Deliverable 5.3.

Report on the assessment of soil infiltration and water-holding capacity under different CA agricultural practices in Mediterranean countries

Authors: Mirko Castellini and Jorge Lampurlanes

Approved by all Principal Investigators: Carlos Cantero-Martínez, UdL; Jorge Álvaro-Fuentes, CSIC; Michele Rinaldi (CREA).

Approved by Leader of Work Package (WP5): Carlos Cantero-Martínez (UdL)

Approved by Project Coordination: Michele Rinaldi (CREA)

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Executive summary

This report summarizes the results obtained in the CAMA task aimed at evaluating the impact of conservation agriculture (CA) on soil infiltration and water-holding capacity under different CA in Mediterranean countries, i.e., Italy (Foggia) and Spain (Senes).

In accordance with the findings collected at Foggia in a long-term experiment of southern Italy, no-tilled soil was, in general, significantly more humid and compact than tilled soil in the spring-summer period. A greater induced porosity by tillage have induced a more quickly surface (top 10cm of soil) soil drying. A general equivalence between the two soil management systems, i.e., no-tillage and minimum tillage (NT and MT, respectively), also was recorded in terms of hydrodynamic soil properties because, although saturated hydraulic conductivity, K_s was generally higher in MT than NT soil, only in few of considered cases such differences were significant from a statistical point of view. The study of the soil properties near water saturation highlighted an increase in hydraulic conductivity values when moving from unsaturated to saturated soil conditions, due to the activation of the macropore system. However, the preferential flow within the larger pores was comparable between the two soil management systems. The results collected in the Foggia site allowed to conclude that long-term soil management impacted especially on the pore system characteristics, i.e., creating smaller and better interconnected pores under no-tillage, probably diversifying the ways in which water is transmitted in saturated soil. When a thorough assessment in terms soil quality, including more than twenty physical, chemical and biological indicators, was carried out, the seven indicators selected (i.e., total organic carbon, alkali-extractable carbon, available phosphorus, water extractable nitrogen, relative field capacity, macroporosity, air capacity) provided a clear discrimination between NT and MT, suggesting positive effect of the undisturbed (NT) system for the soil organic matter accumulation, and improvements mainly linked to fertility, porosity and air capacity of the soil, induced by soil tillage (MT).

Experimental evidence from Senes highlighted a main effect of soil management on soi bulk density as it was significantly lower in tilled than in undisturbed soil, regardless of the method applied. A clear increase in hydraulic conductivity from unsaturated to saturated soil was generally detected. A higher soil permeability was overall recorded in tilled soil, suggesting that macropores network was more effective in transmitting water and air. Based on the analysis performed to discriminate the conductive characteristics as a function of some pore size classes, results allowed to conclude that the higher hydraulic conductivities under tilled soil and close to water saturation, should be linked to greater porosity rather improved pore connectivity.

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1. Introduction

1.1. Scope of the document and objectives

The main scope of this document (Deliverable 5.3) was to account for the main results obtained in the Task 5.3, regarding the assessment of soil infiltration and water-holding capacity under different CA agricultural practices in Mediterranean countries. This Deliverable 5.3 will be upload in the CAMA website as source of dissemination and, therefore, it will be available for readers.

Two different geographical areas were selected for this activity, i.e., Foggia and Senes, respectively in Italy and Spain. Consequently, the two experimental sites were deeply investigated.

Some preliminary investigations were conducted in Foggia, for example, to evaluate the spatial structure of the "field experimental device" selected within the CAMA projects, i.e., plot 32 (Popolizio et al., 2022b), to study the sampled soil volume effect on soil properties determination and soil physical quality estimation (Castellini et al., 2020). More generally the two sites were the subject, in the past years, of previous investigations which allowed to optimize the CAMA-activities, and better interpret the behaviour of the sites and the obtained results.

Among the planned research activities of CAMA project for CA optimization, a major role was cut for soil conservation assessment, with attention to nitrogen and water use efficiency, hydrological properties, soil water holding capacity, soil fertility, soil erosion control and soil organic carbon sequestration.

Some of the field techniques applied in this Task (5.3) were the basis (i.e., specifically adapted) for further investigations aimed at assessing the impact of CA on soil conservation, namely, using proxy indicators able to study the impact of CA on soil erosion (task 6.2).

In this general framework, the main objective of the Task 5.3 was to evaluate the impact of soil management on soil infiltration and water-holding capacity. For this purpose, agronomic treatments under CA were selected and compared with the traditional ones (conventional tillage), in order to establish the possible impact of soil management on soil hydraulic functions and properties. Water retention curve and hydraulic conductivity function allowed us to estimate several soil indicators (i.e., macroporosity, air capacity, plant available water capacity, and so on), useful for comparing the investigated systems and evaluate the soil quality, also in comparison to the reference values, as suggested by the literature. The main soil properties were deduced taking into account the well-known spatio-temporal variability, which affects the averages' reliability and, therefore, the proper interpretation of the results. For this reason, robust datasets were collected during several dates and soil conditions, that were analyses to adequately meet the goals of the task.

1.2. Notations, abbreviations and acronyms

α*	Soil texture/structure parameter for soil capillarity estimation
AC	Air capacity
BEST	Beerkan Estimation of Soil Transfer parameters procedure
BEST-slope	BEST algorithm
BEST-intercept	BEST algorithm
BEST-steady	BEST algorithm

C biomass	Microbial biomass carbon
CA	Conservation Agriculture
CAMA	Conservation Agriculture in the Mediterranean Area
CAP	Common Agricultural Policy
CDERP	Communication, dissemination and exploitation of results plan
EC	European Commission
ϕ	Soil porosity
h	Soil pressure head
HA FA	Humic and fulvic acid carbon
h_g	Water retention scale parameter
$h(\theta)$	Soil water retention curve
IPR	Intellectual Property Rights
i_s	Steady-state infiltration
K_s	Saturated hydraulic conductivity
$K(\theta)$	Hydraulic conductivity function
K_3	Unsaturated hydraulic conductivity at h=-3 cm
MT	Minimum Tillage
N	Total nitrogen
NT	No-Tillage
PAWC	Plant available water capacity
PCA	Principal Component Analysis
PLSR	Partial Least Squares Regression
P_{MAC}	Soil macroporosity
PMT	Project Management Team
P Olsen	Olsen available phosphorus
PSD	Particle-size distribution of the soil
θ_i	Volumetric soil water content at the time of experiments
θ_s	Saturated soil water content
θ_{10}	Volumetric water content of the soil matrix
θ_{100}	Volumetric water content of soil field capacity
θ_{15300}	Volumetric water content of the soil wilting point
ρ_b	Dry bulk density
RCBD	Randomized Complete Block Design
RD&I	Research, Development and Innovation
RFC	Relative Field Capacity
RIA	Research and Innovation Action
S	Soil sorptivity
SDA	Stepwise Discriminant Analysis
SFH	Simplified Falling Head technique
SPQ	Soil Physical Quality
SST	Steady-state Single Test
TEC	Alkali-extractable carbon
TOC	Total Organic Carbon
TI	Tension Infiltrometer

TRL	Technological Readiness Level
VIP and PLS-VIP	Variable Importance for Projection
WEN	Water Extractable Nitrogen
WEOC	Water Extractable Organic Carbon
WP	Work Package
WT	Work Task

1.3. Background

The key principles of conservation agriculture (CA) are minimum soil disturbance (reduced or no-tillage), soil cover (crop residues and/or cover crops) and crop diversification (rotation and/or intercropping). Consequently, several agro-environmental benefits can be obtained from CA, including reducing soil degradation and erosion, increasing soil organic matter, improving soil water infiltration and water retention, increasing water efficiency use, stable crop yields, and an overall reduction in cultivation costs. Mediterranean rainfed cropping systems could profit of CA benefits but, to date, a low adoption is observed in Mediterranean countries, as only about 2% of cultivated soils is allocated to such agronomic approaches (Rinaldi et al., 2022).

In 2020, the Food and Agriculture Organization of the United Nations (FAO) published the first version of its "Protocol for the Assessment of Sustainable Soil Management" (FAO, 2020). In practice, the protocol lists several key indicators and a set of tools to assess soil functions based on its physical, chemical and biological properties (FAO, 2020). The protocol is defined as "a fundamental tool to assess if any intervention implemented in the field, such as improvement of productive systems, innovation and new technologies, ecosystem restoration and carbon sequestration, is carried out in a sustainable manner according to the definition of sustainable soil management" (FAO, 2020). Therefore, it could be taken into due account for agro-environmental investigations. Among the "physical" indicators for sustainable soil management, the bulk density of the soil was primarily mentioned, as it can account for the changes in soil structure, porosity and compaction, and indicate how readily water, air and plant roots can move through the soil. However, when soil degradation is caused by specific and identified threats, additional indicators are needed to more specifically assess the impact of the implemented management practices, including the plant-available water capacity, infiltration rate and penetration resistance of the soil. Overall, measurements collected directly in the field were mentioned as suitable to reflect the real physical conditions of the soil. In this view, it is important to identify the time of the year in which evaluations, or comparisons, are made, because the seasonal variability in the soil's physical and hydraulic properties is a key factor for a reliable assessment of sustainable soil management.

Modifications induced by tillage practices on soil physical and hydraulic properties are not always easy to detect, and field studies have often provided contrasting results (Blanco-Canqui et al., 2017). The presence of unstable conditions, when investigations are carried out in the short- and medium-term period, and also the spatial variability of the soil properties over the field experimental area may cause difficulty in discerning the effects. Spatial heterogeneity is suggested as a primary source of error (Bevington et al., 2016). When spatial variability occurs at a scale smaller than the block (and plot) size, the effect of experimental treatments on the response of primary variables may be confounded (among others, Ventrella et al., 2016). Several studies have reported that neglecting the spatial dependence can cause misinterpretation errors, and consequently, improper management decisions (Hong et al., 2005; Hu et al., 2009). Therefore, it is necessary adopting an appropriate soil sampling scheme to obtain reliable results and, when it is possible, preliminarily investigate the spatial structure of the site under study.

Knowledge of the seasonal (or temporal) variability in the soil's physical and hydraulic properties is important (or even essential) for crop modelling or to evaluate the sustainability of cropping systems. However, it is relatively expensive both in terms of costs and experimental efforts. The main reason lies in the fact that, for a given sampling date, several measurements are required to consider the spatial variability of the field (Castellini et al., 2019c). Consequently, such reasons have stimulated the scientific community to propose new measurement techniques, or substantially improve those that are already well known, to share relatively accurate, quick and inexpensive tools for soil hydraulic characterization (Castellini et al., 2021). Specifically, during the last decades, a great effort has been made in soil sciences to develop relatively easy, robust, and inexpensive methods for soil hydraulic characterization. For instance, the simplified falling head (SFH) infiltrometer technique and the single-ring infiltration experiment of the Beerkan type are now widespread methods for rapid determination of soil field-saturated hydraulic conductivity. Moreover, the Beerkan Estimation of Soil pedoTransfer (BEST) parameters procedure (Lassabatere et al., 2006) is perhaps even more widespread for a complete soil hydraulic characterization (Castellini et al., 2021).

The soil physical quality (SPQ) estimation makes use of capacitive soil indicators (among others, macroporosity, air capacity, plant available water capacity) obtained from the soil water retention curve Reynolds et al., 2009; Castellini et al., 2019a). They have proven to be a useful diagnostic tool for evaluating the environmental sustainability of Mediterranean agroecosystems (i.e., Cherubin et al., 2016), and there is a large literature on this topic. Soil quality can be inferred by identifying and measuring the soil quality indicators, which are specific soil properties and processes sensitive to land use and management (Manici et al., 2019). Most Authors have used single indicators to assess soil quality and its relationship with land uses. However, univariate approaches do not always allow a comprehensive judgement on soil status. In addition, increasing the number of indicators may increase collinearity or provide conflicting results, making difficult the soil quality evaluation. A selection and combination of indicators of different nature (physical, chemical and biological), through the computation of soil quality indices (SQIs), is essential to gain a "holistic image" of soil quality.

Therefore, standard and relatively more innovative measurement techniques and data analysis methods were applied, both in the field and in the laboratory, to study the impact of soil management on the physical and hydraulic properties of selected soils in the Mediterranean environments of Foggia and Senes.

2. Experimental sites

2.1. CREA-AA (Italy)

The studies have been carried out at the experimental farm of the Council for Agricultural Research and Economics (CREA-AA), Foggia (41°27’03’’N, 15°30’06’’E) (Figure 1), in a long-term field experiment performed on a monoculture of durum wheat (Triticum turgidum subsp. durum Desf.) and on a rotation with leguminous. According to USDA classification, the soil texture is clay, with 42.7% and 27.7% of clay and silt, respectively. The climate of the area is “accentuated thermo-Mediterranean” (UNESCO FAO, 1963), with annual rainfall mostly concentrated during the autumn–winter months (mean 550 mm over a 50-year period 1965–2015) (Garofalo et al., 2019). From the 2002–2003 to the 2019–2020 growing season, a monoculture of durum wheat (namely, 18 consecutive growing seasons) was performed to compare the effects of two different soil management practices, minimum tillage (MT) and no-tillage (NT). The treatments were compared in a randomized complete block design (RCBD) with three replicates and unit plots of 500 m^2. Subsequently, from 2020–2021, each plot of the RCBD was split into two subplots (250 m^2 size), where wheat was cropped in rotation with chickpea. In this new experimental design, soil management (MT and NT) was considered as the main-plot factor, while the crop was the subplot factor. Durum wheat and chickpea were sown during December 2020 and March 2021, respectively. In the following year (the 2021–2022 growing season), crop rotation was managed by replacing wheat with legumes (chickpea) and vice versa. The experimental design used over the years is schematized in Figure 2.

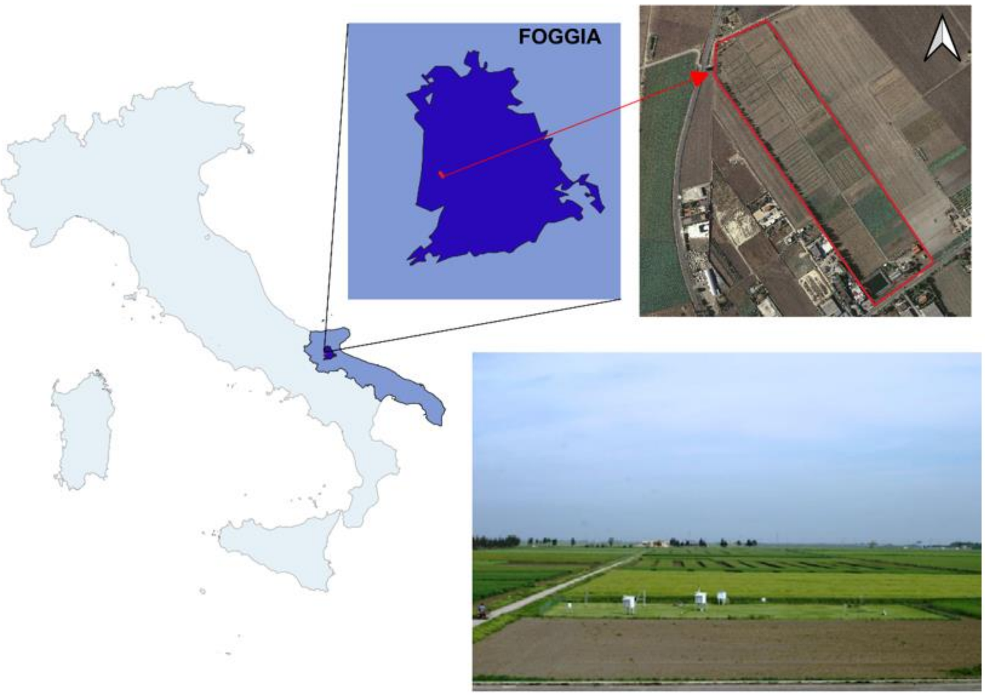


Figure 1. Location and view of experimental farm of the Council for Agricultural Research and Economics, Agriculture and Environment Research Center (CREA-AA) in Foggia, Apulian region, southern Italy.

Minimum tillage consists of a two-layer soil tillage at 40 cm depth (i.e., a chisel and rotary tiller combination) performed in autumn before durum wheat sowing. No-tillage consists of a direct sowing of durum wheat after a chemical weeding treatment. For both treatments, in September straw was chopped into 10- to 15-cm lengths and spread back onto the plot. Weeding with glyphosate was carried out in early November on NT plots. Sowing was performed for both treatments at the end of November with a seeder for direct sowing, appropriately equipped with shaped blades. All other agronomic techniques (fertilization, pest control and weed management during crop growth) were carried out uniformly for the two soil management compared. At harvesting, yield was measured at each soil location within a subarea of 1 × 1 m. Further information on plot management can be found in Castellini et al. (2019). An overall image of the plots studied, in December shortly after tillage, is shown in Figure 3.

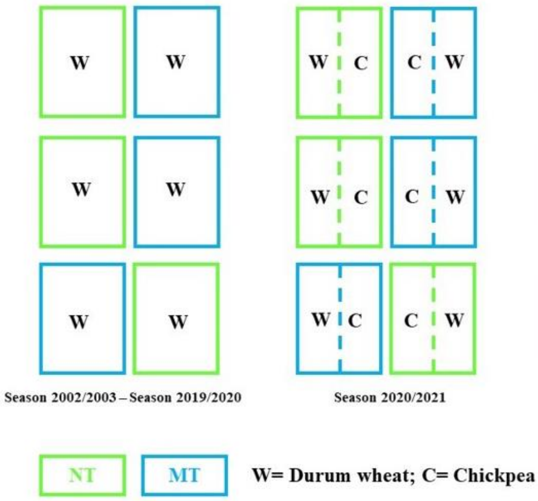


Figure 2. Experimental design of long-term field experiment located in the farm of CREA-AA, Foggia.

