction is expected, depending on the considered agro-environment climate, i.e. humid or dry [11]; comparable yields between CT and NT were highlighted only under dry climates, as higher grain yield reductions are generally expected under humid ones (i.e., not higher than 10%). However, findings by Van de Putte et al. [8] based on 47 European studies have shown that adoption of conservation agriculture may decrease the yield from 4.5 to 8.5%, also in drier climatic conditions. Results of our investigation, carried out in a relatively dry climatic environment, showed differences in grain yields not higher than 10%. Factors that plausibly have influenced this result were mainly meteorological, namely an adequate water supply during pre-germination and tilling stages, a higher water retention of tilled soils, and a corresponding greater plants density. Therefore, although our results seem to be more in agreement with the thesis by Pittelkow et al. [11], the findings of this investigation should be taken with relative caution since they account for only one year of investigation. In order to mitigate both the yield losses of no-tillage and an excessive, potentially harmful, increase in soil compaction, suggested actions can contemplate: (i) a periodic minimum tillage of the soil or (ii) regularly alternating CT and NT within a rotation of different crops [8,78].

Finally, as compared to the methods commonly applied for similar investigations, mainly point-measurements, BEST represents a parametric procedure which allows the soil hydraulic functions to be obtained. In particular, as discussed above, soil water availability determination represents key information for the economic sustainability assessment of NT compared to CT under rainfed environments and differences in soil water retention were shown both for long-term and short-term conversion. Therefore, application of physical-based models that make use of the Richards equation [79,80] enables an accurate assessment of the long-term no-tillage sustainability both under present [81] or under future climate change scenarios [82] in Mediterranean regions.

5. Conclusions

In this study, the comparison between alternative soil management strategies for durum wheat cultivation, CT and NT, has shown a substantial equivalence in terms of soil hydrodynamic properties in the two farms investigated. Although the conversion time from CT to NT was very dissimilar between farms, i.e. 24/6 years in Gravina/Candela farms, negligible discrepancies in hydrodynamic soil properties were detected. In fact, differences between CT and NT were equal with factors of 1.3 and 1.4 (cumulative infiltration or infiltration rate), 2.1 and 1.7 (soil sorptivity), 0.6 and 0.6 (saturated hydraulic conductivity), and 1.3 and 0.8 (conductive pore size and soil hydraulic functions) for the Gravina and Candela sites, respectively. Although sporadic significant differences between soil management strategies were detected (NT soil was either more compact or more organic), NT soil management does not seem to have worsened the main physical properties, i.e., bulk density or structure, of investigated clay soils. However, significant differences in the number of hydraulically active pores were detected for Gravina-NT as compared to Gravina-CT so that, for this farm, long-term no-tilled soil can be presented as a functionally similar hydrodynamic system to CT but characterized by a prevalence of a relatively higher number of small pores. However, as this result was not obtained in Candela and some inconsistencies in soil relationships for this farm were highlighted, we cannot rule out that the short time from the conversion, i.e., only six years, may have made more some results uncertain. Therefore, for considered agro-environment, a logical implication of this investigation is also that until six years of no-tillage, it is not possible to state that steady soil properties were reached and that the investigated soil of Candela was in the final period of transition. BEST-procedure alone has made it possible to highlight suspiciously low and non-variable λ_m values due to soil compaction under CT at Candela, while capacity-based indicators application, obtained from the measured retention curve, allowed verification of the agronomic and environmental sustainability of no-tillage treatment for durum wheat cultivation. Therefore, the integrated approach adopted seems to be applicable to assess the impact of soil management strategies on the physical and hydraulic properties of the soil.

Further research on this topic should conduct new long-term field experiments in Mediterranean environments to accurately monitor the main variables of the soil–plant–atmosphere system (climate, soil, and agronomic management), to establish the long-term agronomic and environmental sustainability of the no-tillage strategy under wheat. As wheat straw cover may protect the no-tilled soil surface from rainfall impact, research aimed at quantifying the soil sealing reduction will be carried out in the future, as it represents a main topic both for hydrology and management of the soil.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/11/3/484/s1, Table S1: Summary of the main cultivation practices carried out at the investigated sites during the growth season 2016–2017.

Author Contributions: M.C. outlined the investigation, has carried out data analysis and wrote the manuscript. F.F, P.G, L.G, C.V. and A.V.V. have carried out the experimental work. All authors contributed to critically discuss the results and review the manuscript.

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