Published May 3, 2019

Application of Multivariate Analysis Techniques for Selecting Soil Physical Quality Indicators: A Case Study in Long-Term Field Experiments in Apulia (Southern Italy)

Mirko Castellini*
Council for Agricultural Research and Economics–Research Center for Agriculture and Environment (CREA–AA)
Via C. Ulpiani 5
70125 Bari, Italy

Anna Maria Stellacci
Dep. of Soil, Plant and Food Sciences
Univ. of Bari "Aldo Moro"
Via G. Amendola 165/a
70126 Bari, Italy

Emanuele Barca
Water Research Institute (IRSA)–National Research Council (CNR)
Bari, Italy

Massimo Iovino
Dep. of Agricultural Food and Forest Sciences
Univ. of Palermo
Viale delle Scienze
90128 Palermo, Italy

Long-term field experiments and multivariate analysis techniques represent research tools that may improve our knowledge on soil physical quality (SPQ) assessment. These techniques allow us to measure relatively stable soil conditions and to improve soil quality judgment, thereby reducing uncertainties. A monitoring of SPQ under long-term experiments, aimed at comparing crop residue management strategies (burning vs. incorporation of straw, FE1) and soil management (minimum tillage vs. no tillage, FE2), was established during the crop growing season of durum wheat. The relationships between five SPQ indicators (bulk density [BD], macroporosity [P_{MAC}], air capacity [AC], plant available water capacity [PAWC], and relative field capacity [RFC]) were evaluated, and two techniques of multivariate analysis (principal component analysis and stepwise discriminant analysis) were applied to select key indicators for SPQ assessment. According to the used indicators, an SPQ from optimal to intermediate (i.e., not definitely poor) was detected in 65% of the observations in FE1 and in 54% in FE2. The main results showed a significant negative relationship between RFC and AC, and multivariate analysis identified RFC as a key SPQ indicator, mainly in FE2. Plant available water capacity and BD showed the highest discriminating capability in the FE1 dataset. The highest scores of RFC assessment were highlighted for burning and minimum tillage treatments (+1 and +2). An optimal AC range, derived from optimal RFC limits, was obtained and was suggested to better assess the AC of agricultural soils ($0.10 \leq AC \leq 0.26\ cm^3\ cm^{-3}$).

Abbreviations: AC, air capacity; B, burning; BD, bulk density; I, incorporation; MT, minimum tillage; NT, no tillage; PAWC, plant available water capacity; PCA, principal component analysis; P_{MAC}, macroporosity; RFC, relative field capacity; SDA, stepwise discriminant analysis; SPQ, soil physical quality; ST, sampling time.

Core Ideas

- **Soil physical quality (SPQ) on two long-term experiments was evaluated.**
- **Relationships among five SPQ indicators (BD, P_{MAC}, AC, PAWC and RFC) were evaluated.**
- **Two multivariate analysis techniques (PCA, SDA) were applied to select key indicators.**
- **PCA and SDA generally identified RFC as a key soil physical indicator.**
- **An optimal AC range was suggested to assess the air capacity of agricultural soils**

Soil quality indicators are important tools that may support economic and environmental sustainability evaluations of agricultural practices because they account for changes (i.e., improvement or impoverishment) in the physical, chemical, and biological attributes of agricultural soils. Among these, soil physical quality (SPQ) indicators are linked to the soil's ability to store and transmit water and air (Reynolds et al., 2002, 2008; Iovino et al., 2016); therefore, they may be able to evaluate the impact of agricultural practices on soil water conservation.

Several examples of physical quality evaluations of agricultural soils are available in the literature (e.g., Miralles et al., 2009; Reynolds et al., 2008, 2009; Zornoza et al., 2015). In addition to these, studies have investigated marginal agricultural areas (Castellini et al., 2016; Iovino et al., 2016) or areas subjected to cattle grazing (Cournane et al., 2011; Zhou et al., 2010). However, a relatively small number of investigations has been performed under long-term field experiments (Armenise et

Soil Sci. Soc. Am. J. 83:707–720
doi:10.2136/sssaj2018.06.0223
Received 11 June 2018.
Accepted 11 Jan. 2019.
*Corresponding author (mirko.castellini@crea.gov.it).

al., 2013; Castellini et al., 2013, 2014; Karlen et al., 2013; Kiani et al., 2017; Reynolds et al., 2014a; Van Eerd et al., 2014).

Long-term field studies, performed on experimental farms, are relatively rare and thus constitute important research tools (Körschens et al., 2006; Peterson et al., 2012) to assess, for example, the SPQ, given that relatively stable conditions can be expected in these soils (Castellini et al., 2014; Reynolds et al., 2014a). Several basic soil properties (e.g., organic carbon content, bulk density, physical and hydraulic properties, and capacitive indicators) can in fact exhibit two-stage responses to change: a short-term rapid response (i.e., from 1 to 5 yr) and a long-term gradual response (approximately ≥10 yr) (Ferrara et al., 2017; Reynolds et al., 2014a). Reynolds et al. (2014a, 2014b) summarized the main scientific and practical benefits of long-term-field studies and provided examples of impacts assessment of 48 yr of cropping, fertilization, and land management on the physical quality of a clay loam soil. Continuous bluegrass sod production, for example, determined negligible soil degradation of SPQ in the surface layer given that bulk density, organic carbon, air capacity (AC), available water capacity, relative field capacity (RFC), and saturated hydraulic conductivity were similar to those of a neighboring virgin soil. This substantial equivalence between cultivated and virgin soils was attributed to similar plant types (i.e., continuous bluegrass vs. continuous native grass, respectively) and land management (i.e., no soil disturbance and reduced passage of agricultural machinery). Conversely, long-term monoculture crop production or long-term corn–oat–alfalfa–alfalfa rotation determined a significant or minimal-to-moderate degradation of SPQ, mainly due to the abundance of biopores (i.e., corn and alfalfa roots) throughout the soil profile in the latter (Reynolds et al., 2014a).

In their investigation on a loamy soil, Kiani et al. (2017) identified a suitable set of soil quality indicators (mass fractal dimension of soil aggregates, Dexter's S-index, available water capacity, soil organic carbon, and microbial biomass carbon) among contrasting land management strategies (i.e., simple vs. complex crop rotations or manure vs. balanced fertilization) at two long-term experimental fields that lasted at least 40 years. Their results showed how complex crop rotations (which include perennials crops) may improve soil quality and crop yields because both balanced fertilization and manure addition improved soil function. Results of their investigation suggested that the soil indicators used may be considered as useful tools for evaluating management options that also influence agricultural productivity (Kiani et al., 2017).

A main topic that needs further investigation is the choice regarding the type and number of indicators to use for SPQ assessment. Several indicators have been used to assess SPQ such as dry bulk density (BD), macroporosity (P_{MAC}), AC, RFC, plant available water capacity (PAWC), saturated hydraulic conductivity, structure stability index, organic carbon content, and Dexter's S-index (Reynolds et al., 2009). Based on the available literature, for each of these indicators, "references" or "optimal" values were provided so that a not entirely arbitrary SPQ evaluation may be obtained (Reynolds et al., 2009). Therefore, for a given application or comparison, the use of a large number of these indicators should provide a more robust assessment of SPQ, as compared with a small number of them. On the other hand, a large number of simultaneous indicators may sometimes provide redundant or conflicting results, making an SPQ evaluation difficult (Castellini et al., 2014; Cullotta et al., 2016). Therefore, it is necessary to apply appropriate statistical procedures to obtain a minimum set of key indicators (Armenise et al., 2013). Moreover, various researchers showed that some SPQ indicators are strongly correlated with others (i.e., AC and RFC as well as AC and P_{MAC}), suggesting that some of them might be neglected (Cullotta et al., 2016; Reynolds et al., 2014a). Furthermore, available investigations generally give an account of results (i.e., SPQ evaluation and correlations among soil indicators) of the effects of different agricultural practices corresponding to one or a few textured soils. Therefore, further investigations aimed to (i) deepen the relationships among SPQ indicators, (ii) apply and evaluate appropriate statistical procedures to obtain a minimum set of representative key indicators, and (iii) verify the results on larger data set (e.g., different soil textures, soil bulk density, and organic carbon content values) are necessary. To reach such goals, long-term field experiments, performed in the experimental farms of agriculture research centers, may be considered ideal research tools because they represent "open-air laboratories" in which relatively stable soil properties and crop yields may be obtained and where agronomic practices are performed and repeated in a rigorous way (Ventrella et al., 2016). Moreover, establishing a seasonal monitoring of soil properties that begins after preparatory tillage for seedbed creation and ends after harvesting allows us to investigate both optimal and nonoptimal soil conditions so that it is possible to evaluate the applicability of SPQ indicators.

In this research, two long-term field experiments, aimed at comparing different crop residue management strategies (i.e., burning [B] vs. incorporation [I] of straw) and soil management strategies (i.e., minimum tillage [MT] vs. no tillage [NT]) were selected and monitored throughout the crop growing season of durum wheat to evaluate the effects induced by 21 and 14 yr of repeated agronomic practices. The general objective of this investigation was to study the SPQ under long-term field experiments and to identify the indicators most able to highlight changes in soil status. In particular, (i) the relationships among five SPQ indicators (BD, P_{MAC}, AC, PAWC, and RFC) of two different data sets were analyzed, and their relative importance was evaluated; (ii) two techniques of multivariate analysis (principal component analysis [PCA] and stepwise discriminant analysis [SDA]) were applied to select key indicators of SPQ; (iii) an evaluation on the validity of selected key indicators and checks on the reliability of considered optimal ranges or critical limits of significant SPQ indicators, as suggested in the literature, was performed; and (iv) selected key indicators were used to compare the impact of alternative agricultural managements on soil water–air conservation.