Figure 3. Soil images in December after MT and view of partially decomposed straw layer on the NT plot.

2.2. UdL-CSIC (Spain)

The field experiment was established in 2010 in Senés de Alcubierre (NE Spain, 41°54'12" N; 0°30' 15" W) in a rainfed area. The climate is temperate continental Mediterranean. The general information on soil and climatic characteristics are reported in Table 1. Soil properties were measured at the beginning of the experiment (October 2010). The experimental design consisted of the combination of two tillage practices (CT, conventional tillage and NT, no-tillage) and three N fertilization rates (0, 75 and 150 kg N ha^{-1}) based on two different types of fertilizer (mineral N and organic N with pig slurry) in a randomized block design with three replications. Plot size was 40 m × 12 m in the organic fertilization treatments and 40 m × 6 m in the mineral N fertilization and control treatments. The cropping system during the experiment consisted of a barley (Hordeum vulgare L., cv. Meseta) monocropping. From 2014-15 growing season a Pea-Barley-Wheat-Barley crop rotation has been following until date. The CT treatment consisted of one pass of disk plow (15 cm depth) followed by a cultivator. However, due to the dry conditions of soil in 2011 two passes of chisel were used. A non-selective herbicide (1.5 L 36% glyphosate per hectare) was applied before sowing in the NT treatment. Sowing was carried out with a no-till seeder equipped with disk type furrow openers set to 2–4 cm depth. The combination of fertilizer types and N rates led to five fertilization treatments: 0, control,75 Min and 75 Org, 75 kg N ha^{-1} with mineral and organic N at the beginning of tillering, respectively, and 150 Min and 150 Org,150 kg N ha^{-1} with mineral and organic N applied at equal rates before sowing and at the beginning of tillering. For the mineral N treatments ammonium sulphate (21% N) and ammonium nitrate (33.5% N) were used before sowing and at the beginning of tillering, respectively. Mineral N applications were performed manually. The organic fertilization treatment consisted on the application of slurry from fattening pigs of a commercial farm close to the site. The application was carried out spreading the slurry with a commercial vacuum tanker fitted with a splash plate (Beguer mod. 12500, Barbastro, Spain) as it is common in the area. Previously to each application pig slurry was analysed for its N content and the tanker was calibrated accordingly to apply the precise N rate. Harvest of the plots was carried out with a commercial medium-sized combine. Combine chopped and spread over the soil surface the crop residues. Since the 1970s soil management at the site was based on the use of a subsoiler and a chisel. Four years before the establishment of the experiment (i.e. 2006) soil management was switched to NT. Daily air temperature and rainfall data were recorded with the use of an automated weather station located in the site and equipped with a data-logger.

Table 1. Soil and climatic characteristics of the Senes site (0–30 cm)	
Elevation (m a.s.l.)	395
Annual precipitation (mm)	327
Mean annual air temperature (◦C)	13.4
Annual PET (mm)	1197
Soil classification (USDA)	Typic calcixerept
pH (H2O, 1:2.5)	8.0
EC1.5 (dS m^{-1})	1.04
Organic C (g kg^{-1})	15.6
Organic N (g kg^{-1})	1.4
Sand (2000–50 m) (%)	6.2
Silt (50–2 m) (%)	63.3
Clay (<2 m) (%)	30.5

3. Metodology

3.1. Soil hydraulic conductivity

The hydraulic conductivity of the soil was determined both under saturated and unsaturated soil conditions. In the following subsections, the main information on the applied methods, briefly but comprehensively, are reported. Overall, two methods were used to study the saturated hydraulic conductivity, i.e., BEST and SFH, while the Tension Infiltrometer (TI) method was applied to study the unsaturated one.

3.1.1 Saturated hydraulic conductivity

The Beerkan Estimation of Soil Transfer parameters (BEST) procedure (Lassabatère et al., 2006) is generally applied to determine simultaneously the water retention curve, h(θ), and the soil hydraulic conductivity function, K(θ) of the soil. In other words, it allows to simultaneously estimate the hydraulic functions of the soil. It therefore also allows obtaining the saturated hydraulic conductivity of the soil, K_s. BEST focuses specifically on the van Genuchten (1980) relationship with the Burdine (1958) condition for the water retention curve, and the Brook and Corey (1964) relationship for hydraulic conductivity. Please refer to the review paper by Castellini et al. (2020) for further information on the BEST-procedure or the BEST-literature. To estimate the soil hydraulic parameters, BEST requires the cumulative infiltration curve obtained with the beerkan test (Braud et al., 2005), the soil particle-size distribution (PSD), the bulk density, ρ_b, and the volumetric soil water content at the time of experiments, θ_i (Castellini et al. 2021). Therefore, all these variables were determined, in the field or lab, for its application. In particular, BEST estimates the shape parameters using the PSD and the soil porosity, ϕ, while the cumulative infiltration is modelled to estimate the soil sorptivity, S, and the scale parameters h_g and the saturated hydraulic conductivity, K_s (Castellini et al. 2021). The beerkan test involves the determination of the 3-D cumulative infiltration resulting from the application of a slightly positive water pressure head over a disk source. Practically, a cylinder with inner diameter of 15 cm was inserted shallowly into the soil (e.g., 1 cm), a given small volume of water (200 mL in our case) was poured in the cylinder at the start of the measurement and the elapsed time during the infiltration is measured. When the amount of water has completely infiltrated, an identical amount of water is poured into the cylinder, and the time needed for the water to infiltrate is logged. The procedure was repeated until the difference in infiltration times between consecutive trials become negligible, indicating a practically steady state infiltration. This soil condition was achieved using fifteen water pourings. As usual in many BEST applications, ϕ was calculated from the ρ_b data, assuming a soil particle density of 2.65 g cm^{-3}, and θ_s is assumed to coincide with f (Bagarello et al., 2014). Three main BEST algorithms were developed to estimate the soil hydraulic properties, BEST-slope (Lassabatere et al., 2006), BEST-intercept (Yilmaz et al., 2010) and BEST-steady (Bagarello et al., 2014b). Briefly, the three algorithms make use of the same input data, but differ by the way they fit the experimental data to the infiltration models for transient and steady states (Di Prima et al., 2018). In particular, a fitting of the infiltration model to the transient data is required with BEST-slope and BEST-intercept, but these differ by the use of steady-state conditions described respectively by the slope, i_s (L T^{-1}), and the intercept of the straight line fitted to the part of the experimental cumulative infiltration curve. Both of these last two terms are required by BEST-steady that does not need any data fitting to the transient stage of the run but relies solely on the steady state portion of the curve (Castellini et al. 2021). In accordance with the objectives of the research conducted, all the main BEST-algorithms were used for the CAMA investigations (Castellini et al., 2020; Popolizio 2022a; Popolizio 2022b).

The Simplified Falling Head, SFH technique (Bagarello et al., 2004) it is a transient method for K_s estimation. It consists of quickly pouring a known volume of water on the soil confined inside a ring inserted at a fixed depth into the soil, and measuring the time necessary for the poured volume to fully seep through to the surface area. Taking into account that the considered infiltration model applies to 1-D flow, the depth of the wetting front, at the end of the SFH experiment, should be less than or equal to the ring depth into the soil, and should not emerge from the bottom ring edge. In practice, the volume of water should be less than or equal to the volume of voids, within the bulk soil volume confined by the ring (Castellini et al. 2021). SFH technique was applied in two consecutive years (i.e., during eight sampling dates) to determine the field saturated soil hydraulic conductivity (Figure 4). In particular, SFH tests started about five months after pipe insertion; this made it possible to exclude (or attenuate) the possible compaction during cylinders insertion. Overall, eight sampling dates were considered (Castellini et al., 2020). For each considered agronomic treatment (MT and NT), ten PVC pipes of 30 cm in inner diameter and 30 cm in height (with relatively sharpened edge) were inserted into the soil (in mid-November) at a depth d=15 cm.

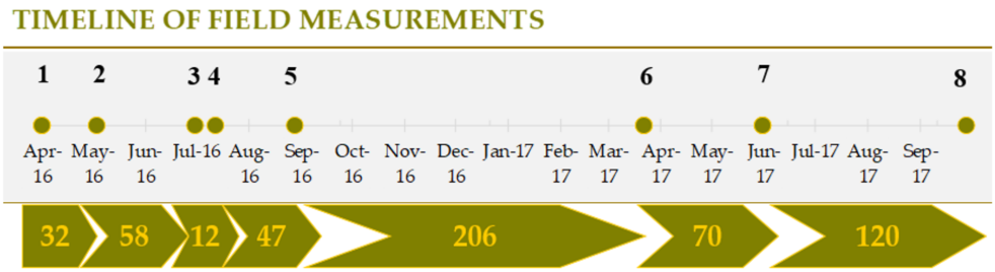


Figure 4. Timeline of field measurements (i.e., K_s, θ_i and ρ_b) carried out under MT and NT using the SFH technique. At the bottom, the time intervals (days) between two successive SFH measurements are also reported inside the arrows.

Using the bucket loader of a tractor, the insertion of the PVC pipe was conducted step by step ensuring that the upper rim of the pipe remained horizontal. A spirit level was used to check the horizontality of the cylinder. To obtain a flat infiltration surface, the small depressions of the cylinder inner area were filled with soil collected in situ. The PVC pipes were always removed immediately before the start of the next crop cycle (at the beginning of November) (Figure 5). According to the procedure reported by Bagarello et al. (2004), two undisturbed soil cores (5 cm in height by 5 cm in diameter) were collected near the ring at the 0 to 5 and 5 to 10 cm depth about 24 hours before the measurements to determine in the laboratory the dry soil bulk density, ρ_b (g cm^{-3}) and the soil water content at the time of sampling, θ_i (cm^3 cm^{-3}). The saturated soil water content, θ_s was estimated using the measured ρ_b and considering a mean value of soil particle density of 2.65 g cm^{-3}, as is usual for this procedure (Castellini et al. 2021). A choice of the most suitable α^* parameter can be made following the guidelines of Elrick and Reynolds (1992). However, according to previous experimental investigations carried out on investigated soil (Castellini et al. 2015), a value of the α^* equal to 0.012 cm^{-1} was used to calculate K_s.

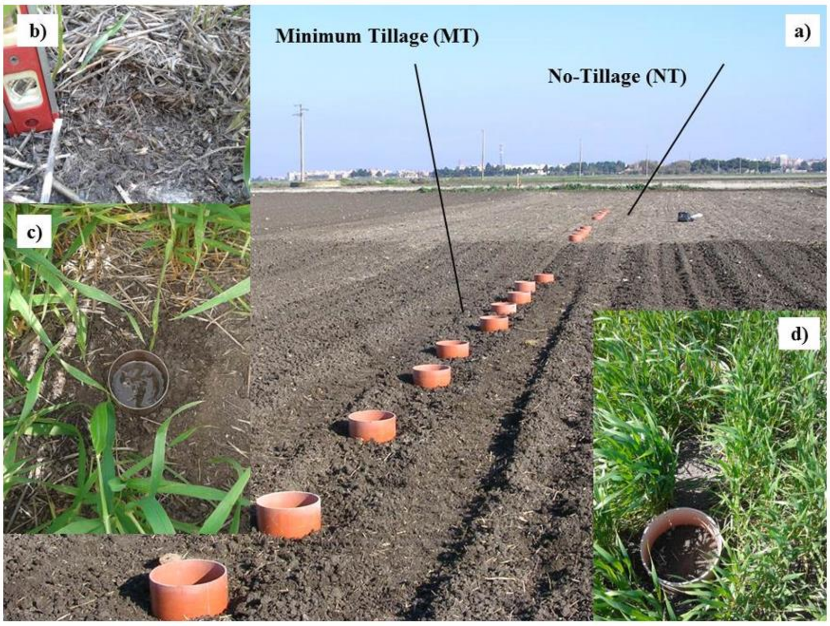


Figure 5. View of the experimental site for hydraulic properties determination under MT and NT soil management (a); detail of the layer thickness of wheat straw (NT) in November (b); detail of beerkan infiltration experiments (c) and of SFH technique (d) in April.

3.1.2 Unsaturated hydraulic conductivity

Unsaturated hydraulic conductivity at the pressure head, h, value of 3 cm, K_3, was determined by TI method (Bagarello et al., 2007) (Figure 6), and the Steady-state Single Test (SST) was applied for such purpose (Bagarello et al., 2004b). Overall, TI method is widely used for measuring the near-saturated hydraulic conductivity in the field (among others, see Bagarello et al., 2007). The said h-value was selected because discriminates the activation of soil macropores (Messing and Jarvis, 1993) and because it has also been verified as reliable in previous investigations for the same soil (Castellini and Ventrella, 2012).

Briefly, for a given ratio of the metal ring used in the field (15 cm in our experiment), SST method allows to obtain the hydraulic conductivity corresponding to the applied pressure head value, (K_3, in our case) from both the steady-state infiltration rate, soil sorptivity and the difference in soil water content due to the infiltration experiment, i.e., the difference in θ values between end and beginning of the water infiltration (Bagarello et al., 2004b). The standard tension infiltrometer device, with separate water supply and base-plate units with a 20 cm diameter disc, was used for field tests (Perroux and White, 1988). Although no water supply recharge was made during infiltration experiments (i.e., only a water reservoir was used for SST tests), quasi steady-state flow conditions were reached. More details about the adopted experimental procedure can be found in Castellini and Ventrella (2012).

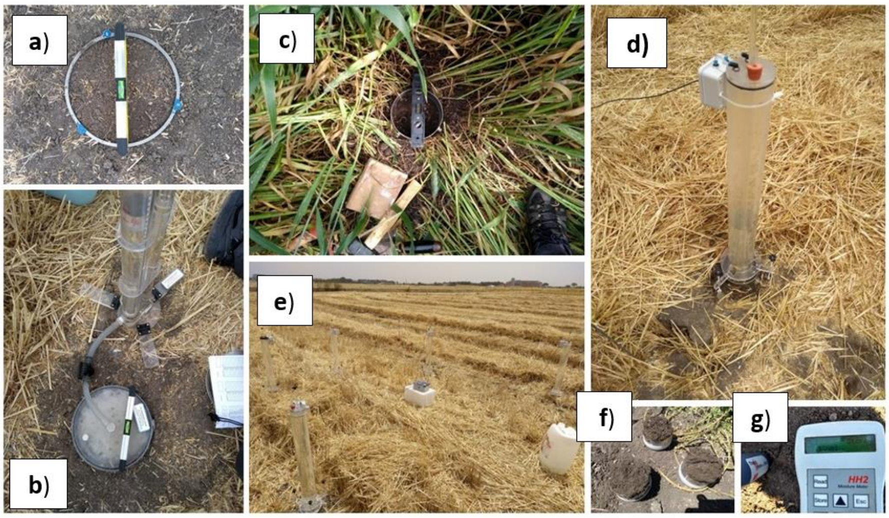


Figure 6. Images of infiltration experiments applying tension infiltrometer (a,b) and beerkan (c-e) methods, soil cores sampling for water retention determination (f) and volumetric soil water content measurements (g).

3.2. Soil water retention curve, volumetric soil water content, bulk density and ancillary measurements

Soil water retention curve was measured both directly in the laboratory, applying standard methods (tension hanging water column apparatus, pressure plate extractors), and estimated using the BEST procedure.

For laboratory determination, undisturbed soil cores were randomly sampled in the soil layer 0–10 cm, using stainless steel rings with different volume, and approximately equal to 100 and 200 cm^3 (precisely, 98 and 204 cm^3; H = 5 cm, D = 5.0 or 7.2 cm, respectively). Soil sampling was carried out following general rules to accurately extract cores from the soil and prevent soil compaction. The steel rings with sharp edges were carefully inserted into the soil using a rubber hammer and a wooden board. Once extracted, soil cores were sealed with plastic film and stored in the refrigerator at a constant temperature, of about 5°C, until processing in the laboratory. Depending on the number of samples to be processed in the laboratory at the same time, two different experimental installations, conceptually equivalent in their functioning, were used for measuring some points of the soil water retention curve. In particular, Buchner apparatus (Burke et al., 1986), and ceramic suction table (pF laboratory station, ecoTech Umwelt-Meßsysteme, Germany) (Wolf et al., 2013) methods, were used to trigger a drainage process on an initially saturated soil sample, placed on a synthetic porous septum. Specifically, during the transient of drainage, some values of soil pressure head, h, were imposed, until the hydrostatic equilibrium corresponded to the imposed h value was reached. Experiments on Buchner apparatus were carried out overall using a sequence of seven h values (i.e., −5, −10, −20, −40, −70, −100, and −130 cm), while those on the suction table were carried out by a sequence of five h values (i.e., −10, −30, −60, −100, and −600 cm). Therefore, the volumetric water content, q, corresponding to the final h value (i.e., −130 and −600 cm), was obtained by the thermogravimetric method, and the other θ values were deduced adding the drained water between successive h values (as usual in this procedure) (Castellini et al., 2019a). At the end of the desorption experiments, the undisturbed soil cores were used to determine ρ_b, assuming a particle density of 2.65 g cm^{-3} (Castellini and Iovino, 2019). A standard procedure was also applied to obtain θ values at lower pressure heads (i.e., h = −1030, −3060, and −15300 cm) on repacked soil samples by the pressure plate method (Dane and Hopmans, 2002). Therefore, for each set of θ-h values, appropriate models of soil water retention were adopted to parameterize the water retention curve of the soil using similar fitting codes, i.e., RETC code or SWRC fit (Castellini, et al., 2020). For further details on the methodology adopted, please refer to the paper by Castellini and Iovino (2019).