MATERIALS AND METHODS

Study Area

The study was performed at the experimental farm of the Council for Agricultural Research and Economics (CREA-AA), Foggia (41°27′03″N, 15°30′06″E), in two long-term field experiments performed on a monoculture of durum wheat (Fig. 1). The first long-term experiment (FE1), begun in 1990, evaluated the effects of two residues management systems (B and I). The second experiment (FE2), started in 2002, compared the effect of MT and sod-seeding (NT) on wheat yields. Experiments FE1 and FE2 represent the first considered dataset (Apulian dataset).

The climate of the area is classified as "accentuated thermo-mediterranean" (Unesco-FAO classification), with temperatures that may fall below 0°C in winter and exceed 40°C in summer. Rainfall is unevenly distributed throughout the year and is mostly concentrated in the winter months, with a long-term annual average of 550 mm.

Monitoring of SPQ indicators was performed in the cropping seasons 2010 to 2011 and 2015 to 2016 for FE1 and FE2, respectively. Experimental design of FE1 (B vs. I) is a completely randomized block design with three replicates and unit plots of 240 m^2 size. Straw and stubble were chopped into 10- to 15-cm lengths and spread back onto the plot, and in the first week of October the residues (burned and unburned) were incorporated into the soil through surface disc-harrowing to a depth of 20 cm. Sowing was performed in the fourth week of November. Further information on plot management can be found in Castellini et al. (2014). The FE2 (MT vs. NT) experiment is a completely randomized block design with three replicates and unit plots of 500 m^2 size. For both treatments, straw was chopped into 10- to 15-cm lengths and spread back on the plot in the first week of September. Depending on the year, after 1 mo, a chemical weed control was performed. Minimum tillage consists of a two-layer soil tillage at 40 cm depth (i.e., a chisel and rotary tiller combination) performed in the first week of November. Fertilization and sowing followed after 1 or 2 d. According to USDA classification, the soil texture is clay, with 42.7 and 27.7% of clay and silt, respectively (Castellini et al., 2014), and is classified by Soil Taxonomy–USDA as fine, mesic, Typic Chromoxerert (Soil Survey Staff, 2010). General information regarding the hydrodynamic properties of the investigated soil can be found in the literature (i.e., saturated conductivity, Castellini et al. [2015]; unsaturated hydraulic conductivity, Castellini and Ventrella [2012]). Moreover, a low-susceptibility risk of soil compaction is expected because optimal soil water contents for favorable workability conditions (~0.32–0.34 $cm^3\ cm^{-3}$) were noted (Francaviglia et al., 2015). Cracks due to soil shrinkage generally occur only at very low soil water contents. Therefore, soil sampling was performed before this condition occurred.

Figure 1. (a) Geographical location of experimental farm CREA-AA. (b) View of the whole farm in June. (c) Detail of burning (B) and incorporation (I) plots on FE1 and minimum tillage (MT) and no-tillage (NT) plots on FE2.

Soil Sampling, Laboratory Measurements, and Soil Physical Quality Indicators

For each crop residue (i.e., B, I) and soil management strategy (MT, NT), soil water retention curve and soil bulk density were experimentally determined in the laboratory. In detail, five or six sampling dates were considered during the crop season (i.e., between November and June) to account for optimal and nonoptimal conditions of SPQ. For each sampling date and treatment (i.e., B, I, MT, and NT), 5 to 12 undisturbed soil cores were collected at randomly selected points into stainless steel rings with sharp edges (8 cm inner diameter; 5 cm height) to determine soil BD and water retention curve at high pressure heads ($h \geq -120$ cm). The 0- to 20-cm soil layer was used to investigate the tillage depth (i.e., MT) and the soil layer in which the root system develops. Each steel ring was vertically inserted into the soil by hammering gently on the top of the ring with a rubber hammer and progressively removing the surrounding soil up to the established depth to reduce disturbance during sampling. Soil cores were packaged with transparent film and stored at 4°C to inhibit microbial activity until their use. A disturbed soil sample was collected close to the undisturbed sample collection points to determine the water retention curve at low pressure heads ($h \leq -330$ cm).

Volumetric water retention, θ, data were determined on each undisturbed soil core by a hanging water column apparatus (Burke et al., 1986) for pressure head, h, values ranging from −5 to −120 cm and on repacked soil cores by pressure plate method (Dane and Hopmans, 2002) for h values ranging from −330 to −15,300 cm (Bagarello et al., 2005). The hanging water column apparatus consists of a sintered porous plate (borosilicate glass Buchner funnels) having an air entry value of −200 cm (filter porosity 4) connected to a graduated burette, which may be moved in height to establish a given h value and which allowed measurement of the drained water from the core. The cores were previously saturated on the porous plate by wetting from below and then equilibrated at established decreasing h values. A drainage sequence of seven h values was then imposed (i.e., −5, −10, −20, −40, −70, −100, and −120 cm). The volumetric water content corresponding to the last equilibrium h value was determined by oven-drying the core. The volume of water drained into the burette was recorded and used to calculate the volumetric water content corresponding to the equilibrium pressure heads. At the end of the experiment, the undisturbed soil cores were used to determine BD. A standard procedure was used to obtain θ values at low pressure heads (i.e., −330, −1030, −3060, and −15,300 cm) on repacked soil samples by pressure plate method (Dane and Hopmans, 2002).

The soil water retention function (i.e., the relationship between θ and h) was obtained fitting the experimental data with the van Genuchten (1980) model, as is common in parameterization procedures (Castellini et al., 2018). For this purpose, the Solver routine of Microsoft Excel software was used (Microsoft, Redmond, WA).

Five soil indicators were selected in this investigation to assess the SPQ: soil BD, P_{MAC}, AC, PAWC, and RFC. The four capacity-based indicators (P_{MAC}, AC, PAWC, and RFC) were obtained from the water retention curve. Relationships for calculating the considered SPQ indicators as well as the optimal ranges or critical limits considered in this investigation are summarized in Table 1.

To check the correlation among selected indicators, an additional set of data (Sicilian dataset) was considered to account for different soil texture and land uses. In particular, the same experimental procedure described before was applied to determine the water retention curves of 138 soil samples collected in the area of Menfi (M; sample size, n = 84; main crops: vineyard and olive grove) and Santa Ninfa (S; n = 54; main crops: pinewood, eucalyptus tree plantation, gariga, and fallow). The considered SPQ indicators were calculated to verify the correlations obtained from Apulian sites. Detailed information about the Sicilian dataset can be found in Castellini and Iovino (2019) and in Supplemental Figure S1 for soil textures.

Data Analysis

Preliminary Statistical Analysis

Capacitive indicators of SPQ are generally assumed to be normally distributed (Castellini et al., 2016; Reynolds et al., 2009). However, descriptive statistics were computed for each of the datasets considered in this investigation (respectively, B-I and MT-NT; S-M) to summarize the main features of data distribution for the soil variables under study (BD, P_{MAC}, AC, PAWC, and RFC). In addition, the variables were tested for heteroscedasticity by sampling time and by management treatment with Bartlett's homogeneity of variance test.

Correlation and Multivariate Analysis

Relationships among soil variables (BD, P_{MAC}, AC, PAWC, and RFC) were investigated using bivariate (correlation) and multivariate (PCA and SDA) analysis (SAS Institute Inc., 2012). In particular, to deepen the relationships between soil indicators, considering different soil management strategies (i.e., B and I, MT and NT) and soil textures (i.e., S and M), correlation and PCA were performed on the whole datasets (B + I and MT + NT; S + M) and on each set of data separately (i.e., B, I, MT, NT, S, M). As a first step, a linear correlation matrix was computed, with the aim of individuating redundant or similar information as well dissimilar or unique information. Principal component analysis was then performed on the correlation matrix of the soil indicators to obtain few new components that explain most of the variation of the initial data. The principal components (PCs) that explained cumulatively >80% of the total variance were retained. Variable loadings were examined to identify the variables that most contribute to each selected PC and to investigate their relationships. Stepwise discriminant analysis was finally performed to determine the variables enabling maximum discrimination among the plant residues and soil management treatments compared. Wilks' lambda statistic (Schuenemeyer and Drew, 2011) was used as a multivariate measure of separability (Thenkabail et al., 2004). The use of SDA requires that a set of assumptions should be checked, including normality of data distributions, homogeneity of variances (homoscedasticity), and not complete redundancy of considered variables (Lachenbruch, 1975). However, a moderate departure from such assumptions

Table 1. Selected indicators of soil physical quality and corresponding optimal ranges or critical limits according to Reynolds et al. (2009).