As an alternative to the thermogravimetric method, spot measurements of the volumetric water content of the soil in the 0-5 cm layer, were also carried out using the Theta probe (Delta-T Devices ML2x) with 5-cm steel rods.

Soil dry bulk density was determined from the soil core samples, using the samplers mentioned above, and by drying at 105°C as usual for this soil variable determination.

WEOC and WEN, that are indicators for labile organic C and N pools, were extracted from field-moist soil samples (Stellacci et al., 2021). TOC, TEC, HA_FA and total N were quantified on dried and 2-mm sieved samples. For TOC quantification, soil samples were ground to a fine powder (0.5 mm) using an agate ball mill. TEC was obtained by 0.1 M NaOH + 0.1 M $Na_4P_2O_7$ extraction at 65 °C for 48 h. Humic and fulvic acids were fractionated by acidification to pH = 2.0 with H_2SO_4. The purification of FA from non-humic substances was carried out by adsorption onto polyvinylpyrrolidone columns. Total organic carbon in soil samples, as well as C fractions in alkali extracts and C and N fractions in water extracts, were quantified through dry combustion using a TOC Vario Select analyzer (Elementar, Germany), which conducts a catalytic combustion of the sample at high temperatures in air environment. Total N was quantified according to the Kjeldahl procedure. For further references on chemical determinations, please refer to the paper by Stellacci et al. (2021).

3.3. Data Analysis

For each main variable considered (i.e., ρ_b, θ_i, P_{MAC}, AC, PAWC, …, RFC), a given dataset was generally summarized by calculating the mean and the associated coefficient of variation. Therefore, arithmetic means were calculated in that case. Conversely, when considering soil variables with a log-normal distribution (i.e., hydraulic conductivity), an appropriate geometric mean and associated coefficient of variation was considered, as generally suggested for these soil properties. A probability level of P = 0.05 was always assumed, unless otherwise indicated.

Capacitive-based soil physical quality indicators (i.e., P_{MAC}, AC, RFC and PAWC) were calculated from fitted soil water retention functions, using the van Genuchten model (1980), according to the following relationships: macroporosity ($P_{MAC} = \theta_s - \theta_m$) (cm^3 cm^{-3}), air capacity ($AC = \theta_s - \theta_{FC}$) (cm^3 cm^{-3}), relative field capacity ($RFC = \theta_{FC}/\theta_s$) (dimensionless) and plant available water capacity ($PAWC = \theta_{FC} - \theta_{PWP}$), where θ_s, θ_m, θ_{FC}, θ_{PWP}, are the volumetric water contents corresponding to a pressure head of 0, –10, –100 and –15300 cm, respectively. Evaluation of soil physical quality (SPQ) was carried out according to classifications gathered from literature (Reynolds et al., 2009). In particular, the SPQ was considered optimal when $0.9 \leq \rho_b \leq 1.2$ g cm^{-3}, $P_{MAC} \geq 0.07$ cm^3 cm^{-3}, $AC \geq 0.14$ cm^3 cm^{-3}, $0.6 \leq RFC \leq 0.7$ and PAWC 0.20 cm^3 cm^{-3}. Supplementary information on the described indicators can be found in Castellini et al. (2019a).

Temporal variability of selected soil properties, using the SFH technique (4.1.1 section), was evaluated by comparing the mean values obtained from the Tukey's Honestly Significant Difference (THSD) test, whereas the statistical significance between NT and MT was performed according to a two-tailed t-test. For further references on this specific data analysis, please refer to the paper by Castellini et al. (2020).

For the seasonal and soil use dependent variability of soil properties (4.1.2 section), beerkan infiltration runs were considered randomized within each plot. Only the effect of soil management over the two seasons was investigated. Data on the physical and hydraulic soil properties and soil quality indicators were tested for normality using the Shapiro–Wilk test. A nested analysis of variance (ANOVA) was separately conducted for each season considering the replicates within plots as pseudo-replicates. The homogeneity of the variances across the sampling seasons was verified through the F test. When the variances were homogeneous, a combined analysis of variance (combined ANOVA) of data was used. Conversely, when the variance was heterogeneous, a weighted least square (WLS) analysis was run. The means of BEST parameters and capacity-based soil indicators, measured for different times of sampling and soil management, were separated by an LSD test. For further references on this specific data analysis, please refer to the paper by Popolizio et al. (2022).

For the soil quality assessment (4.1.4 section), a preliminary data analysis was carried out to summarize the main features of data distribution of response variables to be used in the regressive approach. Variables were tested for normality, using Shapiro-Wilk and Kolmogorov-Smirnov tests, and for heteroscedasticity by soil management with Levene homogeneity of variance test. Data distribution and presence of heteroscedasticity were also examined for soil variables. The set of twenty soil variables, grouped in chemical (TOC, N, TEC, HA_FA, WEN, WEOC, P_Olsen, Ca^{2+}, Mg^{2+}, Na^+, K^+, pH, EC), physical (Clay, Silt, Sand, ρ_b, P_{MAC}, AC, RFC) and biological (microbial biomass carbon) indicators was first analysed through a nested analysis of variance (ANOVA) considering replicates within plots as pseudo-replicates. Then, data were analysed using Principal Component Analysis (PCA), Stepwise Discriminant Analysis (SDA) and Partial Least Square Regression (PLSR) with Variable Importance for Projection (VIP) statistics. For further references on this specific data analysis, please refer to the paper by Stellacci et al. (2021).

4. Results and conclusions

4.1. CREA-AA (Italy)

4.1.1. Temporal variability of soil properties using the SFH technique

The general objective of this investigation was to assess the temporal variability of physical and hydraulic properties of a fine-textured soil, in the long-term experiment in Foggia considering MT and NT soil management (Castellini et al. 2020). The specific objectives were to: i) apply the SFH technique and consider the main physical and hydraulic properties of the soil, including bulk density, soil water content at the time of experiments and saturated hydraulic conductivity; ii) investigate the temporal variability of such properties during a two years campaign; iii) use the acquired experimental information to assess the agro-environmental sustainability of MT and NT from the perspective of soil physical and hydraulic properties. Since this research activity also considered the application of the BEST procedure, and therefore a comparison between methods was made, please refer to the CAMA-manuscript by Castellini et al. (2020) for further information on soil hydrology results.

The results of ρ_b and qi at the time of SFH experiments under MT and NT are reported in Figures 7 and 8, respectively. Overall, higher ρ_b values were observed under NT than MT as, on average, they changed in the range (min–max) of 0.98–1.19 g cm^{-3} under MT and 1.19–1.32 g cm^{-3} under NT. On five of the eight sampling dates, ρ_b values under NT were significantly higher than under MT (Figure 7). A lack of temporal variability was observed for ρ_b because significant differences were identified only under MT between sampling dates 2 and 3 (i.e., between the beginning of May and July). Overall, detecting some discrepancies of ρ_b values at the beginning of the crop cycle is quite expected as a result of the residual effects of the last soil tillage. However, a comparison with bulk densities obtained in the same period in previous years suggests possible underestimation in May under MT due to unknown factors that make them difficult to assess. Soil water contents were higher under NT (0.28–0.41 cm^3 cm^{-3}) than under MT (0.19–0.37 cm^3 cm^{-3}) (Figure 8). Specifically, θ_i values showed significant differences between MT and NT on four dates (i.e., 3, 5, 7, and 8), namely between the end of spring and the beginning of autumn (Figure 8). Moreover, compared to ρ_b, a relatively higher temporal variability was identified, because qi value of the sampling date 7 was significantly lower than other dates, i.e., 1, 2, 4 and 5. This suggests that under MT/NT alters θ_i more than ρ_b over time due to the different soil management.

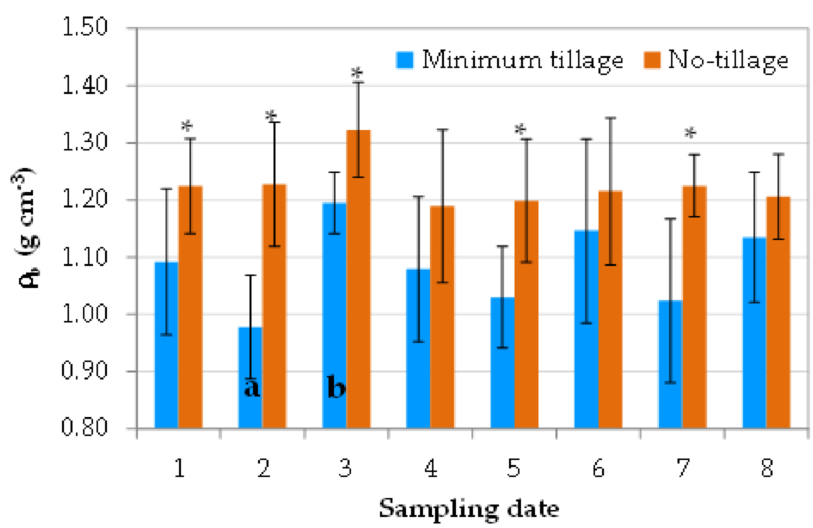


Figure 7. Soil bulk density (ρ_b) at the time of the SFH experiments. For a given sampling date, mean values of minimum tillage or no-tillage marked with an asterisk were statistically different to a t-test (P=0.05). For a given soil management, only values of sampling date marked with a different lowercase letter (i.e., ab) were statistically different to a THSD-test (P=0.05).

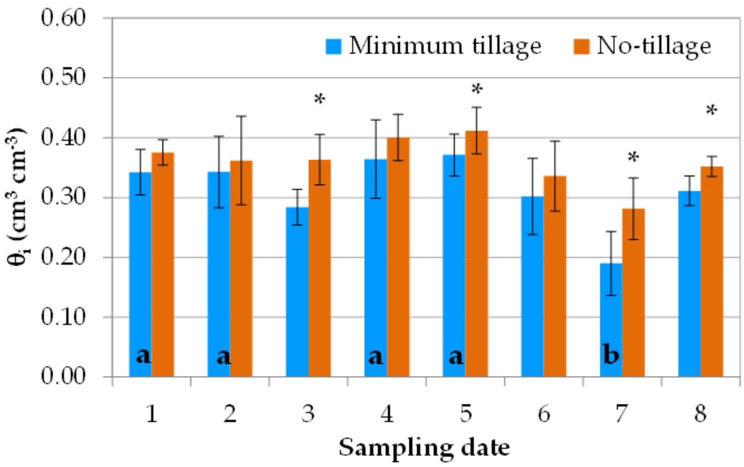


Figure 8. Volumetric soil water content (θ_i) at the time of the SFH experiments. For a given sampling date, mean values of minimum tillage or no-tillage marked with an asterisk were statistically different to a t-test (P=0.05). For a given soil management, only values of sampling date marked with a different lowercase letter (i.e., ab) were statistically different to a THSD-test (P=0.05).

Table 2. Minimum (Min), maximum (Max), geometric mean (GM) and associated geometric coefficient of variation (CV) of field saturated hydraulic conductivity (mm h^{-1}), carried out under MT and NT during each sampling date with SFH technique.

Minimum tillage (MT)								
Sampling date	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min	3	2	1520	131	23	1617	258	930
Max	837	718	3800	1028	295	2606	2158	2349
GM	66 a*	45 a	2240 a	322 a	93 a	2210 a	799 a	1389 a
CV (%)	732	375	28	72	117	13	67	33
No-tillage (NT)								
Sampling date	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min	8	3	1074	33	195	801	182	529
Max	351	271	2050	384	659	1896	1476	2023
GM	81 b	28 b	1487 a	108 a	357 a	1474 a	590 b	1155 b
CV (%)	211	297	22	89	42	25	75	48

* For a given sampling date, mean values of alternative soil management (i.e., MT and NT) followed by the same letter are not statistically different according to a two-tailed *t-test* (P=0.05).

Field saturated hydraulic conductivity (K_s) changed over time within two or three orders of magnitude when the minimum-maximum interval or the geometric mean was considered, respectively (Table 2). K_s was generally higher under MT than NT (by a factor 1.2-3.0); however, NT was higher on two occasions (sampling dates 1 and 5) by a factor 1.2-3.8 (Table 2). According to a two-tailed t-test the differences between MT and NT were significant in the first two and the last two sampling dates (Table 2). According to the THSD-test, that provides comparisons across all sampling dates (i.e., 28 possible combinations), results of the temporal variability showed that Ks was significantly different according to the different sampling dates in 60% of considered cases (i.e., 17 of the 28 cases) under MT and 64% (18/28) under NT (Table 3). This confirms a relatively high temporal variability of field saturated hydraulic conductivity. Temporal dynamic of K_s between MT and NT was quite similar, because results of THSD-test were simultaneously significant or not significant in 75% of cases (i.e., 21 out of 28 cases) (Table 3). However, although qi values were generally comparable under MT and NT and their ratio was close to one (i.e. 0.9), discrepancies in Ks values were detected according with the soil use, as only 3-5 sampling dates (2, 3, 6, 7, and 8) showed a ratio of K_s values close to 1. A further deepening about the similarities among aforementioned sampling dates (i.e., applying a cluster analysis) suggests three main groups (namely 4, 1 and 5, all the remaining groups), but no link on the month of the year was found.

Table 3. Results of Tukey's Honestly Significant Difference (THSD)-*test* (P=0.05), on mean values of field saturated hydraulic conductivity measurements carried out with SFH technique under minimum tillage (a) and no-tillage (b), for each sampling time (from I to VIII). Note that discrepancies in temporal variability between soil management were highlighted in red.

a)	I	II	III	IV	V	VI	VII		b)	I	II	III	IV	V	VI	VII	
II	NS								II	NS							
III	X	X							III	X	X						
IV	**X**	X	X						IV	**NS**	X	X					
V	**NS**	**NS**	X	**NS**					V	**X**	**X**	X	**X**				
VI	X	X	NS	X	X				VI	X	X	NS	X	X			
VII	X	X	NS	**NS**	**X**	NS			VII	X	X	NS	**X**	**NS**	NS		
VIII	X	X	NS	X	**X**	NS	NS		VIII	X	X	NS	X	**NS**	NS	NS	

NS = not significant difference; X = significant difference

In conclusion, after about fifteen years of field experiments, characterized by continuous soil management and conducted with the methodological rigor typical of experimental farms, the differences in terms of physical (i.e., ρ_b and θ_i) and hydraulic properties (K_s) during eight sampling dates, showed a substantial equivalence between MT and NT for the fine-textured soil investigated; however, compared to qi and K_s, a slight greater soil management impact on ρ_b was detected (NT > MT). Overall, evaluating the temporal variability of the physical and hydraulic properties of the soil is crucial for crop modelling and, therefore, to assess the economic and environmental sustainability of specific soil management practices. In our study, the temporal dynamic of Ks was comparable between MT and NT given that in 75% of the considered cases the same the same result was obtained from a statistical point of view. A practical outcome of the research was to show the ability of the SFH method to enable intensive monitoring of temporal changes of saturated hydraulic conductivity, with an inexpensive and fairly accurate approach. Negligible discrepancies in terms of ρ_b values were detected between soil management, but higher differences were detected in terms of water content, as qi values showed significant differences between MT and NT between the end of spring and the beginning of autumn.

4.1.2. Seasonal and soil use dependent variability of physical and hydraulic properties

The main objective of this investigation was to develop, and study, a robust field data set across two seasons to investigate the spatial and temporal variability of some main physical and hydraulic soil properties in a typical Mediterranean agro-environment. Specific goals of this study were: i) to detect possible summer–autumn temporal variability in physical and hydraulic soil properties, and ii) to quantify the impact of different soil managements, i.e. minimum tillage and no-tillage, that were repeatedly applied over time, and under the long-term field experiment in Foggia.

Non-homogeneous variances were recorded for ρ_b, K_s, θ_{100} and PAWC. Therefore, these data were transformed. Results of combined ANOVA showed that the soil management had significant effects on ρ_b K_s, and PAWC. The sampling season, summer and autumn, significantly affected θ_{10} and θ_{15300}; highly significant effects were recorded for qi and K_s, ρ_b, θ_{100} and PAWC (Table 4). The interaction between soil management and sampling season was not significant for all physical and hydraulic soil properties and capacity-based indicators investigated in this study (Table 4). Minimum-tilled soil showed on average a significantly higher saturated hydraulic conductivity (0.0497 mm s^{-1}) than no-tilled soil (0.0427 mm s^{-1}) and a lower bulk density (1.0794 vs 1.1204 g cm^{-3}, respectively; Table 5). Greater PAWC values were also recorded in MT soil (Table 6). θ_i was greater in autumn than in summer (0.3471 and 0.2912 cm^3 cm^{-3}, respectively). Conversely, ρ_b recorded greater mean values in summer (1.1905 g cm^{-3}) than in autumn (1.0093 g cm^{-3}). K_s was significantly lower in autumn than in summer. The mean K_s values ranged from 0.0345 mm s^{-1} (recorded for NT in summer) to 0.0640 mm s^{-1} (recorded for MT in summer) (Table 5). θ_{10}, θ_{100} and θ_{15300} showed the greatest values in autumn. Macroporosity (P_{MAC}), air capacity (AC) and relative field capacity (RFC) were not significantly affected by sampling season. Mean values were 0.0216 and 0.0174 cm^3 cm^{-3} for P_{MAC}, 0.1943 and 0.1784 cm^3 cm^{-3} for AC and 0.6856 and 0.6751 for RFC in autumn and summer, respectively. On the other hand, significantly higher values of plant available water capacity indicator (PAWC) were recorded in autumn (0.2780 cm^3 cm^{-3}) than in summer (0.2491 cm^3 cm^{-3}) (Table 6).

Table 4. Combined ANOVA carried out on soil management and sampling season for physical and hydraulic soil properties and capacity-based indicators.

Parameters	Soil Management (SM)	Sampling Season SS)	SM x SS
θ_i	ns	**	ns
K_s	*	**	ns
ρ_b	*	***	ns
θ_{10}	ns	*	ns
θ_{100}	ns	***	ns
θ_{15300}	ns	*	ns
P_{MAC}	ns	ns	ns
AC	ns	ns	ns
PAWC	*	***	ns
RFC	ns	ns	ns

* significant at *p*-value ≤ 0.05, ***p*-value ≤ 0.01, *** *p*-value ≤ 0.001; ns = not significant. Soil management (df) = 1; Sampling season (df) = 1; Soil management x Sampling season (df) = 1.

Figure 9 shows the differences in terms of water retention curve, and hydraulic conductivity function, for each season sampling and soil management. The sampling season showed relatively greater differences than soil management. BEST returned $\theta(h)$ having lower soil water contents for the summer season and no-tillage management, especially for $0 < |h| < 100$ mm ($h > -100$ mm). On the other hand, for $|h| > 100$ mm ($h < -100$ mm), more evident differences were observed only by comparing the sampling seasons, with the soil water content values higher in autumn than in summer. Likewise, higher discrepancies for $K(\theta)$ were detected only by comparing the sampling seasons, despite also significant differences between MT and NT were recorded in terms of saturated hydraulic conductivity (K_s). Specifically, $K(\theta)$ estimated in summer was higher than that estimated in autumn. $\theta(h)$ and $K(\theta)$ relating to the interaction between the sampling season and soil management are shown in Figure 9. Relatively lower soil water contents were shown in summer close to water saturation for MT and NT, while BEST returned insubstantial differences for h < -100 mm. Although low discrepancies were observed in summer between minimum tillage and no-tillage, soil managed with MT was more conductive in summer and less conductive in autumn than in NT.

Table 5. Mean separation and coefficients of variation of variables measured in field (θ_i, ρ_b) and estimated with BEST procedure (K_s)

Source of variation	θ_i cm^3 cm^{-3}	ρ_b (g cm^{-3})	K_s (mm s^{-1})
MT	0.3216	1.0794 b	0.0497 a
NT	0.3166	1.1204 a	0.0427 b
$CV_{(A)}$ (%)	11.0	0.9	8.8
Autumn	0.3471 a	1.0093 b	0.0431 b
Summer	0.2912 b	1.1905 a	0.0492 a
Autumn MT	0.3598	0.9913	0.0354
Autumn NT	0.3343	1.0273	0.0509
Summer MT	0.2834	1.1674	0.0640
Summer NT	0.2989	1.2135	0.0345
$CV_{(B)}$ (%)	5.0	2.8	50.7

within each column, data followed by different letters are significantly different at a *p*-value of 0.05 (LSD test). $CV_{(A)}$ and $CV_{(B)}$ represent, respectively, coefficients of variation calculated for the data both across the soil management ($CV_{(A)}$) and across the different seasons and their interaction with the soil management ($CV_{(B)}$).

Table 6. Mean separation and coefficients of variations of volumetric soil water contents (θ_{10}, θ_{100}, θ_{15300}) and capacity-based indicators.

Source of variation	θ_{10} (cm^3 cm^{-3})	θ_{100} (cm^3 cm^{-3})	θ_{15300} (cm^3 cm^{-3})	P_{MAC} (cm^3 cm^{-3})	*AC* (cm^3 cm^{-3})	*PAWC* (cm^3 cm^{-3})	*RFC* (-)
MT	0.5734	0.4017	0.1362	0.0194	0.1911	0.2650 a	0.6774
NT	0.5585	0.3947	0.1314	0.0197	0.1816	0.2620 b	0.6833
$CV_{(A)}$ (%)	1.8	0.7	4.7	48.4	12.0	0.6	5.7
Autumn	0.5986 a	0.4249 a	0.1469 a	0.0216	0.1943	0.2780 a	0.6856
Summer	0.5333 b	0.3716 b	0.1207 b	0.0174	0.1784	0.2491 b	0.6751
Autumn MT	0.6084	0.4359	0.1517	0.0176	0.1901	0.2842	0.6957
Autumn NT	0.5887	0.4138	0.1421	0.0256	0.1985	0.2717	0.6755
Summer MT	0.5383	0.3676	0.1207	0.0211	0.1920	0.2458	0.6591
Summer NT	0.5283	0.3756	0.1206	0.0138	0.1647	0.2523	0.6910
$CV_{(B)}$ (%)	4.7	4.8	7.6	32.2	8.3	3.2	3.4

within each column, data followed by different letters are significantly different at a *p*-value of 0.05 (LSD test). $CV_{(A)}$ and $CV_{(B)}$ represent, respectively, coefficients of variation calculated for the data both across the soil management ($CV_{(A)}$) and across the different seasons and their interaction with the soil management ($CV_{(B)}$).

The aim of measures repetition in large, or relatively large-scale, experiments is to investigate the susceptibility of treatment effects to space and time variation. In our study, we mainly evaluated the seasonal variability of physical and hydraulic properties of a soil, where minimum tillage and no-tillage were used repeatedly over time in a long-term experiment. Combined analysis of variance of data (combined ANOVA) was used to estimate the average response to treatments and to test consistency of the responses in two different time of sampling and the interaction of the treatment effects with seasons. In general, measurement campaigns were selected to account for a similar time elapsed from the last main soil tillage, so as to be relatively confident of having overtaken the phase of rapid consolidation of the soil and, consequently, of studying relatively comparable soil conditions. However, the different sampling seasons, summer and autumn, represented the prerequisite for investigating different soil moisture conditions, that are known as a main factor affecting variability in soil physical properties. Consequently, the effect induced by soil management (NT and MT) on soil structure (summarized by ρ_b and K_s) was simultaneous evaluated.

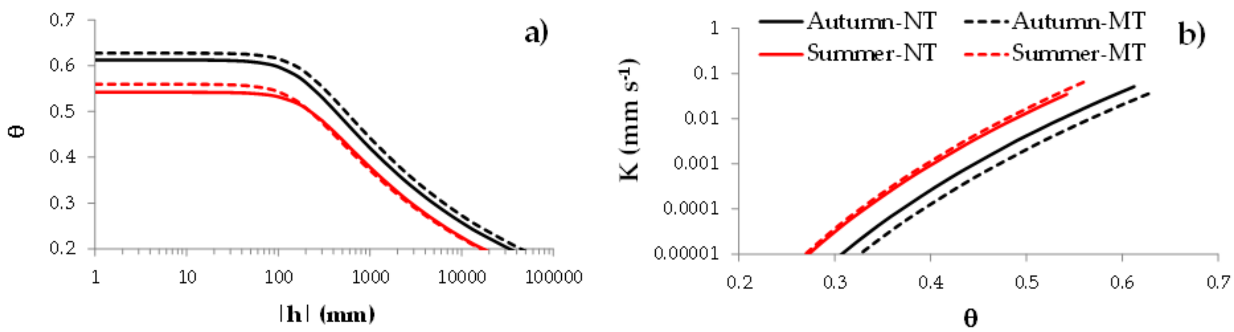


Figure 9. Water retention curves (a) and hydraulic conductivity functions (b) obtained with BEST-steady for minimum tillage (MT) and no-tillage (NT) in Autumn and Summer.

With specific reference to the variables directly determined during the investigation (θ_i, ρ_b and K_s) and regardless of soil management, effects of seasonality (autumn vs summer) were consistent with expectation. It was confirmed that the significantly higher soil moisture contents, typical for autumnal season, were associated with significantly lower soil bulk density values, and with corresponding significantly lower saturated hydraulic conductivities. One of the main factors hypothesized for the significant differences in ρ_b values could be linked to the general expandability of clay soil because, although it was considered generally negligible based on several water retention laboratory measurements, qi values differed by a factor of 1.12 between seasons. However, the relationship between soil compaction and soil water content is well established in the literature, as a negative (inverse) correlation between θ_i and ρ_b is reported (Zhao et al., 2022; Vaz et al., 2011). On the other hand, the significant differences in saturated hydraulic conductivity between seasons agreed with the literature (among others, Kreiselmeier et al. (2020), Kool et al. (2019), Kargas et al. (2016)), as well as specifically consistent with previous results obtained for the same soil, with K_s that decreased as soil water content increased (Castellini et al., 2015). Conversely, although the direct relationship between K_s and ρ_b could be not self-explanatory or considered to be inconsistent with the results discussed, the significant higher soil water content in autumn than summer could have reduced the soil pores space (i.e., volume reduction of macropores or cracks, pores occlusion, or a reduction in hydraulic continuity within porosity). Overall, rigid soils (coarse textured soils, as sandy soils) show the same soil volume regardless of the soil water content, while finer texture soils tend to swell (or contract), depending on the degree of wetness (Hillel, 1998). The soil under study did not show evident swelling characteristics in past investigations, and infiltration measurements were made on soil surfaces without evident surface cracks. However, swelling phenomena affecting the pore system cannot be excluded, and our findings seem move in this direction. In general, this plausible soil behaviour is not uncommon to find in the literature (Hu et al., 2012). For instance, Hu et al. (2012) investigating the seasonal changes in surface ρ_b and K_s in natural landscapes, concluded that the temporal pattern of K_s followed the temporal changes of ρ_b but that the opposite was not always true, because temporal changes of ρ_b cannot fully explain the temporal change of K_s (Hu et al., 2012). In other words, since ρ_b provides a measure of the oven-dry soil mass in relation to its volume, it does not provide any information on the pores network, i.e., volume and continuity, that characterizes the corresponding soil volume (Reynolds et al., 2009). Therefore, although bulk density-based experimental information is widely used or was implemented in the Protocol for the Assessment of Sustainable Soil Management (FAO, 2020), it should be taken with caution because it does not always represent a strong indicator for summarizing the dynamics of water into the soil.

Although the interaction between soil management and sampling season was not significant (p-value = 0.2084), the reduction in saturated hydraulic conductivity observed in autumn under greater soil water content appeared to be on average more pronounced under minimum tilled soil (0.0640 mm s^{-1} vs 0.354 mm s^{-1}, respectively in summer and autumn) (Table 5). In general, relationships between BEST-derived variables and other measured variables met expectations because, for example, P_{MAC} (or AC) increased as ρ_b decreased (Hu et al., 2012); in the same way, similar relationships were detected when relative field capacity was considered, as relatively higher RFC values highlight a reduced availability for soil air (and vice versa) (Manici, et al., 2019). However, regarding the accuracy of capacity-based soil indicators obtained by BEST, a further evaluation was carried out by comparing the summer data of this investigation (ρ_b, P_{MAC}, AC, RFC) with the corresponding measurements (i.e., from measured soil water retention curves) carried out in the same plots in spring 2015 (see data reported in Table 4 by Stellacci et al., 2021). Starting from very similar ρ_b values (differences within a factor 1.2 or 1.3 under NT or MT), the three remaining indicators showed, on average, relatively higher discrepancies under NT (a factor 2.3) than MT (1.7), with the highest difference (overestimation by a factor 4) for the air capacity under no-tillage.

The effects of soil management, NT and MT, on main physical (ρ_b) and hydraulic (K_s) soil properties were quite interesting because, starting from similar (not different) soil moisture conditions, no-tilled soil was significantly more dense and less conductive, as compared to MT. This is not in itself a novel result, even considering findings obtained in the past in the same plots, applying different methods, and measures that have span almost the entire cropping season (Stellacci et al., 2021). However, it provided further evidence that the two soil management systems, investigated in a long-term experiment, may not show substantial differences in their physical and hydraulic behaviour, as summarized by hydraulic functions (Figure 9). Furthermore, the comparison between measurements and reference values of literature has emphasized that ρ_b and K_s fall within the suggested optimal thresholds to avoid risks to crops: i) bulk density was practically always within the optimal range 0.9-1.2 g cm^{-3} (Reynolds et al., 2009), and ii) saturated hydraulic conductivity was not very dissimilar from reference values suggested by Reynolds et al. (2007) for a wide range of agricultural soils (i.e., 0.05-0.005 mm s^{-1}), for promoting rapid infiltration and redistribution of crop-available water, reduced surface runoff and soil erosion, and rapid drainage of excess soil water (Reynolds et al., 2007).

4.1.3. Impact of long-term soil management on the physical and hydraulic properties of a fine-textured soil: insights on the effects close to water saturation

The aim of this section was to report all insights, and investigations, carried out on the of the long-term device close to water saturation. The study of saturated and near-saturated agricultural soils is fundamental to evaluate the soils' susceptibility to preferential flow in the macropores system, water redistribution and, therefore, for soil water conservation. Specific goals of this research were: i) analyse the soil water retention curve, applying uni- and bi-modal models, and using a large dataset specifically collected for this purpose, ii) investigate the impact on both saturated and unsaturated hydraulic conductivity, and iii) use the experimental information obtained to highlight the main differences between no-tillage and minimum tillage, also based on the knowledge acquired on the experimental device in previous investigations.

In general, comparable ρ_b values were detected regardless of considered soil management, because mean bulk density values were equal to 1.07 and 1.12 g cm^{-3}, respectively for MT and NT. Also, a similar variability was detected, since coefficients of variation (CV%) were equal to 9.1% and 11.8% for MT and NT, respectively. The differences in ρ_b values were not significantly according to a two tailed t-test (p=0.05). As a consequence, our results suggested that conservative soil management did not have a negative impact, therefore not causing excessive soil compaction conditions, as compared to more conventional one (i.e., managed with minimal tillage). As an example, Figure 10a shows the comparison in terms of soil porosity, ϕ, where higher mean values were observed under MT (equal to 60%) than NT (58%). This is an obvious result since ϕ and ρ_b are variables inversely correlated (see section 3.3). However, relatively similar information was obtained when, for a comparison, the measured soil water retention close to water saturation (i.e., θ_5) was considered (Figure 10b). As depicted in figure in fact, θ_5 values were lower under NT (0.540 cm^3 cm^{-3}) and higher under MT (0.569 cm^3 cm^{-3}), with comparable CV values (i.e., 7.0% and 6.4%, under NT and MT respectively), but such differences were statistically significant. This suggests that some differences may have existed between the soil systems close the saturation, but that such discrepancies were not entirely detectable by a "simple" soil sampling for f estimation.

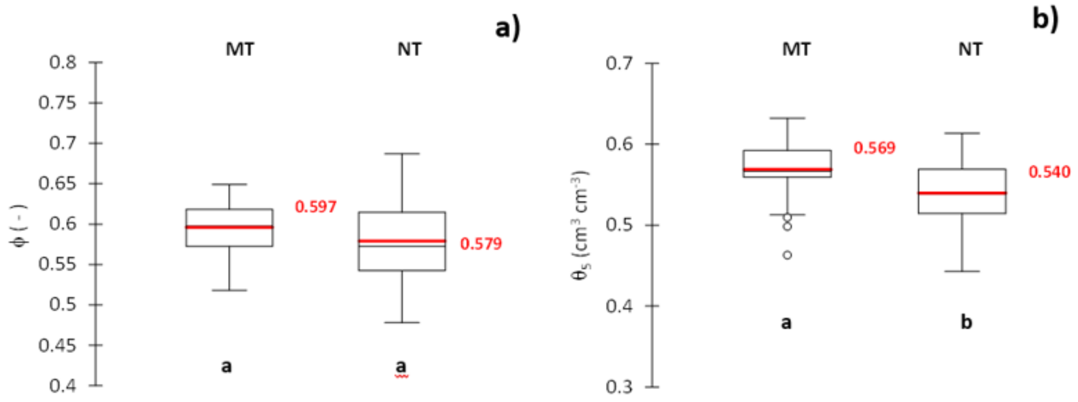


Figure 10. Box plots of soil porosity (a) and measured soil water retention close to water saturation, at h = -5 cm (b), under minimum tillage and no-tillage, respectively. Means labelled by the same letter are not significantly different, according to a two-tailed t-test (P = 0.05).

Table 7. Results of comparison between the water retention data fitted by unimodal (vGum) and bimodal (vGbm) version of the van Genuchten model, in terms of relative error (RE), root mean square differences (RMSD) and average differences (AD).

		RE%	RMSD	AD
MT	vGum	2.9039	0.0122	0.0001
	vGbm	1.1128	0.0047	-0.0002
NT	vGum	3.9195	0.0162	0.0005
	vGbm	1.8731	0.0077	-0.0001

Experimental soil water retention measurements were fitted by using the uni- and bimodal version of van Genuchten model (vGum and vGbm, respectively). Results of this comparison were reported in Table 7 and Figure 11. Regardless of the model used for soil water retention curve parametrization (vGum or vGbm), the goodness of fit was overall always satisfactory, as the comparison between measured and estimated θ values returned low values of root mean square differences (RMSD < 0.016 cm^3 cm^{-3}), as well as of average differences (AD < 5.3E-04 cm^3 cm^{-3}) and relative errors (RE < 3.9%) (Table 7). However, the fitting of the water retention curve was overall better for vGbm, and for NT than MT, as the statistics were higher for the latter soil management by a factor of 1.3-1.7. Figure 11 depict the comparison in terms of macroporosity values obtained applying vGum and vGbm models, to estimate the water retention curve. In general, vGum overestimated P_{MAC} for relatively higher saturated soil water content values; however, this finding was more evident under MT than NT, since it was four time higher for the former than the latter soil management (Figure 11). The discrepancies in P_{MAC} estimation were obtained only for higher qs values (approximately higher than 0.65 cm^3 cm^{-3}), as equivalent θ_{10} estimations were obtained regardless of models (i.e., θ_{10} values estimated by models were always significantly correlated, and the regression line not significantly different from the identity line, according to the calculated 95% confidence intervals for the intercept and the slope). A cluster analysis, carried out on the full data set of saturated soil water contents (MT+NT) confirmed such findings, and allowed to identify more accurately an upper limit, equal to approximately 0.63 cm^3 cm^{-3}, above which the use of the unimodal model is inadvisable.