Soil physical quality indicator†	Abbreviation	Reference values
Soil bulk density, g cm^{-3}	BD	$0.9 \le BD \le 1.2$ optimal; $0.85 \le BD < 0.9$ and $1.2 < BD \le 1.25$ near optimal; $0.85 < BD$ and $BD > 1.25$ critical limits
Macroporosity, $cm^3\ cm^{-3}$ $P_{MAC}=\theta_s-\theta_m$	P_{MAC}	$P_{MAC} \ge 0.07$ optimal; $0.04 \le P_{MAC} < 0.07$ intermediate; $P_{MAC} < 0.04$ poor
Air capacity, $cm^3\ cm^{-3}$ $AC=\theta_s-\theta_{FC}$	AC	$AC > 0.14$ optimal; $0.10 \le AC \le 0.14$ intermediate; $AC < 0.09$ poor
Plant available water capacity, $cm^3\ cm^{-3}$ $PAWC=\theta_{FC}-\theta_{PWP}$	PAWC	$PAWC \ge 0.20$ ideal; $0.15 \le PAWC < 0.20$ good; $0.10 \le PAWC < 0.15$ limited; $PAWC < 0.10$ poor
Relative field capacity, dimensionless $RFC=\frac{\theta_{FC}}{\theta_s}=\left[1-\left(\frac{AC}{\theta_s}\right)\right]=\left(\frac{PAWC+\theta_{PWP}}{\theta_s}\right)$	RFC	$0.6 \le RFC \le 0.7$ optimal; $RFC < 0.6$ water limited soil; $RFC > 0.7$ aeration limited soil

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

does not affect the analysis of outcomes, as shown by a large literature review concerning SDA application (Lachenbruch, 1975; Uddin, 2013; Uddin et al., 2013).

Principal component analysis and SDA were performed on the set of the five soil indicators (i.e., BD, P_{MAC}, AC, PAWC, and RFC). Because RFC and AC are calculated both from the same variables (i.e., θ_s and θ_{FC}), we also investigated the sets of four indicators excluding alternatively RFC and AC. The aim of this further investigation was to highlight the discriminant capability of each of the two variables taken individually and in association with the remaining variables.

Principal component analysis was performed through FACTOR procedure of SAS/STAT (SAS Institute Inc., 2012). Stepwise discriminant analysis was performed with STEPDISC procedure of SAS/STAT using the STEPWISE algorithm (SAS Institute Inc., 2012). Significance level to entry and to stay was set at 0.05.

RESULTS

Soil Water Retention Curves

Fitted soil water retention curves for Apulian soils (B, I, MT, NT) are depicted in Fig. 2, and the corresponding parameters of the van Genuchten model are reported in Supplemental Tables S1 and S2. Relatively higher saturated soil water contents were observed for B than for I (by a mean factor of 1.2) in the first sampling time (Fig. 2a). These differences were higher (by a

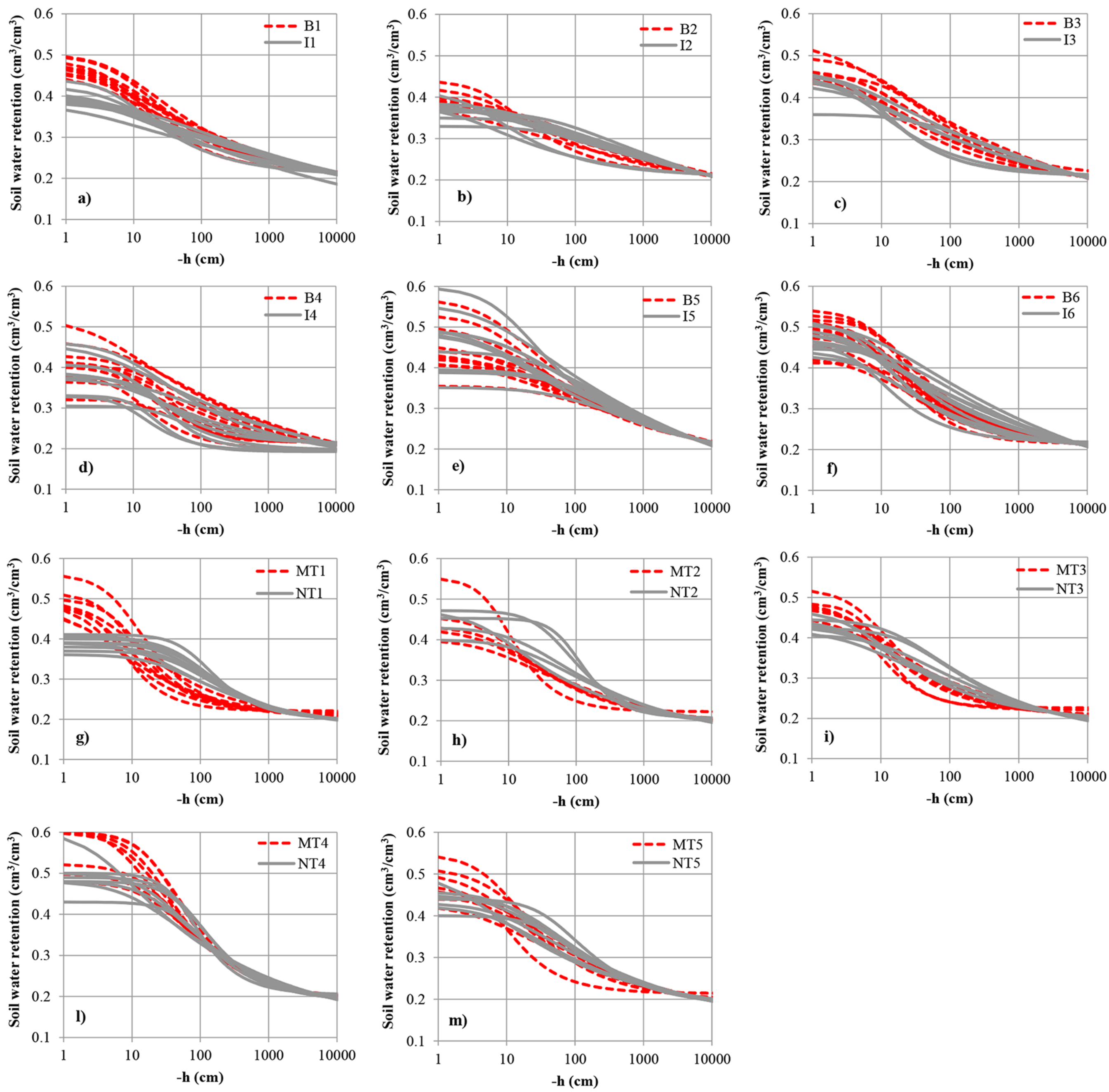

Figure 2. Soil water retention of burning (B) vs. incorporation (I) of crop residues carried out in FE1 (scatterplots from a to f) during each considered sampling time (from 1 to 6) and minimum tillage (MT) vs. no-tillage (NT) carried out in FE2 (scatterplots from g to m) during each considered sampling time (from 1 to 5).

Table 2. Number of samples, mean, and associated SD computed on the variables under study for Apulian (burning, incorporation, minimum tillage, and no tillage) and Sicilian (Menfi and Santa Ninfa) datasets.

Variable†	*n*	Mean	SD	*n*	Mean	SD	*n*	Mean	SD
		Burning			Minimum tillage			Menfi	
BD, g cm^{-3}	62	0.9463	0.0687	38	0.7629	0.0975	84	1.2629	0.1433
P_{MAC}, $cm^3\ cm^{-3}$	62	0.0537	0.0198	38	0.0827	0.0368	84	0.0310	0.0297
AC, $cm^3\ cm^{-3}$	62	0.1483	0.0427	38	0.2106	0.0495	84	0.1269	0.0577
PAWC, $cm^3\ cm^{-3}$	62	0.0954	0.0281	38	0.0882	0.0355	84	0.1681	0.0445
RFC	62	0.6765	0.0677	38	0.5808	0.0736	84	0.7255	0.1190
		Incorporation			No-tillage			Santa Ninfa	
BD, g cm^{-3}	61	0.9413	0.1261	40	0.8878	0.0717	54	1.1345	0.0885
P_{MAC}, $cm^3\ cm^{-3}$	61	0.0522	0.0286	40	0.0285	0.0322	54	0.0401	0.0329
AC, $cm^3\ cm^{-3}$	61	0.1408	0.0573	40	0.1171	0.0452	54	0.1520	0.0683
PAWC, $cm^3\ cm^{-3}$	61	0.0929	0.0423	40	0.1205	0.0238	54	0.1945	0.0351
RFC	61	0.6882	0.1051	40	0.7379	0.0750	54	0.7457	0.0949

† AC, air capacity; BD, soil bulk density; PAWC, plant available water capacity; P_{MAC}, macroporosity; RFC, relative field capacity.

factor of 1.3) in the same sampling time of FE2 between MT and NT (Fig. 2g). However, visual (Fig. 2) and analytical inspections suggest that the observed differences between treatments decrease during the growing season of wheat (Supplemental Tables S1 and S2). Therefore, similar behavior is expected for some of the SPQ indicators considered.

Preliminary Statistical Analysis

Descriptive statistics for the soil variables under study and related to the comparison B-I (FE1) and MT-NT (FE2) of Apulian dataset are reported in Table 2 and Supplemental Table S3. Mean values of considered soil indicators were very similar between B and I; therefore, relatively small differences in SPQ indicators are expected among sampling dates. On the contrary, higher discrepancies were detected between MT and NT, which differed by a factor of 1.1 to 2.9 (BD and P_{MAC}, respectively). This can result in greater differences between soil indicators and in a different impact of soil management on soil water (or air) capacity. Kolmogorov-Smirnov test results were significant only for RFC in B-I (FE1) and for PAWC and RFC in MT-NT (FE2) (Supplemental Table S3). However, coefficients of skewness and kurtosis for all variables were close to zero, indicating no substantial departure from normal distribution; therefore, data were analyzed in the original scale.