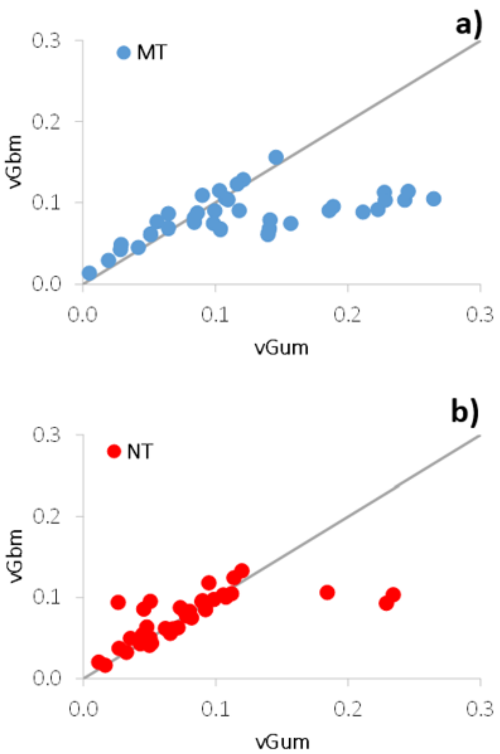


Figure 11. Comparison of soil macroporosity values obtained under minimum tillage (a) and no-tillage (b) soil management, using the unimodal (vGum) and bimodal (vGbm) version of the water retention model.

The volumetric soil water content at the time of sampling was slightly higher under NT than MT, because it was equal to 0.31 cm^3 cm^{-3} (CV = 8%) and 0.30 cm^3 cm^{-3} (CV = 12%) under no-tillage and minimum tillage, respectively. As a consequence, such differences were not significant. In general agreement with the results reported so far, TOC values were higher under NT than MT. Mean values of 18.4 g kg^{-1} (CV=7.9%) and 21.7 g kg^{-1} (CV = 7.4%) in fact were detected under MT and NT, respectively; such differences were significant. The geometric mean of saturated and unsaturated hydraulic conductivity, i.e., K_s-K_3, obtained with beerkan and TI methods, was equal to 77.9-0.99 mm h^{-1} (CV = 69-23%) under MT and 90.3-1.04 mm h^{-1} (CV = 54-29%) under NT (Figure 12), always resulting not statistically different between soil management. Therefore, a high increase in hydraulic conductivity in soil macropores, both under MT and NT (i.e., a factor 79-87) was observed, suggesting some bimodality of the investigated clay soil.

Our findings showed that, at the end of a wheat crop cycle, NT soil was significantly wetter and more compact but no less conductive than MT. Although ρ_b values were not significantly different between soil treatments, in fact, detectable differences in hydrostatic soil properties close to water saturation were detected, since θ_5 was significantly different between soil management (Figure 10b). The relationship between soil water content and soil pressure head was adequately parameterized, according to the statistics results reported; this was showed regardless of the model applied, i.e., vGum or vGbm, although the latter returned more reliable estimates of saturated soil water content. In fact, when P_{MAC} was calculated using θ_s from both parametrizations, macroporosity deviated from the identity line plotting vGbm vs. vGum data in 8% and 39% of cases, respectively under NT and MT. Since such deviation always occurred for highest soil porosity values, namely when were approximately higher than $\theta_s > 0.63$ cm^3 cm^{-3}, above this threshold the use of vGbm model is advisable.

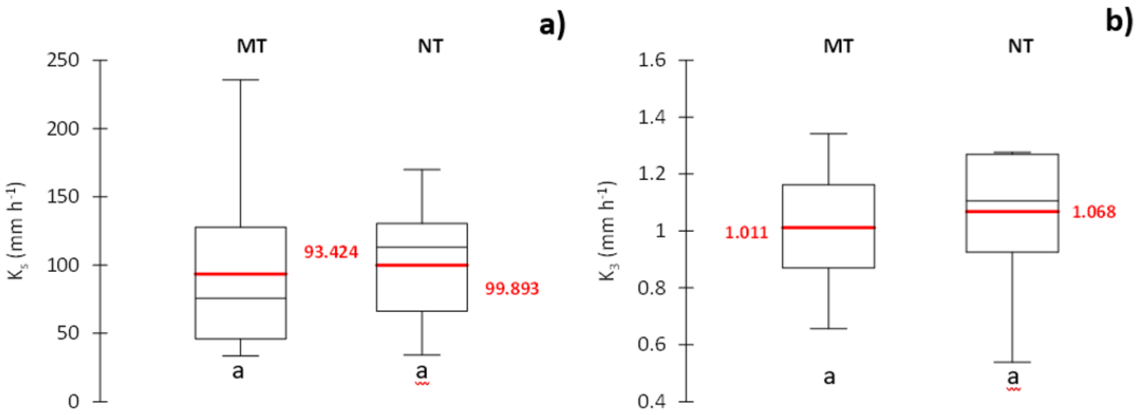


Figure 12. Box plots of saturated (a) and unsaturated (b) hydraulic conductivity, under minimum tillage and no-tillage, respectively. Means labelled by the same letter are not significantly different, according to a two-tailed t-test (P = 0.05).

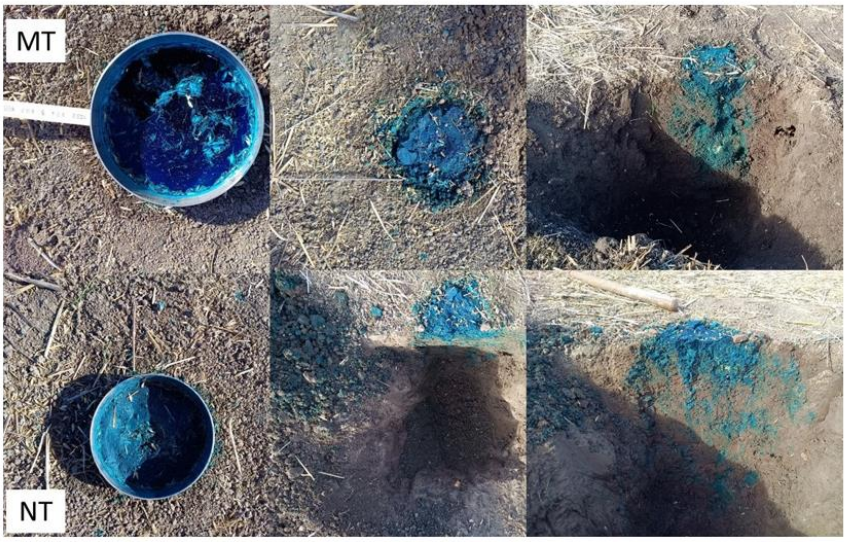


Figure 13. Infiltration experiments of beerkan type with dye tracer under NT and MT.

Despite the findings obtained, a higher, although not significant, hydraulic conductivity, i.e. both saturated and unsaturated soil condition, was detected under NT. This suggests that long-term soil management (it was more than twenty years old), modified the hydrostatic rather than hydrodynamic properties of the soil studied and, probably, also modified the volume and connectivity of conductive pores. In this sense, a relatively high hydraulic conductivity increases in soil macropores on both under MT and NT (a factor 79-87, in the transition from K_3 to K_s) was also observed, suggesting some bimodality of the investigated soil.

To further verify the general results obtained and find further support regarding the hydrological interpretation made, two ponded infiltration tests were performed in late autumn with a dye tracer, to verify the characteristics of the saturated water flow under NT and MT (Figure 13). Infiltration experiments of beerkan type consisted of 35 water pourings by 200 mL each; therefore, a total of 7 L was used for an infiltration experiment. The brilliant blue, FCF (E133), at a concentration of 4g/l, was used as dye tracer, and the maximum depth reached by the water flow was detected by means of opening a trench. This experimental set up was considered to have reasonable certainty of reaching the undisturbed soil layer, i.e., the undisturbed soil layer of MT soil. Obviously, although not exhaustive from the point of view of the experiment replicability, and/or to account for the spatial variability of the soil, our check confirmed a similar dynamic of the saturated flow, as the maximum water flow depth was estimated at approximately 45 and 55 cm under NT and MT. However, differences were detected, as a saturated bulb more developed radially (NT) than vertically (MT) (Figure 13); this finding would further support the conclusions reached, with a larger mean pore size under tilled soil, responsible for a prevailing gravity flow, and relatively smaller pores (but probably better interrelated with each other) under undisturbed one, responsible for a main capillary flow.

4.1.4. Assessment of soil quality under MT and NT with multiple indicators

The main objective of this investigation was to apply, and compare, different statistical methods for selection of soil indicators, to identify the variables that most discriminated soil status under minimum tillage and no-tillage. Twenty soil indicators (chemical, physical and biological) including, for example, bulk density, relative field capacity, organic and extractable carbon contents, or exchangeable potassium, collected in the CREA-AA long-term field experiment (Foggia), account for the upper soil layer (0–0.20 m) were considered. The main objectives of this study were to i) identify the most suitable variables for discriminating soil status under different soil management strategies and ii) compare the performance of three multivariate statistical approaches to select soil indicators.

Preliminary statistical analysis carried out on grain yield and protein content, response variables in PLSR, showed close mean and median values and coefficient of skewness and kurtosis equal or lower than 0.5. These results were confirmed by normality tests indicating for both variables a not significant deviation from normal distribution (P = 0.5198 and P = 0.0970 for the Shapiro-Wilk test, for grain yield and protein content, respectively). Variances were homogeneous over management treatments for both variables according to Levene test (P = 0.4128 for grain yield and P = 0.2432 for protein content). Average values of grain yield and protein content were respectively 5.247 Mg ha^{-1} and 13.39 g 100 g^{-1}.

Soil variable distributions did not significantly deviate (microbial biomass C, TOC, TEC, HA_FA, N, Olsen P, pH, K^+, Mg^{2+}, Na^+, ρ_b, AC, RFC, clay and sand) or only slightly deviated (EC, Ca^{2+}, P_{MAC}) from normal distribution, except for WEOC and WEN. Homoscedasticity was also observed in the larger part of the cases (except for WEN and P_{MAC}). For this reason, data were analysed for all the variables in the original scale.

Table 8. Results of nested analysis of variance carried out on soil chemical and biological parameters.

Source of Variation	WEOC mg kg^{-1}	WEN mg kg^{-1}	C_biomass mg kg^{-1}	TOC g kg^{-1}	TEC g kg^{-1}	HA_FA g kg^{-1}	N g kg^{-1}	P_Olsen mg kg^{-1}	pH	EC dS m^{-1}	Ca^{2+} mg kg^{-1}	K^+ mg kg^{-1}	Mg^{2+} mg kg^{-1}
Soil management (mean) Pr(>F)	49.351 0.1732	25.186 0.0273 *	491.03 0.8461	19.66 0.0325 *	12.088 0.0415 *	6.782 0.3280	1.470 0.4441	54.045 0.4609	8.10 0.1674	0.139 0.6251	6880.9 0.9698	1043.89 0.0233 *	215.84 0.1663
NT	70.44	10.11 b	509.8	21.87 a	13.63 a	6.23	1.52	60.72	8.07	0.14	6880.3	1120.18 a	211.65
MT	28.26	40.26 a	472.3	17.45 b	10.54 b	7.34	1.42	47.37	8.14	0.13	6881.6	967.60 b	220.03

* and ** indicate respectively differences at P ≤ 0.05 and P ≤ 0.01. Means followed by different letters are significantly different according to the SNK test (P = 0.05). Pr(the probability value (p-value) to determine whether to reject the null hypothesis. WEOC = water extractable organic carbon; WEN = water extractable nitrogen; C_bioma biomass carbon; TOC = total organic carbon; TEC = alkali-extractable carbon; HA_FA = humic and fulvic acid carbon; N = total nitrogen; P_Olsen = Olsen available phos electrical conductivity; Ca^{2+}, Mg^{2+}, Na+, K^+ = exchangeable cations. (n = 24)

Analysis of Variance showed that the different soil management strategies significantly affected both total organic and total extractable carbon (TOC and TEC), and water extractable nitrogen (WEN) concentrations, with higher TOC and TEC content observed in the upper soil layer under more conservative soil management (Table 8). In particular, an average TOC value of 21.87 g kg^{-1} was recorded under no-tillage (NT) in comparison to 17.45 g kg^{-1} under minimum tillage (MT) management. A greater significant concentration of exchangeable potassium (K^+) was also observed in untilled soils (Table 8). Under minimum tillage, higher WEN concentrations were observed. Soil management also affected physical properties with a significantly greater bulk density (ρ_b) in untilled soils and, as a consequence, lower air capacity (AC), indicating a tendency to soil compaction (Table 9). Macroporosity (P_{MAC}) confirmed this trend, although not significant differences were recorded. Relative field capacity (RFC), that gives an account of the balance between water capacity and air capacity of the soil (in other words, it is an index of the relative importance of meso-micropores to total porosity), was higher in NT than in MT, suggesting major potential risks of anaerobic conditions due to reduced presence of air in the soil porosity. According to Reynolds et al. (2009), optimal and intermediate values were observed under MT for bulk density (0.9–1.2 g cm^{-3}, optimal range), air capacity (0.10–0.14 cm^3 cm^{-3}, intermediate range) and macroporosity (0.04 −0.07 cm^3 cm^{-3}, intermediate range) and values slightly over than the optimal threshold for RFC (0.6–0.7, optimal range). Except for ρ_b, values recorded under NT were all indicative of limited aeration conditions. The long-term iteration of the different management strategies slightly affected grain yield response (P = 0.0603), with average values of 5.45 and 5.04 Mg ha^{-1} recorded under no-tillage and minimum tillage, respectively. No significant effect of the management compared was instead observed for grain protein content.

Table 9. Results of nested analysis of variance carried out on soil physical and hydrological parameters.

Source of Variation	ρ_b g cm^{-3}	P_{MAC} cm^3 cm^{-3}	AC cm^3 cm^{-3}	RFC -	clay g $100g^{-1}$	sand g $100g^{-1}$
Soil management (mean)	0.96729	0.03329	0.08473	0.8151	48.15	11.03
Pr(>F)	0.0316 *	0.0992	0.0370 *	0.0302 *	0.1854	0.5042
No-tillage (NT)	1.04516 a	0.00890	0.04112 b	0.90814 a	45.44	11.41
Minimum tillage (MT)	0.90240 b	0.05362	0.12107 a	0.73764 b	50.85	10.65

* and ** indicate, respectively, differences at P ≤ 0.05 and P ≤ 0.01. Means followed by different letters are significantly different according to the SNK test (P = 0.05). Pr(> F) indicates the probability value (p-value) to determine whether to reject the null hypothesis. ρ_b = dry bulk density; P_{MAC} = macroporosity; AC = air capacity; RFC = relative field capacity. (n = 22 for BD, PMAC, AC, RFC. n = 24 for clay and sand)

Table 10. Eigenvalues and variance explained by the first five principal components (PCs) of the analysis carried out on the set of (a) chemical and biological indicators (14 variables) and (b) physical indicators (6 variables).

(a) Eigenvalues of the Correlation Matrix: Total =14 Average = 1					(b) Eigenvalues of the Correlation Matrix: Total =6 Average = 1				
	Eigenvalue	Difference	Proportion	Cumulative		Eigenvalue	Difference	Proportion	Cumulative
1	5.1000	2.6932	0.3643	0.3643	1	3.7885	2.7698	0.6314	0.6314
2	2.4068	0.7911	0.1719	0.5362	2	1.0187	0.1054	0.1698	0.8012
3	1.6158	0.4237	0.1154	0.6516	3	0.9133	0.6757	0.1522	0.9534
4	1.1921	0.2644	0.0851	0.7368	4	0.2376	0.1971	0.0396	0.993
5	0.9278	0.2123	0.0663	0.803	5	0.0404	0.0389	0.0067	0.9998
	……….					……….			

PCA was first performed separately on the set of chemical and physical variables, and then carried out on the whole dataset. In the analysis of the chemical indicators, the first three components (PCs) explained about 65.16% of total variance, whereas in the analysis of the physical indicators, the first two PCs were able to explain 80.12% of total variance (Table 10). The score plots of the first two components showed that both chemical and physical variables were able to discriminate the different soil management compared (Stellacci et al., 2021). The inspection of the loadings of the first PCs highlighted that no-tilled soils (NT) were characterized by a greater TOC and TEC, together with exchangeable K^+ content, and by a larger bulk density and RFC, whereas a lower P_{MAC} and AC were detected. The analysis on the whole set of soil indicators (chemical, physical and biological) confirmed these results with an even clearer treatment discrimination and the same highly weighted variables showing the greatest loadings (Tables 11 and 12). In detail, the first four PCs explained cumulatively about 72.54% of total variance (Tables 11). In the first PC (41.21% of total variance) the highly weighted variables were TOC and TEC among chemical variables, whereas RFC and AC, followed by P_{MAC}, for the hydrological soil parameters (Table 12). Slightly under the threshold of 10% of the highest factor loading, there were exchangeable K^+ and bulk density and, at a lower extent, WEN (Stellacci et al., 2021). In the second PC (12.61%), available P and humic and fulvic acids showed the highest loadings, with microbial biomass carbon and pH slightly under the threshold. In the third (10.65%) and fourth (8.07%) components, exchangeable Ca^{2+} and N were selected, respectively (Table 12). The inspection of these results showed that the first PC summarized main findings of the analysis of variance. The second component highlighted instead the role of available nutrients (P) and some carbon fractions (humic and fulvic acids C and microbial biomass C), adding, in this way, further elements to explain differences observed in the experimental conditions.