Results of Bartlett's homogeneity of variance test indicated that for B-I (FE1), variances were homogeneous over sampling times for BD, P_{MAC}, and PAWC; heteroscedasticity was instead observed for the other variables (AC and RFC) and for all the variables when tested over treatments. However, when variances were tested within each sampling time, homoscedasticity was observed in the larger part of the cases. Regarding the MT-NT (FE2) dataset, variances were homogeneous over sampling times and soil management, except for PAWC.

Table 2 summarizes the statistics related to M and S (n = 138). Due to the higher heterogeneity of this dataset (Castellini and Iovino, 2019), relatively higher coefficients of variation were observed for Sicilian soils. However, the maximum value of coefficient of variation, which was always observed for P_{MAC}, was never higher than 75% (i.e., P_{MAC} ranged from 0.00009 to 0.1745 $cm^3\ cm^{-3}$); therefore, not dissimilar levels of variability may be associated to Apulian and Sicilian datasets.

Soil Physical Quality Indicators

Results of SPQ evaluations are reported in Fig. 3. Regarding the five SPQ indicators measured in the six sampling times of the B and I plots, the results in Fig. 3 suggest a general satisfactory SPQ evaluation because optimal, near-optimal, or intermediate values (in other words, not definitely poor values) were detected in 65% (39/60) of cases. In particular, for B plots, BD was always optimal or near optimal (i.e., within the range of 0.86–1.01 g cm^{-3}), P_{MAC} and AC were intermediate or optimal (0.04–0.07 and 0.11–0.19 $cm^3\ cm^{-3}$, respectively), PAWC was always poor or limited (0.07–0.13 $cm^3\ cm^{-3}$), and RFC showed both optimal (0.61–0.68) or aeration-limited (0.73–0.74) conditions, depending on the sampling time (ST). Relatively similar results were generally detected for I plots because BD was optimal ($0.91 \leq$ BD ≤ 1.08 g cm^{-3}), with the exception of ST1 (November), when poor conditions were detected (BD = 0.78 g cm^{-3}). The value of P_{MAC} ranged from optimal (0.07–0.08 $cm^3\ cm^{-3}$) to poor (0.03 $cm^3\ cm^{-3}$), as did values for AC (0.08–0.20 $cm^3\ cm^{-3}$); PAWC was always poor or limited (0.06–0.15 $cm^3\ cm^{-3}$), whereas RFC showed optimal (0.64–0.69), aeration-limited (0.76–0.80), or water-limited (0.58) conditions.

Soil management treatments (MT or NT) showed on average a lower soil quality because optimal, intermediate, or good values were reached in 54% (27/50) of considered cases (Fig. 3). Bulk density under MT was generally lower than suggested critical limits (BD $\leq$0.80 g cm^{-3}) but was near optimal (BD = 0.87 g cm^{-3}) in ST5 (end of June); therefore, P_{MAC} and AC were almost always optimal ($0.04 \leq P_{MAC} \leq 0.12$ $cm^3\ cm^{-3}$; $0.18 \leq$ AC ≤ 0.24 $cm^3\ cm^{-3}$), and plant available water was always lower than the critical limit (PAWC <0.14 $cm^3\ cm^{-3}$), suggesting poor-limited values for crop growing. In agreement with the results of each ST, RFC showed optimal ($0.61 \leq$ RFC ≤ 0.62) or water-limited (RFC <0.55) values. Optimal BD values were generally observed under NT ($0.86 \leq$ BD $\leq$ 0.92 g cm^{-3}), except for ST2, where critical limits were detected (BD = 0.82 g cm^{-3}), together with poor or intermediate values

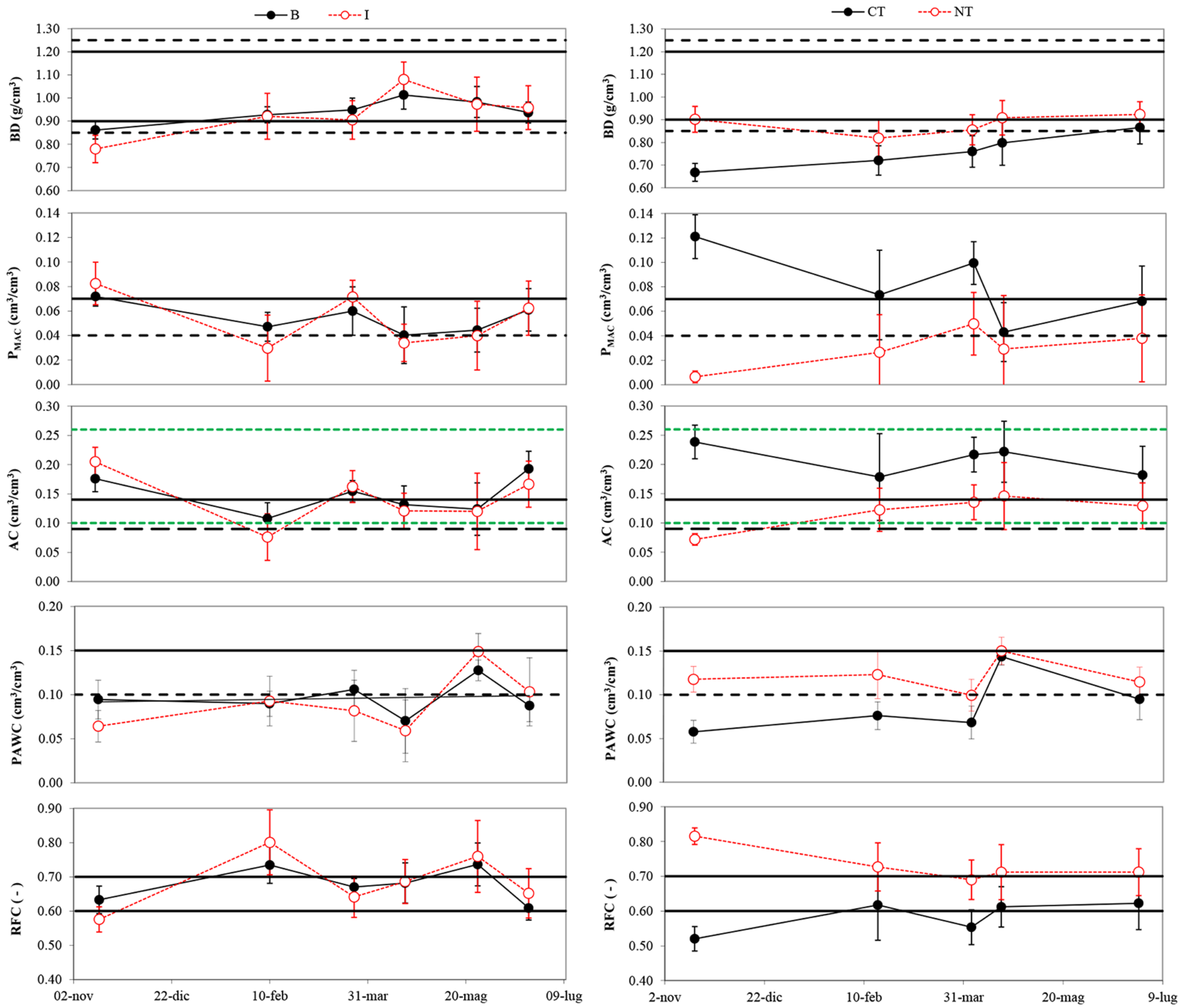

Figure 3. Seasonal evolution of soil physical quality indicators for burning (B) and incorporation (I) of crop residues for FE1 and minimum tillage (MT) and no-tillage for (NT) for FE2. Horizontal bold black lines demark the considered optimal intervals, dashed black linesindicate the critical limits (Table 1), and dashed green lines indicate the proposed optimal air capacity (AC) interval ($0.10 \leq AC \leq 0.26$ cm^3 cm^{-3}). Bars represent SD.

for P_{MAC} (0.01–0.05 cm^3 cm^{-3}), or from poor to optimal values for AC (0.07–0.15 cm^3 cm^{-3}). Compared with MT, slightly higher PAWC values were detected under NT, with limited or good values ($0.10 < PAWC < 0.15$ cm^3 cm^{-3}), whereas RFC was optimal only in ST3 because, in general, results suggested aeration-limited soil conditions ($0.71 \leq RFC \leq 0.82$).

On the basis of the reported results, the set of five indicators used in this investigation allowed an easy assessment of SPQ only for the B vs. I comparison because burning highlighted the higher relative percentage of optimal or intermediate (in other words, not definitely poor) values of SPQ. This judgment, obtained on the basis of all available experimental information, is shown in Fig. 4. On the contrary, although MT showed the highest SPQ percentages (i.e., 100% for P_{MAC} and AC), NT could be considered the best choice because it provided (i) the only positive rating of PAWC, (ii) higher scores for BD, and (iii) relatively satisfactory results in terms of AC. Therefore, considering that the set of five indicators can lead to questionable conclusions at

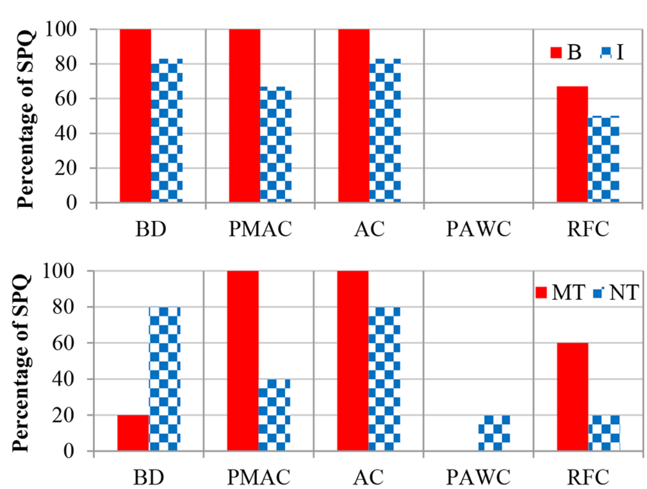

Figure 4. Relative percentage of optimal or intermediate values of soil physical quality indicators (bulk density [BD], macroporosity [P_{MAC}], air capacity [AC], plant available water capacity [PAWC], and relative field capacity [RFC]), obtained for the considered sampling dates in the FE1 (upper subpanel) and FE2 (lower subpanel).

Table 3. Eigenvalues and variance explained by each component of the principal component analysis (total = 5, average = 1)

	Burning (n = 62)				Incorporation (n = 61)					Whole dataset (n = 123)			
	E†	D	P	C		E	D	P	C		E	D	P	C
1	3.0621	1.9367	0.6124	0.6124	1	3.5934	2.7384	0.7187	0.7187	1	3.3961	2.4503	0.6792	0.6792
2	1.1253	0.5358	0.2251	0.8375	2	0.8550	0.3973	0.1710	0.8897	2	0.9457	0.4365	0.1891	0.8684
3	0.5895	0.3727	0.1179	0.9554	3	0.4577	0.3738	0.0915	0.9812	3	0.5092	0.3706	0.1018	0.9702
4	0.2168	0.2104	0.0434	0.9987	4	0.0838	0.0738	0.0168	0.9980	4	0.1387	0.1284	0.0277	0.9979
5	0.0064		0.0013	1	5	0.0100		0.0020	1	5	0.0102		0.0021	1

† E, Eigenvalues; D, differences; P, proportion; C, cumulative.

least in one case out of two (i.e., MT vs. NT), the selection of key indicators is necessary to better assess the soil physical quality.

Correlation and Multivariate Analysis

Overall, significant correlations were observed among soil variables in the different crop residue management strategies (B and I) as well as in the whole dataset (B + I) (Supplemental Table S4a–c; FE1). The highest (negative) correlations were observed between RFC and AC (r = −0.949, −0.956, −0.952), followed by those between P_{MAC} and AC (r = 0.766, 0.926, 0.870). Plant available water capacity showed the lowest correlations with the other soil variables except RFC (Supplemental Table S4a–c). Bulk density was more correlated to P_{MAC}. Lower correlations were in general observed on burning (Supplemental Table S4a).

In the PCA performed on the set of five variables on the two residue management strategies separately and on the whole dataset (Table 3), the first two factors accounted cumulatively for a percentage of total variance >80%. The first factor summarized the strong relationship among RFC, AC, and P_{MAC}, which showed the highest loadings (Table 4). On the second factor, PAWC was the only highly and significantly weighted variable. These results were summarized in the biplots of the first two factors; in Fig. 5, as an example, the biplots of the analysis performed on the whole dataset are reported. The inspection of the variable loadings and factor scores showed the inverse relationship between RFC and BD on one side and P_{MAC} and AC on the other (first component). In particular, higher P_{MAC} and AC values were recorded mainly on June (ST6) and November (ST1), whereas higher RFC and BD were recorded in February (ST2) and May (ST5) (Fig. 5a). Lower PAWC values were finally observed in April (ST4) (second component). These behaviors seemed to be more accentuated under crop residues incorporation (Fig. 5b).

Table 4. Variable loadings of the first two components of principal component analysis retained in each analysis. Values are multiplied by 100 and rounded to the nearest integer.

	Burning (n = 62)		Incorporation (n = 61)		Whole dataset (n = 123)	
Variable†	Factor 1	Factor 2	Factor 1	Factor 2	Factor 1	Factor 2
BD	−73‡	−5	77‡	−27	76‡	−18
P_{MAC}	87‡	32	−95‡	19	−92‡	24
AC	94‡	4	−95‡	15	−94‡	14
PAWC	−13	98‡	52‡	84‡	41‡	90
RFC	−93‡	24	96‡	11	96‡	13

† AC, air capacity; BD, soil bulk density; PAWC, plant available water capacity; P_{MAC}, macroporosity; RFC, relative field capacity.

‡ Indicates significance of variable loadings.

Stepwise discriminant analysis performed on the set of five variables on the whole dataset did not select any significant variable; this probably indicated that residue management had a slight effect on overall SPQ, as confirmed by the negligible differences between indicator means and by the distribution of the scores in the biplot of PCA (Fig. 5b). When SDA was performed per time, the variables enabling maximum discrimination among the residue management strategies (with a significant threshold to entry and to stay of 0.05 P) were BD in November and April and PAWC in May (Table 5).

In the PCA performed on the sets of four variables on the two residue management strategies separately and on the whole dataset (Supplemental Tables S5a–c and S8a–c, excluding AC and RFC, respectively), for both four-variable sets a slight decrease of the variance was associated with the first component, although the sum of the first two PCs remained close to that observed for the PCA performed on the five variables (Table 3). This may highlight that information brought by RFC and AC did not completely overlap. When AC was excluded from the analysis, RFC showed the highest loadings (Supplemental Table S6a–c). When RFC was excluded, the highest loadings were observed for P_{MAC} (Supplemental Table S9a–c), indicating once more that AC and RFC were not equivalent.

Stepwise discriminant analysis results did not change when analyzing five (Table 5) or four (Supplemental Tables S7 and S10) variables; this similarity can be attributed to the secondary

Table 5. Summary selection of STEPDISC procedure carried out on different plant residue managements dataset (burning vs. incorporation); no variable was entered in the process (P = 0.05) for the missing sampling times (February, March, June) and for the whole dataset. The sampling time is reported in parentheses.

Dataset	Nov. (1)	Apr. (4)	May (5)
N	20	22	22
Step	1	1	1
Number in	1	1	1
Entered	BD†	BD	PAWC‡
Removed	–	–	–
Partial R^2	0.4262	0.2071	0.3116
F value	13.37	5.22	9.05
Pr > F	0.0018	0.0333	0.0069
Wilks' lambda	0.5737719	0.7929012	0.6884064
Pr < lambda	0.0018	0.0333	0.0069
ASCC§	0.42622814	0.20709877	0.3115936
Pr > ASCC	0.0018	0.0333	0.0069

† Bulk density.

‡ Plant available water capacity.

§ Average squared canonical correlation.

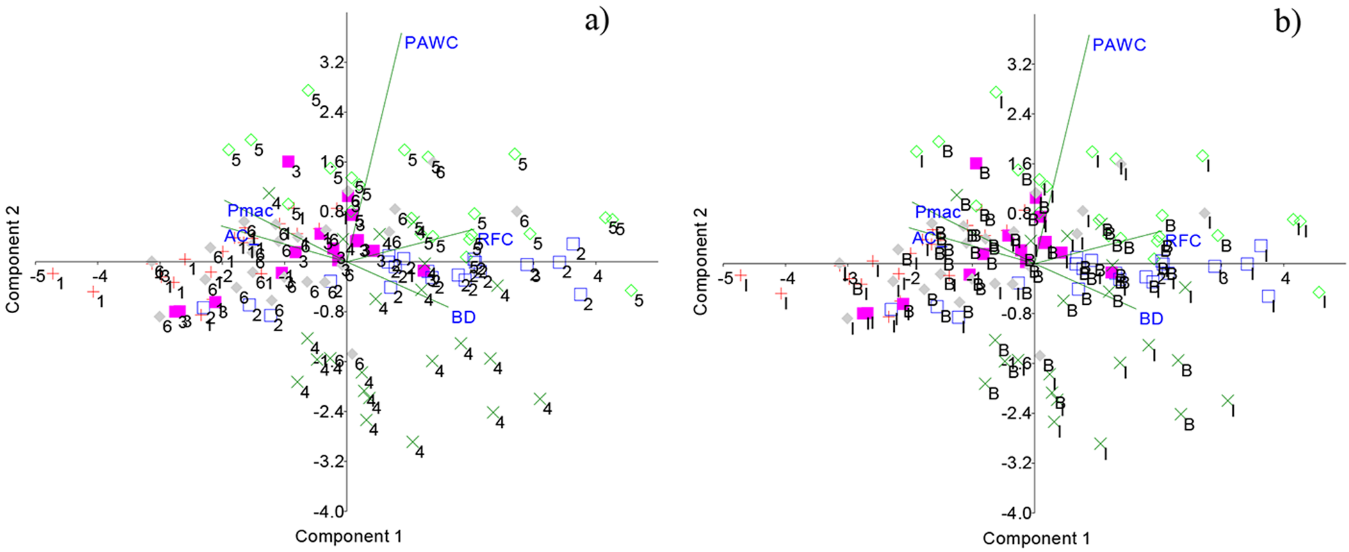

Figure 5. Biplots of the first two components in the analysis carried out on the whole dataset. (a) Scores labeled according to sampling time: 1 = November, 2 = February, 3 = March, 4 = April, 5 = May, 6 = June. (b) Scores labeled according to the plant residue management. B, burning; I, incorporation.

role of RFC and AC in discriminating the two residue management strategies (B vs. I).