Table 11. Eigenvalues and variance explained by the first five principal components (PCs) of the analysis carried out on the whole dataset of soil indicators (20 variables).

Eigenvalues of the Correlation Matrix: Total =20 Average = 1				
	Eigenvalue	Difference	Proportion	Cumulative
1	8.2424	5.7211	0.4121	0.4121
2	2.5213	0.3911	0.1261	0.5382
3	2.1302	0.5153	0.1065	0.6447
4	1.6149	0.4059	0.0807	0.7254
5	1.2089	0.2821	0.0604	0.7859
	……….			

Table 12. Variable loadings of the first four components in the analysis carried out on the whole dataset. Values are multiplied by 100 and rounded to the nearest integer. Variance explained: PC1 = 41.21%; PC2 = 12.61%; PC3 = 10.65%; PC4 = 8.07%.

	Factor1		Factor2		Factor3		Factor4	
WEOC	54	*	−22		44	*	5	
WEN	−77	*	4		−11		6	
C biomass	32		53	*	21		53	*
TOC	**91**	*	−29		12		2	
TEC	**93**	*	−27		6		15	
HA_FA	−36	*	**−59**	*	7		40	*
N	36	*	7		34		**60**	*
P Olsen	33		**−63**	*	−21		26	
pH	−70	*	52	*	−14		−3	
EC	50	*	43	*	13		42	*
Ca^{2+}	2		2		**79**	*	−23	
K^+	82	*	−8		−36	*	26	
Mg^{2+}	−46	*	−9		57	*	18	
Na^+	−52	*	41	*	43	*	12	
ρ_b	83	*	37	*	12		−12	
P_{MAC}	**−84**	*	−34	*	16		18	
AC	**−91**	*	−26		8		21	
RFC	**92**	*	27		−6		−18	
clay	−43	*	45	*	−10		12	
sand	23		−21		58	*	−49	*

* indicates the significance of the variable loadings. The sign of variable loadings indicates the positive or negative correlation between the variables and the principal component. WEOC = water extractable organic carbon; WEN = water extractable nitrogen; C_biomass = microbial biomass carbon; TOC = total organic carbon; TEC = alkali-extractable carbon; HA_FA = humic and fulvic acid carbon; N = total nitrogen; P_Olsen = Olsen available phosphorus; EC = electrical conductivity; Ca^{2+}, Mg^{2+}, Na^+, K^+ = exchangeable cations. ρ_b = dry bulk density; P_{MAC} = macroporosity; AC = air capacity; RFC = relative field capacity.

SDA was first performed separately on the set of chemical and physical variables, and then carried out on the whole dataset. Variables enabling maximum discrimination among treatments for the analysis carried out on the dataset of chemical and biological indicators were TOC ($P < 0.0001$) and HA_FA ($P = 0.0004$), followed at a lower extent by Olsen P ($P = 0.0111$), EC ($P = 0.0258$), WEOC ($P = 0.0397$) and TEC ($P = 0.05$). In the analysis carried out on the set of physical indicators, the variables selected were RFC ($P < 0.0001$) and clay ($P = 0.037$). Finally, the analysis carried out on the whole dataset summarized the results obtained, selecting TOC ($P < 0.0001$), RFC ($P < 0.0001$) and WEOC ($P = 0.003$) as variables enabling maximum discrimination among treatments (Table 13).

Table 13. Summary selection of STEPDISC procedure carried out on the whole dataset of chemical, physical and biological indicators.

Step	Number In	Entered	Removed	Partial R-Square	F Value	Pr > F	Wilks' Lambda	Pr < Lambda	Average Squared Can Corr	Pr > ASCC
1	1	TOC		0.8297	97.46	<0.0001	0.17026571	<0.0001	0.82973429	<0.0001
2	2	RFC		0.5631	24.49	<0.0001	0.07439379	<0.0001	0.92560621	<0.0001
3	3	WEOC		0.3941	11.71	0.003	0.0450772	<0.0001	0.9549228	<0.0001

Both PCA and SDA, as well as univariate analysis of variance, returned TOC and RFC among the most influential variables both on the set of chemical and physical data analysed separately as well as on the whole dataset. In addition, WEOC was selected among the most discriminating variables in the SDA carried out on the whole dataset of soil indicators. These findings are in agreement with results reported by previous studies in the selection of the most relevant indicators for assessing soil quality status.

PLSR was applied to gain further information in the selection of the most informative variables to describe the effects of the two soil management practices compared. The method was applied to the whole set of soil indicators and considering grain yield and grain protein content as single response variables (PLS1) and as multiple response variables (PLS2). When wheat grain yield was considered as single response variable, the first two factors accounted cumulatively for 47.20% of total variance in predictors and 48.17% in the response variable. VIP coefficient profiles (Figure 14a) showed that the highest values were recorded for Olsen P and P_{MAC}, followed by TOC, TEC, pH and Mg^{2+} (for the chemical variables) and by clay, RFC and AC (for the physical variables). The use of grain protein content as response variable further modified the rank of indicators selected. The first two factors accounted cumulatively for 49.54% of total variance in predictors and 23.59% in response. The greatest PLS-VIP statistics values were recorded for N and Olsen P, followed by WEN and sand, thus indicating the contribution of macro-elements, with particular regard to N (total and labile form), in affecting grain protein concentration (Figure 14b). In addition, TOC, TEC, Ca^{2+} and pH showed important contribution. The inspection of both VIP profiles (Figure 14a,b) underlined the role of physical soil indicators (P_{MAC}, AC and RFC), which were selected as important variables in both analyses. Finally, PLSR was carried out considering simultaneously, as response variables, the grain yield and protein content (PLS2). The first two factors extracted accounted cumulatively for 48.56% of total variation in predictors and 27.16% in the response variable. From the inspection of the VIP profile (Figure 14c), the role of available nutrients (Olsen P and, secondary, WEN) and hydrological variables (P_{MAC}, AC and RFC) in explaining plant response emerged again. These variables were followed by soil carbon contents (TOC and TEC), pH and exchangeable cations. The inclusion of a response variable in PLSR—yield, protein content or both significantly modified the rank of soil indicators selected, giving greater emphasis to plant macro-nutrients (available P and N), particularly when the grain protein content was used as dependent variable. These results underline the importance of using combined approaches to explore the data and interpret the behaviour of the system investigated. Finally, for a further exploratory purpose, PCA was carried out on the variables more frequently selected with the combined use of SDA, PCA and PLSR, namely TOC, TEC, Olsen P, WEN, RFC, P_{MAC} and AC (Stellacci et al., 2021).

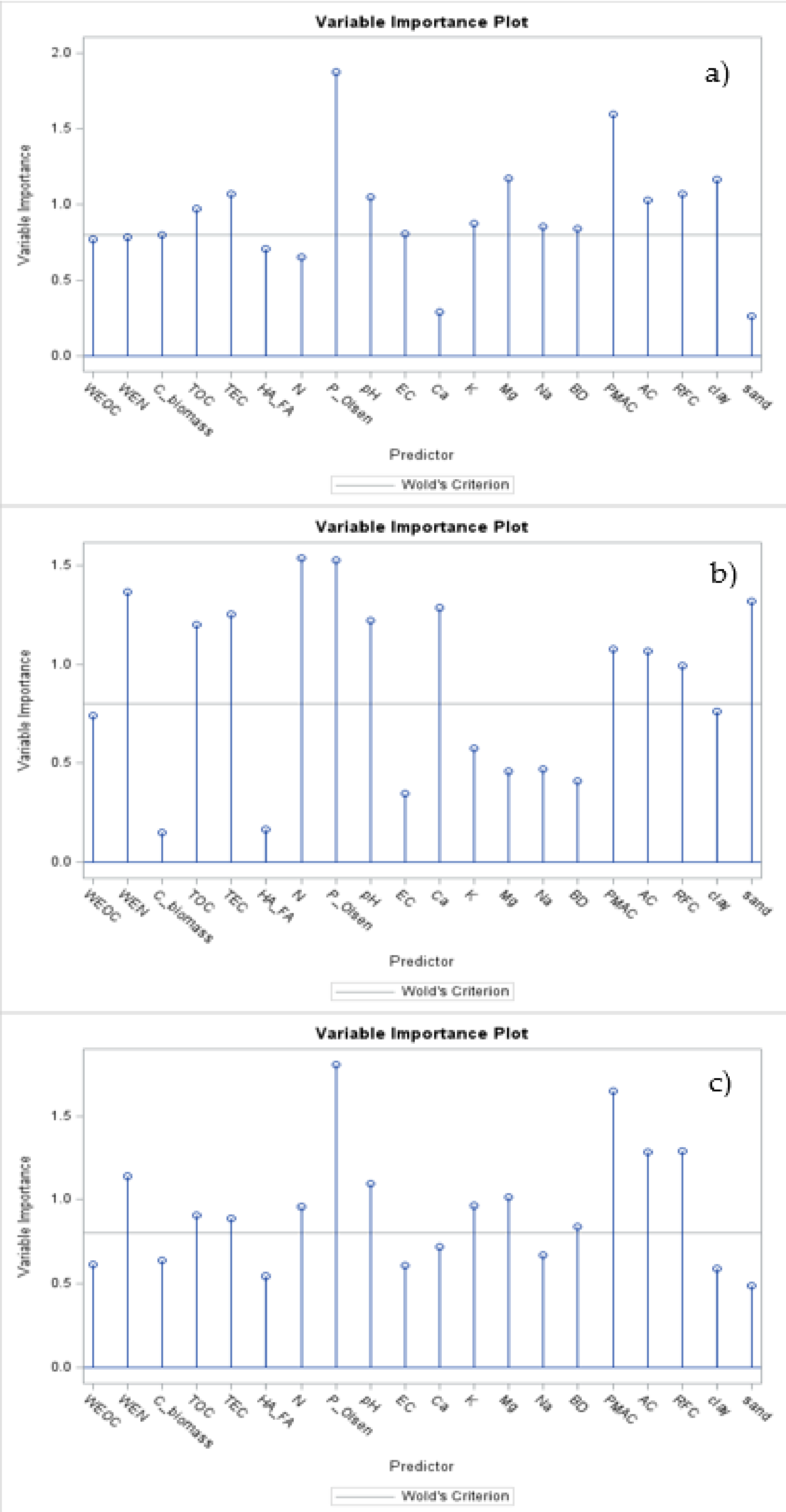


Figure 14. Variable importance for projection statistics (PLS-VIP) obtained using as response variable in PLSR (a) wheat grain yield, (b) grain protein content and (c) both variables. The horizontal black line indicates the threshold of 0.8 to discriminate and select significant variables according to Wold criterion. Note that soil bulk density was identified with the acronym BD.

Long-term experiments can be considered valuable research infrastructures, which enable the long-term study and monitoring of the effects of agricultural strategies or management scenarios. This was the main reason why, both CAMA-partners and CREA-group, concentrated a lot of research on the study of long-term experimental devices. Among agricultural practices, soil tillage, or no-tillage, strategies, are major determinants of soil status and quality. By directly acting on soil physical properties—modifying porosity (total pore space and pore size distribution), soil aggregate size and stability, hydraulic conductivity, soil tillage modifies air-water capacity relationships and thus induces changes in soil organic carbon dynamics, nutrient cycling and solute transport (Castellini et al., 2019a). Significant effects can usually be observed when stable or near-stable conditions are established, after transition periods (Castellini et al., 2019b).

In this study, the long-term iteration (over about 13 years) of two soil management strategies—minimum tillage and no-tillage—considerably affected certain physical and chemical properties of the upper soil layer in the system investigated. Analysis of variance showed that significantly greater bulk density and relative field capacity values and, consequently, lower air capacity, were recorded under no-tillage soil management. Since RFC is the ratio between the water content at the field capacity and that at water saturation, relatively higher RFC values highlight a reduced availability for soil air. In accordance with previous results on fine-textured soils (Castellini et al., 2020), soil physical quality was thus indicative of lower aeration conditions under no-tillage.

The long-term no-tillage soil management also enhanced total organic and extractable carbon contents. The behaviour observed is in agreement with several studies (i.e., Diacono et al., 2020), since the reduced soil disturbance reduces the turnover of soil aggregates favouring the accumulation and stabilization of organic matter within micro- and macro-aggregates, thus leading to a net gain of soil carbon. Significantly different values of C and N of the microbial biomass, bulk density, hydraulic conductivity and average weight of soil aggregates were also observed by Sharma et al. (2005) under conventional and no-tillage in a long-term field experiment. Laudicina et al. (2014), comparing the effect of different cropping systems (wheat/wheat and wheat/bean) and most used tillage managements (conventional, dual layer and no-tillage), in a long-term field experiment on soil organic C pools (total and extractable organic C, microbial biomass C, basal respiration), observed that tillage management affected the soil organic C stored in the first 15 cm of soil more than cropping system. No-tillage caused a 3.6 Mg ha^{-1} increase of C content in a wheat/broad bean rotation, and an increase of 5.6 Mg ha^{-1} in wheat monoculture after 19 years (Laudicina et al., 2014). A greater exchangeable K^+ content was also observed under no-tillage. PCA and SDA confirmed and summarized results of analysis of variance but also underlined the role of organic carbon fractions -humic and fulvic acids and WEOC-, and available P as main sources of variability in describing the data (PCA), and as the variables that most discriminated the treatments compared (SDA).

In a study assessing the suitability of different labile C fractions as soil quality indicators, Bongiorno et al. (2019) found that dissolved organic carbon was not sensitive to soil tillage, unlike the particulate organic C; in any case, WEOC content highly depends on environmental conditions and soil sampling time. In accordance with the present study, López-Fando and Pardo (2009) measured higher concentrations of exchangeable K^+ and available P under no tillage compared to minimum tillage, at a soil depth of 0–20 cm. Similarly, Martin-Rueda et al. (2007) found greater concentrations of plant-available K and P in surface soil (0–20 cm) under no-tillage compared to minimum tillage system, but no difference was observed between the two soil management systems at higher soil depths. The accumulation of available P, K and other nutrients in surface soil layers under no-tillage is usually ascribed to the decomposition of organic matter (which is more abundant in no-tilled soils) and to the accumulation of mineral fertilizers in topsoil (Pavinato et al., 2020). The tillage system also influences the relations occurring between plant roots, soil and microorganisms at the rhizosphere level. After long-term no tillage, a higher activity of alkaline phosphatase and acid phosphatase was measured by Balota et al. (2004). These two enzymes, which can be released both by plant roots and soil micro-organisms, are involved in the release of labile P from the organic pools. Moreover, the organic acids exuded by plant roots and/or released through organic matter decomposition could compete with P for the binding sites on soil particles, thus enhancing P availability (Pavinato et al., 2010).

Application of PLSR, by considering simultaneously soil indicators and plant response (grain yield, protein content or both), selected as important variables the mineral nutrients (available P, and both total and water extractable N), particularly when grain protein content was used as dependent variable, together with soil physical quality indicators (P_{MAC}, AC, RFC), pH and exchangeable cations. To this regard, VIP statistics, being a weighted sum of the squares of PLS X-score coefficients for the retained components, with the weights calculated from the amount of dependent variable (Y) variance explained by each retained component, were able to summarize the contribution of both predictors and response variables. Thus, the contribution of mineral nutrients in determining plant response was also highlighted. Results of both PCA and SDA, as well as of univariate analysis of variance, returned TOC and RFC among the most influential variables both on the set of chemical and physical indicators analysed separately as well as on the whole dataset. Previous studies highlighted the role of RFC among soil indicators in assessing soil physical quality. This variable was able to summarize part of the information given by AC and P_{MAC} and, supported also by ρ_b and plant available water content, showed the highest discriminating capability of the soil and crop residues management strategies compared (Castellini et al., 2019a). TOC selection is important because is a necessary input for soil structural quality indicators (Pieri, 1962). This variable is also indicative of the soil chemical quality, being positively related with soil CEC and nutrient retention capacity. Moreover, TOC can be also indicative of the soil biological quality, due to its key role in maintaining the soil trophic relations and stimulating both the plant and soil microbial activity. Shukla et al. (2006), selecting key soil indicators by means of factor analysis, concluded that TOC was the most dominant measured soil attribute as soil quality indicator for the two soil depths investigated and suggested its use for monitoring soil quality changes. Overall, the inspection of VIP profiles, together with the results of all methods compared, underlined the role of physical soil indicators (P_{MAC}, AC and RFC), which were selected as important variables in all the analyses performed. This reinforces the idea that such soil capacitive indicators (e.g., RFC) can be suggested for several practical applications including, for example, the estimation of optimal rate of amendments in laboratory, before use in the field.

In the assessment of soil quality modifications as effect of agronomic management, the number and type of the indicators considered are strictly related to the aim of the study and to the spatial scale investigated. Our research was performed at field scale and had a methodological and exploratory aim, focused on comparing the strength and ability of different statistical approaches to extract crucial information from soil data and gain an improved understanding of the system investigated. In any case, the combined approach described in this study can be applied to the analysis of different datasets and conditions, including also different spatial scales (Stellacci et al., 2021).