As observed for crop residues management, the highest correlations of the MT-NT dataset (FE2) were observed between RFC and AC (r = −0.9156, −0.9717, −0.9714), followed by those between RFC and P_{MAC} (Supplemental Table S11a–c). Principal component analysis, performed on the two-soil management separately and on the whole dataset (Table 6), showed that the first two factors cumulatively synthesize >90% of total variance, with the first factor explaining 73.87, 70.34, and 81.57%. The first factors summarized the strong relationship between RFC, P_{MAC}, and AC, which had the highest loadings (Table 7). In the second factor, PAWC showed a high and significant rank, together with AC in the MT dataset (Table 7). The biplot of the first two factors from the analysis performed on the whole dataset showed that the soil management strategies compared were clearly discriminated on the first component axis (Fig. 6b), with MT characterized by greater P_{MAC} and AC and NT characterized by higher RFC and BD. This behavior seemed to be more accentuated in the first sampling time (ST1, November) (Fig. 6a).

Higher PAWC values were observed in MT on the second sampling date in April (ST4, 19 April) (second component, Fig. 6a, b). Stepwise discriminant analysis performed on the two-soil management provided results consistent with those obtained with PCA, highlighting the considerable effect of different tillage on soil quality and indicating RFC as the main variable to assess the effect of tillage. Relative field capacity was indeed selected as the variable most able to discriminate the two-soil management on the whole dataset, as well as in November, on 19 April (together with P_{MAC}), and in June (Table 8). In February and on 4 April, PAWC and AC and BD played an important role in discriminating the two treatments (Table 8).

In the PCA performed on the sets of four variables, on the two-soil management separately, and on the whole dataset (Supplemental Tables S12–S13 and S15–S16), it was observed that P_{MAC} showed systematically the highest loadings, although RFC loadings were closer to P_{MAC} (Supplemental Table S13) than AC loadings (Supplemental Table S16).

Regarding SDA, RFC was confirmed to be the most discriminating variable in five out of the six cases (in the whole dataset and in all sampling times except February) (Supplemental Table S14). However, when RFC was removed from the analysis (Supplemental Table S17), AC did not show the same discriminating capability, needing the support of other ancillary variables (P_{MAC}, PAWC, BD) except for the last sampling time (June). These results demonstrated that, although RFC and AC derive from the same variables (θ_s and θ_{FC}), can not be considered perfectly equivalent for the information brought.

The analysis of the relationships among soil variables of the Sicilian independent dataset (M-S) confirmed the main results and features observed on B-I and MT-NT, and a strong association

Table 6. Eigenvalues and variance explained by each component of principal component analysis (total = 5, average = 1).

	Minimum tillage (n = 38)					No tillage (n = 40)					Whole dataset (n = 78)			
	E†	D	P	C		E	D	P	C		E	D	P	C
1	3.6933	2.8287	0.7387	0.7387	1	3.5171	2.5188	0.7034	0.7034	1	4.0787	3.4938	0.8157	0.8157
2	0.8646	0.49174	0.1729	0.9116	2	0.9983	0.5814	0.1997	0.9031	2	0.5848	0.3036	0.1170	0.9327
3	0.3730	0.3080	0.0746	0.9862	3	0.4168	0.3541	0.0834	0.9864	3	0.2812	0.2323	0.0562	0.9889
4	0.0650	0.0609	0.013	0.9992	4	0.0627	0.0576	0.0125	0.9990	4	0.0489	0.0425	0.0098	0.9987
5	0.0041		0.0008	1	5	0.0051		0.001	1	5	0.0064		0.0013	1

† E, Eigenvalues; D, differences; P, proportion; C, cumulative.

Table 7. Variable loadings of the first two components of principal component analysis retained in each analysis. Values are multiplied by 100 and rounded to the nearest integer.

	Minimum tillage (n = 38)		No tillage n = 40)		Whole dataset (n = 78)	
Parameters†	Factor 1	Factor 2	Factor 1	Factor 2	Factor 1	Factor 2
BD	84‡	−7	74‡	42	88‡	7
P_{MAC}	−92‡	−26	−96‡	10	−96‡	−5
AC	−80‡	58‡	−90‡	44	−91‡	41
PAWC	75‡	65‡	59‡	73‡	79‡	60‡
RFC	96‡	−21	95‡	−28	97‡	−21

† AC, air capacity; BD, bulk density; PAWC, plant available water capacity; P_{MAC}, macroporosity; RFC, relative field capacity.
‡ Indicates significace of variable loadings.

between RFC and AC was highlighted for M-S soils (r = −0.9621 for M and −0.9861 for S; −0.9141 for the whole dataset, M + S).

The three statistical methods applied (correlation analysis, PCA, and SDA) provided complementary and supplementary information (Stellacci et al., 2016; Thenkabail et al., 2004), allowing us to better investigate the relationships among selected soil physical indicators (PCA and correlations analysis) and to understand their effects on the management practices compared (SDA).

Regardless of the set of data considered, the analysis highlighted three main results: (i) a strong negative correlation between RFC and AC and a positive correlation between P_{MAC} and AC were detected; (ii) PCA and SDA generally identified RFC as an important soil physical indicator because it showed consistently high loadings in the first PCs extracted and discriminated the soil management strategies (MT vs. NT) in the whole dataset and in three of five sampling dates; and (iii) residues management had a slight effect on overall SPQ, whereas the effect of soil management was more noticeable. In addition, SDA performed on four variables, excluding alternatively AC and RFC, highlighted the primary role of RFC in comparison to AC. In fact, although such capacitive indicators derived from the same water content values (θ_s and θ_{FC}), when RFC was excluded, AC needed the support of other ancillary variables (PAWC, P_{MAC}, BD) to achieve the same discriminating capability shown by RFC alone.

Therefore, the behavior of RFC was more closely investigated to assess SPQ and compared with alternative available indicators.

DISCUSSION

Results of correlation analysis suggested that a strong relationship exists between RFC and AC and between P_{MAC} and AC. However, because RFC was selected as the most representative soil physical indicator (i.e., it showed the highest loadings in the first PCs extracted and allowed to discriminate MT vs. NT in the whole dataset and in three out of five sampling dates), it is necessary to evaluate whether the use of RFC is more appropriate for SPQ evaluations as compared with AC or P_{MAC}. Relative field capacity partially combines the AC and PAWC indicators by expressing soil capacity to store air and water relative to the soil's total pore volume (i.e., $\theta_s \approx$ soil porosity) (Reynolds et al., 2014a). Therefore, decreasing RFC values at increasing AC are expected because both indicators depend on soil water content at saturation and at field capacity. This finding reinforces the idea by Cullotta et al. (2016) that one of the two indicators can be neglected. However, these indicators are not equivalent because, for example, they differ in the suggested reference values (Table 1) and in range of variation (Reynolds et al., 2009). Therefore, their reliability would be better assessed in the light of these two main factors.

Reynolds et al. (2008) reported that an optimal balance between root-zone soil water capacity and soil AC may be obtained when RFC falls within the range of 0.6 to 0.7 because this interval maximizes microbial production of nitrate, which is usually a limiting factor for crop yield on mineral soils. Lower RFC values (RFC <0.6) can reduce microbial activity and nitrate production because of insufficient soil water (water-limited soil), whereas greater RFC values (RFC >0.7) may indicate reduced microbial activity because of insufficient soil air (aeration-limited soil). Reynolds et al. (2009) suggested a value of AC ≥0.10 $cm^3\ cm^{-3}$ for minimum sus-

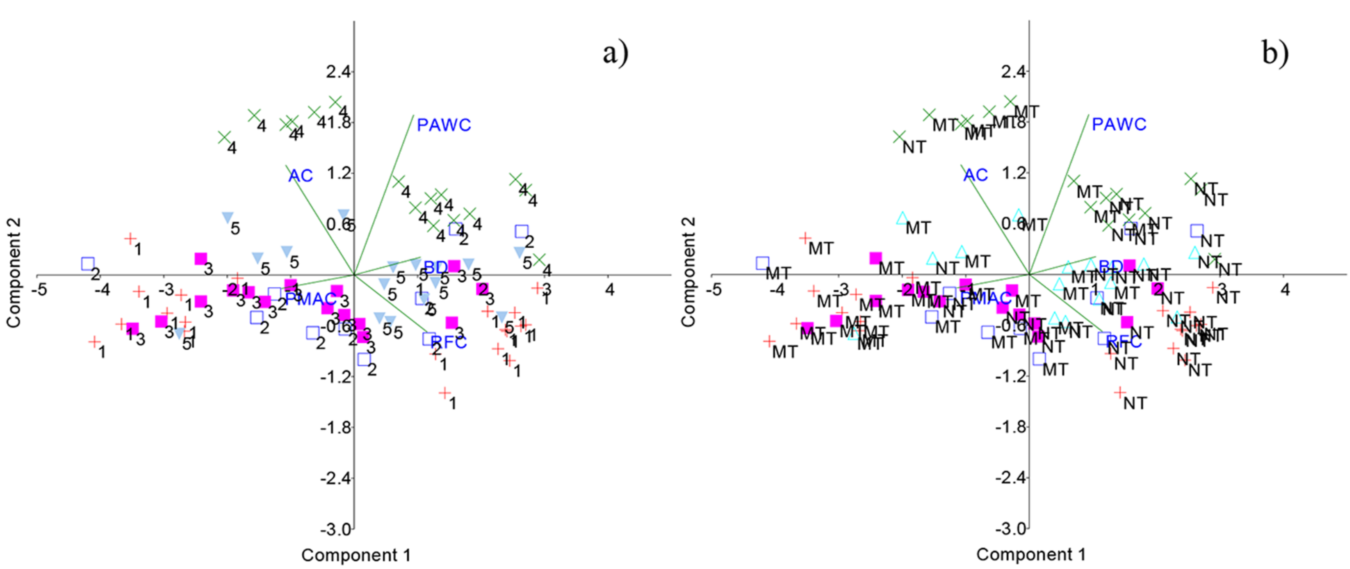

Figure 6. Biplots of the first two components in the analysis carried out on the whole dataset. (a) Scores labeled according to sampling time: 1 = November, 2 = February, 3 = 4 April, 4 = 19 April, 5 = June. (b) Scores labeled according to the different soil management. MT, minimum tillage; NT, no-tillage.