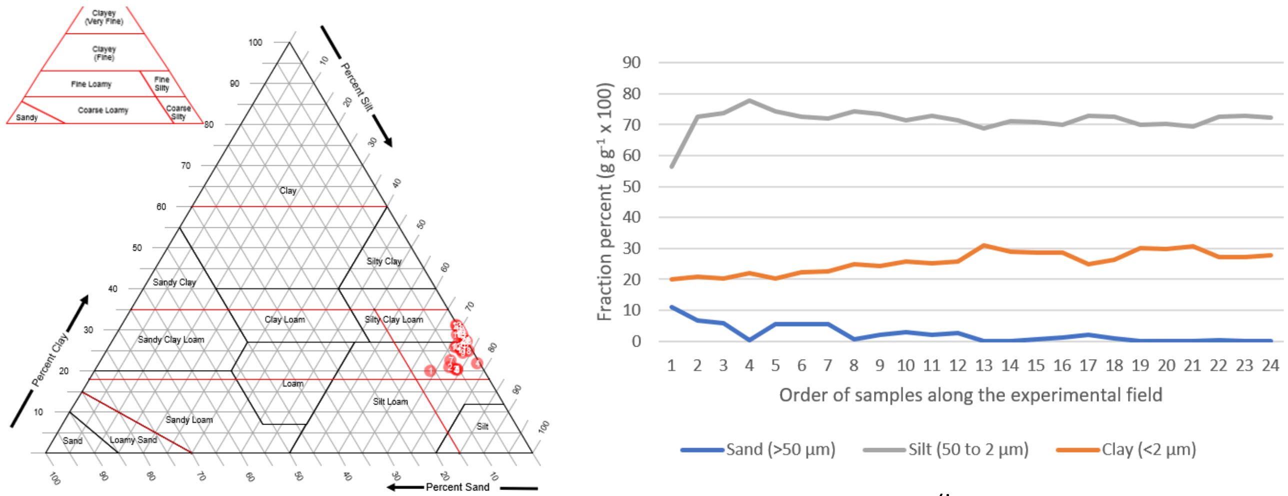
In conclusion, this study shows the effectiveness of using variable selection methods to summarize the information deriving from multivariate datasets and improving the understanding and interpretability of the system investigated. The results also highlight the importance of simultaneously using different approaches because they may provide different and complementary information. The statistical approaches compared provided different results in terms of variables selection and ranking of the selected variables. The presence of a response variable, in the regressive technique, significantly drove the feature selection process. In particular, the inclusion of yield or protein content, as response variables in PLSR, modified the rank of selected soil indicators, giving greater emphasis to plant nutrients, particularly when the grain protein content was considered. The variables more frequently selected with the combined use of the three methods (TOC, TEC, Olsen P, WEN, RFC, P_{MAC}, AC) were able to provide a clear discrimination between the treatments compared, as shown by the PCA carried out on the reduced dataset. Thus, 43% of the selected variables (3 out of 7) accounted for the physical properties of the soil. Also, results finally emphasize the role of multi-year datasets which are invaluable tools to explore benefits and limits of different methodologies and management practices.

4.2. UdL-CSIC (Spain)

4.2.1. Tillage, position, and depth effect on surface and below surface soil physical and hydraulic properties: ponded and tension infiltration.

In summer 2021, a sampling champaign was undertaken in the medium mineral N fertilization plots (75 kg N ha^{-1}) of the ten-years-old Senés field experiment to ascertain the effect of tillage (Intensive tillage, IT, and No-tillage, NT), the position of the measurements with respect to the crop row (between, B-rows, and within the crop rows, W-rows), and the depth of the measurements (on the surface, OnS, and 2 cm below the surface, BelowS).

Soil particle size distribution was determined in two samples per experimental plot, from 0 to 5 and from 5 to 10 cm depth. North to South along the experimental field, soil texture moved from Silt Loam to Silty Clay Loam USDA classes (Figure 15a). The percent of sand decreased from 12 to 0% whereas the percent of clay increased from 20 to 30% (Figure 15b). Silt varied around 70%. The biggest changes were in the first half of the experimental field (samples 1 to 12).



(a) (b

Figure 15. (a) USDA textural triangle (USDA, 2023) with the sample's texture distribution (red dots), and (b) soil particle size percent distribution North to South along the experimental field (0-10 soil depth).

Mean bulk density in the surface soil (0-5 cm depth) ranged between 1.20 and 1.47 g cm^{-3}. Only tillage had a significant effect on bulk density ($p<0.001$, Table 14), that was lower for IT (1.26 g cm^{-3}) than for NT (1.43 g cm^{-3}). No position nor tillage per position interaction effect on bulk density was observed. The same can be said for porosity that was only significantly different for tillage ($p<0.0001$), been higher in IT (0.53 cm^{3}·cm^{-3}) than in NT (0.46 cm^{3} cm^{-3}).

Tillage had a significant effect on sorptivity at saturation (S_s), with higher values in IT than NT (0.31 vs. 0.22 mm s$^{-0.5}$, Table 16). Hydraulic conductivity at saturation (Ks), was significantly higher OnS than BelowS (0.0039 vs. 0.0028 mm s^{-1}, Table 16), but only in NT (0.0048 mm s^{-1}, Figure 16a) and WR (0.0049 mm s^{-1}, Figure 16b).

Table 15. ANOVA p-values and mean comparisons for tillage (intensive tillage, IT, and No-tillage, NT) and position (between crop rows, B-rows, and within crop rows, W-rows) effects on bulk density and total porosity.

ANOVA (Sources of variation)	Bulk density (p-values)	Porosity (p-values)
Tillage	0.0005	0.0001
Position	NS[1]	NS
Tillage x Position	NS	NS
Mean comparisons	Bulk density ($g \cdot cm^{-3}$)	Porosity ($cm^3 \cdot cm^{-3}$)
Tillage		
IT	1.26 b	0.53 b
NT	1.43 a	0.46 a
Position		
B-rows	1.35	0.49
W-rows	1.33	0.50

[1] NS, Non-significant ($p<0.05$).
[2] Different letters indicate significant differences among means at $p<0.05$.
[3] Assuming a soil particle density of 2.65 $g \cdot cm^{-3}$.

Table 16. ANOVA p-values and mean comparisons for tillage (intensive tillage, IT, and No-tillage, NT), position (between crop rows, B-rows, and within crop rows, W-rows), and depth (on the soil surface, OnS, and 2 cm below the surface, BelowS) effects on sorptivity and hydraulic conductivity at saturation (S_s, K_s) applying the BEST-steady method to ponded infiltration runs (beerkan method), for pores <1 mm diameter applying BEST-steady to tension infiltration (-3 cm H_2O) runs ($S_{<1}$ $K_{<1}$), and for pores over 1 mm diameter ($S_{>1}$, $K_{>1}$), obtained by subtraction.

ANOVA (Sources of variation)	S_s (p-values)	K_s (p-values)	$S_{<1}$ (p-values)	$K_{<1}$ (p-values)	$S_{>1}$ (p-values)	$K_{>1}$ (p-values)
Tillage (T)	0.04	NS	0.003	0.0008	0.02	NS
Position (Ps)	NS[1]	NS	NS	NS	NS	NS
T x Ps	NS	NS	NS	NS	NS	NS
Depht (D)	NS	0.03	NS	NS	NS	0.02
T x D	NS	0.03	NS	NS	NS	0.02
Ps x D	NS	0.05	NS	0.002	NS	0.02
T x Ps x D	NS	NS	NS	0.004	NS	NS
Mean comparisons	S_s ($mm\ s^{-0.5}$)	K_s ($mm\ s^{-1}$)	$S_{<1}$ ($mm\ s^{-0.5}$)	$K_{<1}$ ($mm\ s^{-1}$)	$S_{>1}$ ($mm\ s^{-0.5}$)	$K_{>1}$ ($mm\ s^{-1}$)
Tillage						
IT	0.31 a[2]	0.0030	0.062 a	0.0014 a	0.26 a	0.0019
NT	0.22 b	0.0037	0.049 b	0.0011 b	0.16 b	0.0023
Position						
B-rows	0.25	0.0029	0.053	0.0013	0.20	0.0017
W-rows	0.28	0.0038	0.058	0.0013	0.22	0.0025
Depth						
OnS	0.28	0.0039 a	0.054	0.0012	0.22	0.0027 a
BelowS	0.25	0.0028 b	0.056	0.0013	0.20	0.0015 b

[1] NS, Non-significant ($p<0.05$).
[2] Different letters indicate significant differences among means at $p<0.05$.

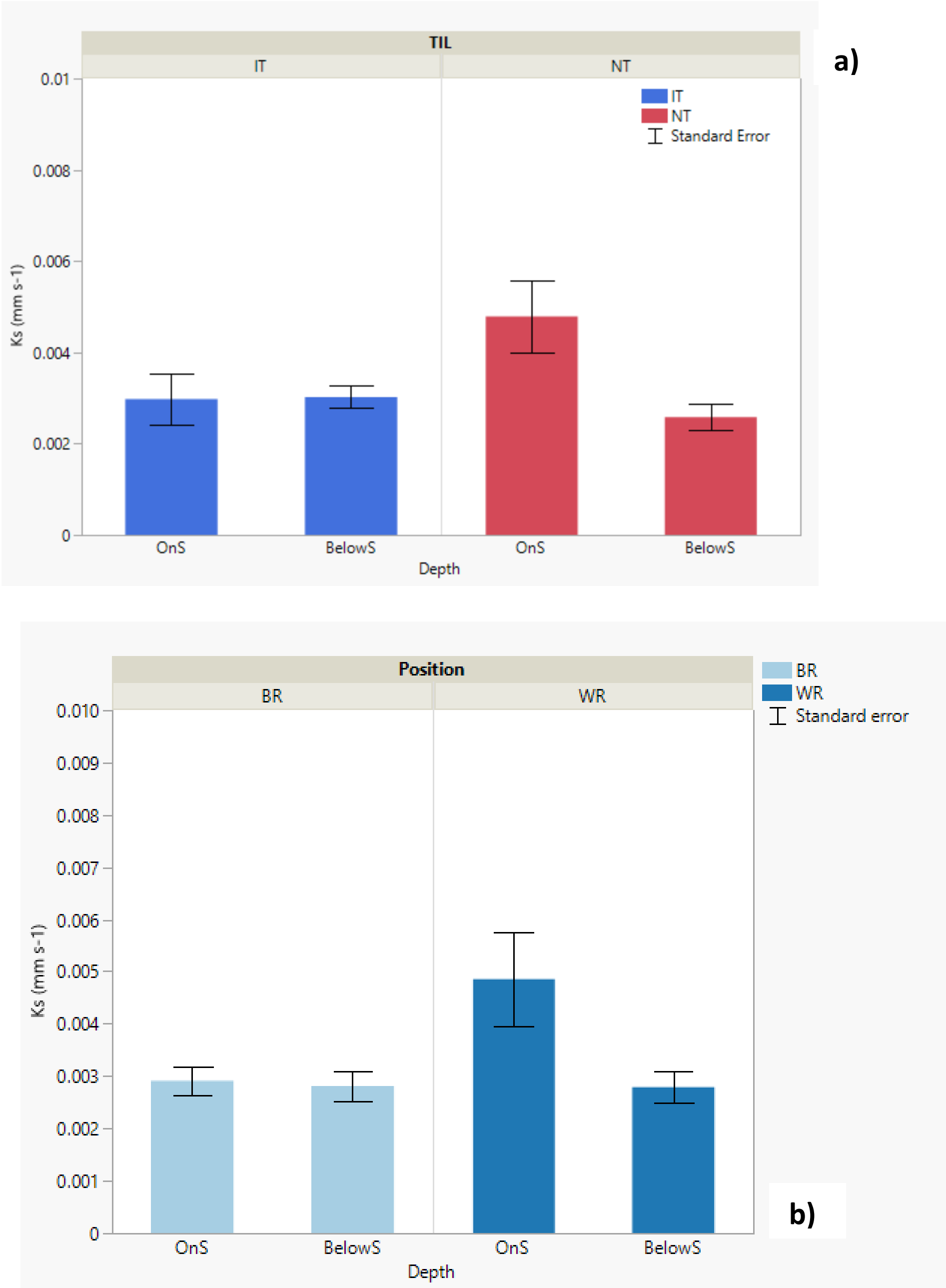


Figure 16. Saturated hydraulic conductivity, K_s (mm s^{-1}) on the soil surface (OnS) and below the surface (BelowS) for (a) different tillage systems (Intensive tillage, IT, and No-tillage, NT), and (b) different positions (between crop rows, BR, and within crop rows, WR).

Once the macroporous flux was supressed by measuring at -3 cm H_2O tension (flux in pores <1mm in diameter), tillage still had a significant effect on sorptivity ($S_{<1}$, Table 16), that was higher in IT than in NT (0.062 vs. 0.049 mm $s^{-0.5}$), nearly an order of magnitude lower than at saturation. Tillage had also a significant effect on unsaturated hydraulic conductivity ($K_{<1}$, Table 16), that was significantly higher in IT than in NT in the soil surface between crop rows and below the soil surface within the crop rows (Figure 17).

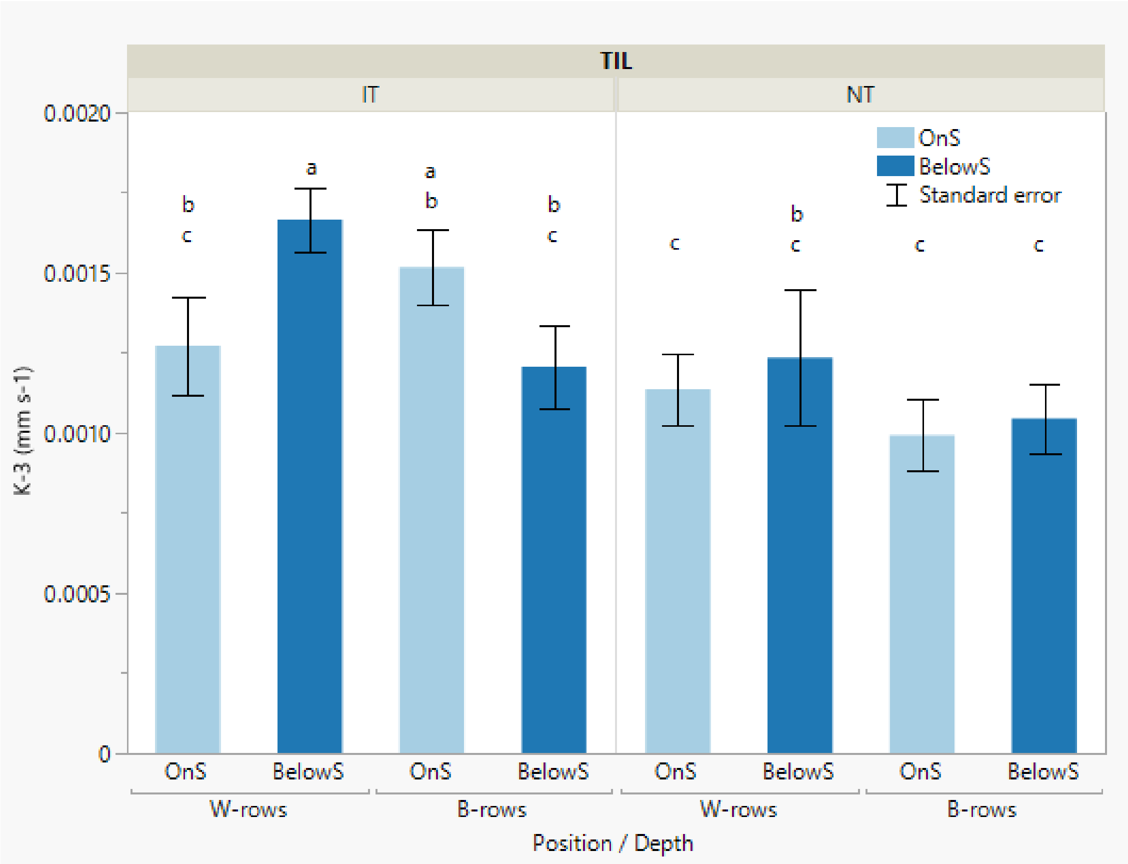


Figure 17. Unsaturated hydraulic conductivity at -3 cm H_2O tension, K-3 (mm s^{-1}) on the soil surface (OnS) and below the surface (BelowS) for different tillage systems (Intensive tillage, IT, and No-tillage, NT), and positions (between crop rows, BR, and within crop rows, WR). Means with the same letter are not significantly different ($p<0.05$).

Sorptivity and hydraulic conductivity in pores over 1 mm diameter were obtained by subtraction: S>1 = Ss-S<1, K>1 = Ks-K<1. Results were quite similar to the ones obtained in saturated condition, confirming the fact that macropores dominate water fluxes. Tillage affected macropore sorptivity (S>1) because was significantly higher in IT (Table 16). On the other hand, depth, tillage and position affected macropore hydraulic conductivity, that was significantly higher on the soil surface in NT and within the crop rows (Figure 18).

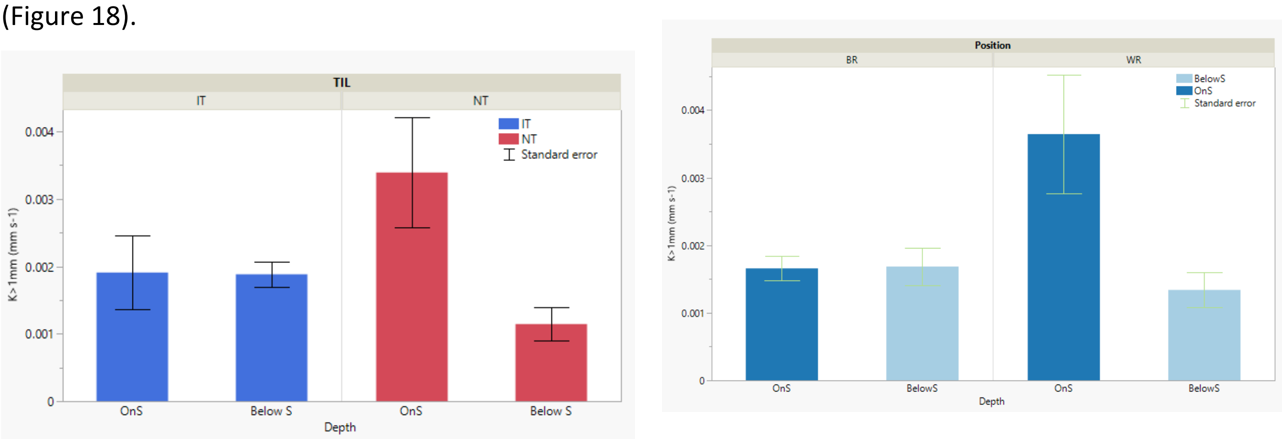


Figure 18. Hydraulic conductivity of pores over 1 mm diameter, K>1 (mm s^{-1}) on the soil surface (OnS) and below the surface (BelowS) for (a) different tillage systems (Intensive tillage, IT, and No-tillage, NT), and (b) different positions (between crop rows, BR, and within crop rows, WR).