Table 8. Summary selection of STEPDISC procedure carried out on different soil managements dataset (minimum tillage vs. no-tillage) on the whole set of data (n = 78) and per sampling time.

Dataset	Whole	Nov. (1)	Feb. (2)	4 Apr. (3)	19 Apr. (4)	June (5)
N	78	20	10	16	16	16
Step	1	1	1	1	1	1
Number in	1	1	1	1	1	1
Entered	RFC	RFC (P_{MAC})†	PAWC	AC (BD)	RFC (P_{MAC})	RFC
Removed	–	–	–	–	–	–
Partial R^2	0.534	0.965	0.5757	0.6832	0.3714	0.3077
F value	87.08	496.62	10.85	30.19	8.27	6.22
Pr > F	<0.0001	<0.0001	0.011	<0.0001	0.0122	0.0257
Wilks' lambda	0.466015	0.034977	0.42434	0.316806	0.6285	0.6923
Pr < lambda	<0.0001	<0.0001	0.011	<0.0001	0.0122	0.0257
ASCC‡	0.533985	0.965023	0.57566	0.683194	0.3714	0.3077
Pr > ASCC	<0.0001	<0.0001	0.011	<0.0001	0.0122	0.0257

† The second selected variable is reported in parentheses.

‡ Average squared canonical correlation.

ceptibility to crop-damaging or yield-reducing aeration deficits in the root zone or a value of AC ≥0.14 $cm^3\ cm^{-3}$ for sandy loam to clay loam soils. However, Cullotta et al. (2016) argued that the suggested criteria to discriminate between good and poor conditions of RFC and AC (i.e., $0.6 \leq RFC \leq 0.7$ and $AC \geq 0.14\ cm^3\ cm^{-3}$) are not consistent because, if an optimal value of RFC is expected to fall back into the range of 0.6 to 0.7, AC may not increase indefinitely, and a maximum value should be suggested. Therefore, starting from the assumption that the optimal range interval of RFC may be used as reference, Cullotta et al. (2016) selected the observed optimal RFC values and used the corresponding θ_s values (i.e., minimum and maximum values of θ_s) to calculate AC and to derive an optimal range for forest and pasture land ($0.11 \leq AC \leq 0.18\ cm^3\ cm^{-3}$). Following their reasoning, we derived a plausible optimal AC range for agricultural soils using the B-I and MT-NT data (Fig. 7). The θ_s values varied between 0.40 and 0.57 $cm^3\ cm^{-3}$ for B and between 0.33 and 0.55 $cm^3\ cm^{-3}$ for I (Fig. 7); optimal AC values (i.e., min and max) were 0.12 to 0.16 and 0.17 to 0.23 $cm^3\ cm^{-3}$ for B and 0.10 to 0.13 and 0.17 to 0.22 $cm^3\ cm^{-3}$ for I. The obtained result (i.e., $0.10 \leq AC \leq 0.23\ cm^3\ cm^{-3}$) is plausible because this optimal range was similar to the range defined by Cullotta et al. (2016), differing slightly only at the maximum value. Although Cullotta et al. (2016) suggested that, in comparison with a good agricultural soil, a good forest soil has a larger ability to store air (i.e., relatively higher AC values), agricultural soils benefit from human-induced porosity (i.e., tillage) or from organic matter inputs (e.g., incorporation of crop residues or of the roots that remain in situ when the soil is undisturbed, incorporation of soil organic matter in the form of compost, etc.). Therefore, results of this investigation suggest that agronomical treatments can cause aeration soil conditions similar to or higher than those of undisturbed virgin soils. Results obtained from independent datasets (M and S) confirmed and extended these conclusions because optimal AC values of Santa Ninfa soils (about a quarter of the total soil samples were within the optimal range $0.6 \leq RFC \leq 0.7$) shifted upward the maximum of AC optimal range to ~0.26 $cm^3\ cm^{-3}$ (Fig. 7). Furthermore, the detected AC optimal interval ($0.10 \leq AC \leq 0.26\ cm^3\ cm^{-3}$) was in good agreement with the literature because Reynolds et al. (2002, 2014a, 2014b) suggested a "lower critical limit" of 0.09 $cm^3\ cm^{-3}$, below which periodic anaerobiosis would likely occur, and maximum values not higher than 0.26 to 0.37 $cm^3\ cm^{-3}$. Cullotta et al. (2016) concluded that the use of capacity-based indicators was the most convincing criterion to assess SPQ; moreover, following the current procedures, only four water retention data points are necessary to establish SPQ of an area of interest (i.e., θ_s, θ_M, θ_{FC}, and $\theta_{PWP,}$ respectively volumetric soi$_l$ water content at saturation of the soil matrix, at field capacity and at permanent wilting point), suggesting that they are usable for SPQ assessment of agricultural and forest (or pasture) soils. Our results confirm and extend these conclusions because only two water retention data points are needed to determine RFC (i.e., θ_s and θ_{FC}), highlighting the strong association in all the investigated datasets between RFC and AC and secondarily between AC and P_{MAC}.

Application of multivariate analysis (i.e., PCA and SDA), on the set of five and four variables, selected RFC as a representative

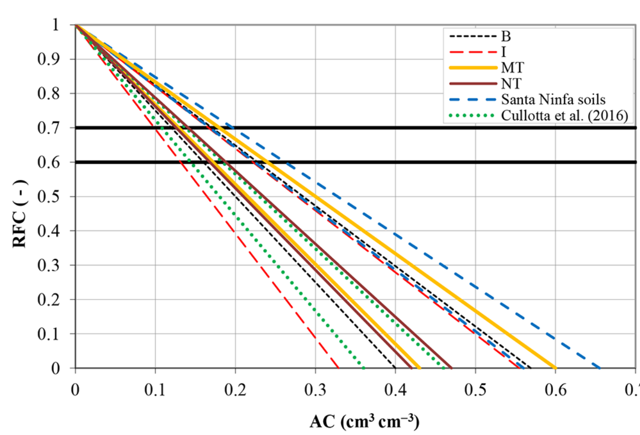

Figure 7. Determination of the air capacity (AC) values corresponding to optimal conditions in terms of relative field capacity (RFC) carried out for agricultural soils on FE1 and FE2 (burning [B], incorporation [I], minimum tillage [MT], and no tillage [NT] treatments). Results of Santa Ninfa soils are included because they provide the upper limit of the suggested AC optimal range ($0.10 \leq AC \leq 0.26\ cm^3\ cm^{-3}$). The optimal AC range for forest and pasture land is also reported (Cullotta et al., 2016). The two horizontal bold lines demark the considered optimal RFC range.

Table 9. Comparison between crop residue managements carried out considering soil physical quality indicators selected in the sampling times by first and second component of principal component analysis and stepwise discriminant analysis.

Statistical analysis†	Sampling times (selected soil physical quality indicator)‡	Crop residue management		Best result§
		Burning	Incorporation	
PC1	1 (RFC)	optimal	water limited	B
	2 (RFC)	aeration limited	aeration limited	=
	3 (RFC)	optimal	optimal	=
	4 (RFC)	optimal	optimal	=
	5 (RFC)	aeration limited	aeration limited	=
	6 (RFC)	optimal	optimal	=
PC2	1 (PAWC)	poor	poor	=
	2 (PAWC)	poor	poor	=
	3 (PAWC)	limited	poor	=
	4 (PAWC)	poor	poor	=
	5 (PAWC)	limited	limited	=
	6 (PAWC)	poor	limited	=
SDA	1 (BD)	near optimal	poor	B
	4 (BD)	optimal	optimal	=
	5 (PAWC)	limited	limited	=

† PC1, principal component 1; PC2, principal component 2; SDA, stepwise discriminant analysis.

‡ BD, bulk density; PAWC, plant available water capacity; RFC, relative field capacity.