From these results we can conclude that sorptivity is greater in IT, independently of the position and the depth. However, hydraulic conductivity is greater on the surface, especially withing the crop rows and in NT. Then, when conducting infiltration runs, the position and the depth of the measurements must be considered as they can affect greatly the results.

4.2.2. Tillage and position effect on near saturated hydraulic properties in undisturbed soil core.

On July-august 2021, undisturbed soil cores were taken from 2-8 cm soil depth to determine the near saturated water retention and hydraulic conductivity curves. The bulk density was also measured. The complementary unit gradient and evaporation methos were used to obtain the experimental data points of both water characteristics, that were adjusted with RETC (van Genuchten et al., 1991) to the van Genuchten-Mualem models. On the following we analyse the results obtained from these adjusted models.

The position with respect to the crop row did not have any effect on bulk density or the van Genuchten-Mualem parameters. However, bulk density was significantly lower in IT (1.24 g cm^{-3}) than in NT (1.49 g cm^{-3}, Table 17). Tillage had also an effect on alpha and Ks parameters, that were higher in IT than in NT (0.029 vs 0.017, and 4.0 vs 1.8 cm d^{-1} respectively). Although there were no differences between tillage systems in the water retention characteristic (Figure 19a), IT showed significantly higher K for water potentials over -10 cm H_2O, corresponding to pores over 300 μm diameter.

Table 17. ANOVA p-values and mean comparisons for tillage (intensive tillage, IT, and No-tillage, NT) and position (between crop rows, B-rows, and within crop rows, W-rows) effects on bulk density and van Genuchten-Mualem functions parameters (van Genuchten et al., 1991).

ANOVA (Sources of variation)	Bulk density (p-values)	θr (p-values)	θs (p-values)	α (p-values)	n (p-values)	Ks (p-values)
Tillage (T)	0.0002	NS	NS	0.05	NS	0.02
Position (Pos)	NS[1]	NS	NS	NS	NS	NS
T x Pos	NS	NS	NS	NS	NS	NS
Mean comparisons	Bulk density ($g \cdot cm^{-3}$)	θr ($cm^3 \cdot cm^{-3}$)	θs ($cm^3 \cdot cm^{-3}$)	α (cm^{-1})	n (-)	Ks ($cm \cdot d^{-1}$)
Tillage						
IT	1.24 b[2]	0.21	0.44	0.029 a	1.64	4.0 a
NT	1.49 a	0.21	0.42	0.017 b	1.43	1.8 b
Position						
B-rows	1.39	0.21	0.43	0.025	1.48	3.0
W-rows	1.34	0.21	0.43	0.021	1.59	2.9

[1] NS, Non-significant (p<0.05).
[2] Different letters indicate significant differences among means at p<0.05.
[3] Assuming a soil particle density of 2.65 $g \cdot cm^{-3}$.

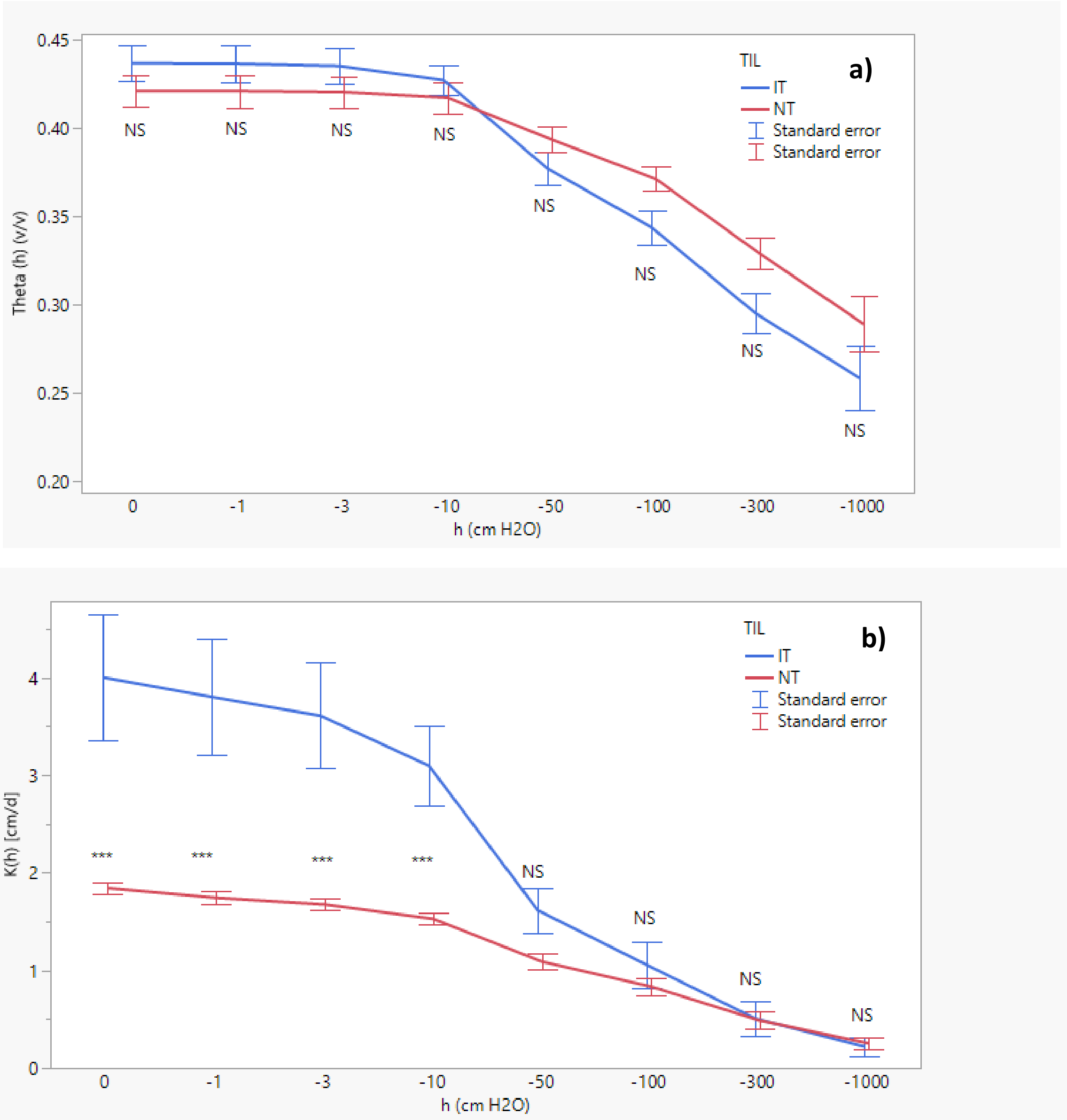


Figure 19. (a) Water retention (Theta, θ), and (b) hydraulic conductivity (K, cm d^{-1}) as a function of soil water potential (h, cm H_2O) for two different tillage systems (Intensive tillage, IT, and No-tillage, NT). NS, non-significant. ***, significant at p<0.001.

Following Ehlers et al. (1995), we obtained the volume (θ_{pc}) and the hydraulic conductivity (K_{pc}) of several pore classes. More than 25% of the soil was occupied by pores below 3 μm, and around 20% for bigger (Figure 20a). In general, no differences on θ_{pc} were found between tillage systems except for the 1000-300 and 300-60 μm pore classes in which IT had significantly higher θ_{pc} (0.008 vs. 0.003, and 0.05 vs. 0.025, respectively). Further, K_{pc} was significantly higher in IT than NT in the pores between 1000 and 10 μm, which explains the higher K_s found in IT.

To further characterize the porous system, we computed the specific hydraulic conductivity (K_{sp}), as K_s/θ_{pc}, and a continuity index for water flow, C_w, for every porous class (Ehlers et al. 1995). When decreasing the porous size, K_{sp} decreased dramatically (Figure 20c). Although K_{sp} tended to be higher in IT, there were no significant differences with NT. Contrarily, C_w increased exponentially while decreasing the pore size up to 3 μm (Figure 20d). Below 3 μm, C_w was lower although still high.

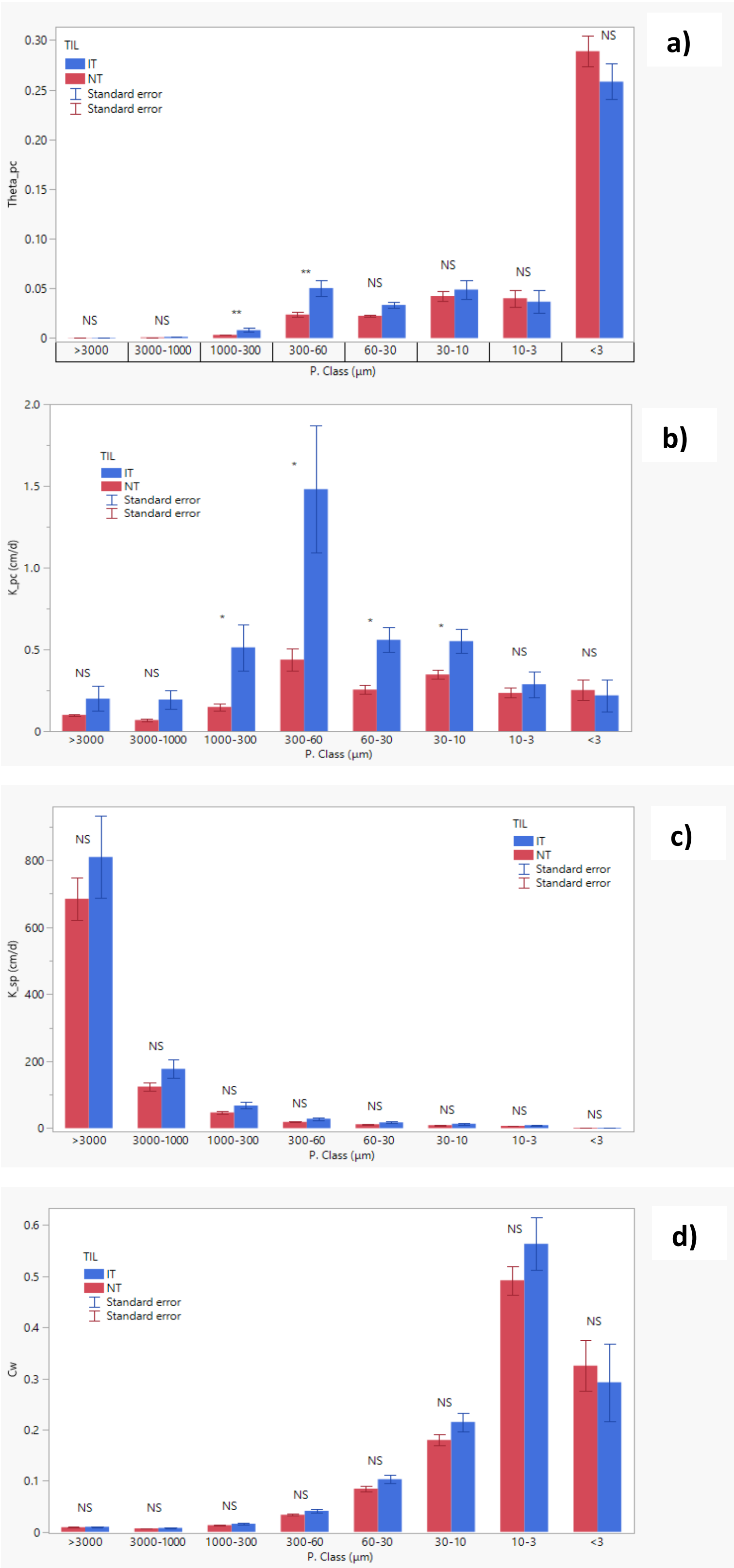


Figure 20. (a) Pore class volume (θ_{pc}), (b) hydraulic conductivity (K_{pc}), (c) specific hydraulic conductivity (K_{sp}), and (d) conductivity index for water flow (C_w) for two different tillage systems (Intensive tillage, IT, and No-tillage, NT). NS, non-significant. *, significant differences at $p<0.05$. **, significant differences at $p<0.01$.

We can conclude that the big differences on hydraulic conductivity found among tillage systems over -10 cm H_2O soil water potential cannot be attributed to a higher specific hydraulic conductivity or continuity of the porous system in IT but to a greater porosity between 1000 and 10 μm which resulted in a much higher hydraulic conductivity on this pore classes compared to NT. The lower hydraulic conductivity of NT and the lack of effect of position agree with the results found in the previous section were higher hydraulic conductivity in NT and between the crop rows was found only at the soil surface.

5. General conclusions

In accordance with the sampling dates considered in the Foggia investigation, no-tilled soil was, in general, significantly more humid and compact than tilled soil in the spring-summer period. Also, a greater induced porosity by tillage have induced a more quickly surface soil drying. Relatively similar results were detected in terms of saturated soil hydraulic conductivity because, although K_s was generally higher (i.e., more conductive) in tilled (MT) than undisturbed (NT) soil, only in few of considered cases such differences were significant from a statistical point of view. Therefore, the results collected in the Foggia activity allowed to conclude that long-term soil management impacted especially on the pore system characteristics, i.e., creating smaller and better interconnected pores under no-tillage, probably diversifying the ways in which water is transmitted in saturated soil. The study of the soil properties near water saturation highlighted an increase in K values when moving from unsaturated to saturated soil conditions, due to the activation of the macropore system. However, the preferential flow within the larger pores was comparable between the two soil management systems.

The seasonal effect of soil management on main physical (ρ_b) and hydraulic (K_s) soil properties showed consistent results because, starting from similar soil moisture conditions, no-tilled soil was significantly more dense and less conductive, as compared to tilled one. This confirmation was also in agreement with the findings obtained, in the past, in the same plots of Foggia site, and applying different methods and measures that have span almost the entire cropping season. Consequently, the collected results provided further evidence that the two soil management systems, investigated in a long-term experiment in Foggia, may not show substantial differences in their physical and hydraulic behaviour, as summarized by hydraulic functions.

Finally, when an environmental sustainability perspective was considered, therefore investigating aspects regarding the physical quality of soil management systems, the comparison between measurements and reference values of literature has emphasized that ρ_b and K_s fall within the suggested optimal thresholds to avoid risks to crops and promoting rapid infiltration and redistribution of crop-available water, reduced surface runoff and soil erosion, and rapid drainage of excess soil water. These results complement the conclusions drawn within Task 6.2 (proxy to study the impact of CA on soil erosion). The in-depth statistical analyses, in fact, were applied to select representative soil variables from a chemical-physical-biological point of view (>20), allowed the selection of a relatively smaller number (7) of variables (TOC, TEC, P-Olsen, WEN, RFC, P_{MAC}, AC). They were able to provide a clear discrimination between compared treatments, suggesting a prevalence of the undisturbed system for the accumulation of organic matter into the soil, and a prevalence of the tilled one for aspects linked to soil fertility or to adequate porosity and air capacity of the soil.

Literature references suggest that the success of the conversion towards a conservative approach basically depends on the water availability for the crop, and comparable wheat yields may be obtained under dry climates. Results of crop yields recorded for the mediterranean environment of Foggia showed low differences between NT and MT both in yields and protein contents from 2021 to 2023 (i.e., mean of crop yield of 4.8 and 5.1 t ha^{-1} under NT and MT), but similar results were obtained when considering the mean values for a time of fifteen consecutive years (for the 2003-2017 period, it was 4.3 t ha^{-1} for both soil management). Therefore, in the specific conditions investigated, the two systems returned comparable results.

Results of Senes site highlighted a prevailing effect of soil management on bulk density since, regardless of the methodological approach adopted, ρ_b was significantly lower in tilled than in undisturbed soil.

Similarly to the Italian site, the experimental evidence from Senes also confirmed a clear increase in hydraulic conductivity from unsaturated to saturated soil conditions (i.e., discrepancies of approximately one order of magnitude), although such increment was lower compared to that detected in Foggia (almost two orders of magnitude). Conversely, higher permeability values were overall recorded in tilled soil, suggesting for such (spanish) site, that macropores network was more effective in transmitting water and air. Based on the in-depth analysis to discriminate the conductive characteristics as a function of the various diameter classes of the pores and, therefore, to account for the connectivity of the soil pore network, it was concluded that the higher hydraulic conductivity values under tilled soil, and close to water saturation, should be ascribed to greater porosity rather than better pores connectivity.

The two soils investigated in Spain and Italy were both fine textured (silty clay loam and clay, respectively), but differed in the type of prevalent fine particles, as the silty fraction predominated in Spanish (30 and 63% of clay and silt), while clay fraction predominated in Italian one (43 and 28% of clay and silt). Consequently, the relatively different soil behaviour is not surprising. Moreover, since the Spanish site was characterized by a more recent conversion to conservation agriculture (about ten years), it is plausible to conjecture that it may not have yet reached the maximum complexity of the pore system, to efficiently transmit water even into smaller pores.

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