§ For each soil indicator, intermediate values of BD and air capacity, as reported in Table 1, were considered as not completely poor and were considered to be part of the higher category (i.e., optimal); likewise, intermediate values of PAWC (i.e., good or limited) were considered, respectively, to be part of ideal or poor PAWC values. The symbol "=" indicates an equivalent result of SPQ assessment.

indicator for SPQ assessment (highest loadings in four out of six cases in PC1). The use of few indicators (only RFC in this case) has made it easier to draft quality judgment and reduce uncertainties. According to this approach, when summing the best RFC judgments as depicted in Fig. 3 for each treatment (i.e., the best judgment at each ST) and neglecting those of equality (simultaneously optimal or poor for both treatments), a slightly better SPQ was established for burning (score = +1; ST1), whereas a slightly more clear-cut result was detected in the FE2 (MT: score = +2; four differences between the second and the fifth sampling time). In this case, MT was selected as the soil management strategy that induces the optimal balance between air and water into the soil. However, regarding FE2, except for ST1, for which the opposite values were highlighted, the seasonal trends of RFC (i.e., MT and NT) were similar, and a mean scale factor of 0.11 (i.e., calculated as mean difference between ST2 and ST5) was highlighted. This value can quantify the effects due to the different soil management strategies (MT or NT).

With the exception of P_{MAC}, which was not selected as a main option, other soil indicators were suggested from time to time by SDA as the best choice (PAWC, BD, and AC) as well as PAWC on PC2. However, although RFC partially gives an account of PAWC and AC (Table 1), a further study was performed to evaluate the impact of alternative indicator selection (by PCA and SDA) on SPQ assessment. Results of this check (Table 9 [FE1] and Table 10 [FE2]) suggested that, even if approximations are needed to account for the intermediate-quality class values (e.g., intermediate values of SPQ are not entirely negative so were considered optimal), using alternative soil key indicators would not have provided a different SPQ response because B and MT were clearly selected as best treatments (Tables 9 and 10). On the other hand, PC2 results (NT score = +1) in Table 10 are not surprising because, for FE2, PAWC was selected as a key indicator. Bulk density was also selected by SDA. Soil BD may be considered a good predictor, especially at the beginning of crop season when soils have higher porosity due to recent tillage (Castellini et al., 2014). Positive relationships between BD and PAWC are well known because, for example, fine-textured soils generally exhibit increasing PAWC values at increasing BD values (Castellini et al., 2014). Because RFC formulation implicitly accounts for PAWC, the choice of this key indicator for SPQ assessment can be specifically suggested for fine-textured soils. Finally, with reference to the beginning of the crop season (i.e., ST1 of Fig. 3), BD and RFC provided consistent results because the same SPQ assessment was achieved in three out of four considered cases (i.e., optimal or near-optimal soil conditions for B, water-limited for MT and I). This provides further corroboration about the reliability of RFC.

Table 10. Comparison between soil management strategies carried out considering soil physical quality indicators selected in the sampling times by first and second component of principal component analysis and stepwise discriminant analysis.

Statistical analysis†	Sampling time (selected soil physical quality indicator)‡	Soil management§		Best result¶
		MT	NT	
PC1	1 (RFC)	water limited	aeration limited	=
	2 (RFC)	optimal	aeration limited	MT
	3 (RFC)	water limited	optimal	NT
	4 (RFC)	optimal	aeration limited	MT
	5 (RFC)	optimal	aeration limited	MT
PC2	1 (PAWC)	poor	limited	=
	2 (PAWC)	poor	limited	=
	3 (PAWC)	poor	limited	=
	4 (PAWC)	limited	good	NT
	5 (PAWC)	poor	limited	=
SDA	1 (RFC)	water limited	aeration limited	=
	2 (PAWC)	poor	limited	=
	3 (AC)	optimal	intermediate	=
	4 (RFC)	optimal	aeration limited	MT
	5 (RFC)	optimal	aeration limited	MT

† PC1, principal component 1; PC2, principal component 2; SDA, stepwise discriminant analysis.

‡ AC, air capacity; PAWC, plant available water capacity; RFC, relative field capacity.

§ MT, minimum tillage; NT, no tillage.

¶ For each soil indicator, intermediate values of bulk density and air capacity, as reported in Table 1, were considered as not completely poor and were considered to be part of higher category (i.e., optimal); likewise, intermediate values of PAWC (i.e., good or limited) were considered to be part of ideal or poor PAWC values, respectively. The symbol "=" indicates an equivalent result of SPQ assessment.

According to the results discussed herein, RFC was used to compare the treatments (i.e., B vs. I and MT vs. NT) over the growing season. With reference to the considered experimental conditions (i.e., soil texture, rainfall, and crop and agronomic practices), RFC results showed that, according to a Tukey's HSD test ($P = 0.05$), there was no seasonal variability for B, MT, and NT from about February onward. This suggests that 4 mo (i.e., MT and NT) or 5 mo (B) are the minimum times required to reach a stable and optimal (or near optimal) ratio between water and air into the soil. This finding is significant especially for NT because, contrary to what is perceived especially by Italian farmers, results of this investigation suggest that long-term NT soil do not result in significant soil compaction; rather, this soil practice positively affects the physical quality of the investigated clay soil. Conversely, a seasonal variability was detected for the incorporation of crop residues practice because, although the lowest RFC values of ST1 may be attributed to the effect of straw incorporation, the higher values observed in ST2 and ST5 (i.e., February and May) must be attributed to direct effect of agronomic practice. Because B and I were investigated in the same year, thus considering the same "boundary conditions" (rainfall on all), results suggest that relatively higher soil water contents, which typically are achieved in the winter-spring season in southern Italy, can adversely affect the soil sampling when soil and straw, often not completely decomposed, are mixed together. Therefore, in the year of the investigation considered, a time frame where SPQ may be considered steadily optimal was not detected for agronomic practice of incorporation of wheat residues.

CONCLUSIONS

Results of this investigation highlighted that bivariate analysis (correlation) showed a significant negative relationship between RFC and AC as well as a positive relationship between P_{MAC} and AC, and multivariate analysis (PCA and SDA) identified RFC as a key soil physical indicator because it generally showed the highest loadings in the first PCs extracted and discriminated between MT and NT. Selection of RFC as key soil indicator improved SPQ assessment because, in at least one of the two comparisons made (MT vs. NT), it discriminated between agronomic treatments, as compared with a SPQ assessment that uses multiple soil indicators simultaneously. Because RFC partially combines the AC and PAWC indicators, thus expressing the optimal air/water ratio into the soil, it appears to be a promising summary indicator that could be used for SPQ evaluations on agricultural soils. Finally, an optimal AC range, derived from optimal RFC limits, was obtained and suggested to better assess the AC of agricultural soils ($0.10 \leq AC \leq 0.26$ cm^3 cm^{-3}).

The findings of our study, by deepening the relationships among the five SPQ indicators, can be considered important and preliminary results toward building a minimum dataset of soil variables to be used for the computation of an overall index of soil quality. The results highlight the complementary and supplementary role of the three data analyses procedures applied (correlation analysis, PCA, SDA) and the importance of simultaneously using different approaches to gain a complete understanding of the processes investigated. The methodological contribution of applying SDA over the two four-variable datasets (excluding alternatively AC and RFC) should be underlined. In this way, the different weight of RFC with respect to AC in the discrimination of the different soil management strategies was clearly evidenced. This finding could have been unexpected because the two variables were derived from the same water content information.

Relative field capacity had a crucial role among SPQ indicators, being able to summarize part of the information given by AC and P_{MAC}; however, the variable was less effective in discriminating the differences between crop residue management (B vs. I). In this case, as well as for the MT vs. NT dataset, BD and PAWC showed the highest discriminating capability, indicating their complementary role in assessing SPQ.

The statistical methodology adopted appears suitable to investigate large datasets of soil indicators, including those of physical, chemical, and biological nature, both separately and simultaneously.

ACKNOWLEDGMENTS

This study was supported by the EU and MIUR in the frame of the collaborative international consortium DESERT "Low-cost water desalination and sensor technology compact module" under the ERA-NET Cofund WaterWorks2014 Call. This ERA-NET is an integral part of the 2015 Joint Activities developed by the Water Challenges for a Changing World Joint Programme Initiative (Water JPI). The study was also supported by the project "STRATEGA, Sperimentazione e TRAsferimento di Tecniche innovative di aGricoltura conservativA," financed by Regione Puglia- Servizio Agricoltura. M.C. outlined the investigation and carried out the experimental work. M.C, A.M.S. and E.B. carried out data analysis for variables selection. All authors contributed to analyze and discuss the results and write the manuscript.

REFERENCES

Armenise, E., M.A. Redmile-Gordon, A.M. Stellacci, A. Ciccarese, and P. Rubino. 2013. Developing a soil quality index to compare soil fitness for agricultural use under different managements in the Mediterranean environment. Soil Tillage Res. 130:91–98. doi:10.1016/j.still.2013.02.013

Bagarello, V., M. Castellini, and M. Iovino. 2005. Influence of the pressure head sequence on the soil hydraulic conductivity determined with the tension infiltrometer. Appl. Eng. Agric. 21:383–391. doi:10.13031/2013.18457

Burke, W., D. Gabriels, and J. Bouma. 1986. Soil structure assessment. Balkema, Rotterdam, The Netherlands.

Castellini, M., and D. Ventrella. 2012. Impact of conventional and minimum tillage on soil hydraulic conductivity in typical cropping system in Southern Italy. Soil Tillage Res. 124:47–56. doi:10.1016/j.still.2012.04.008

Castellini, M., M. Pirastru, M. Niedda, and D. Ventrella. 2013. Comparing physical quality of tilled and no-tilled soils in an almond orchard in South Italy. Ital. J. Agron. 8:149–157.

Castellini, M., M. Niedda, M. Pirastru, and D. Ventrella. 2014. Temporal changes of soil physical quality under two residue management systems. Soil Use Manage. 30:423–434. doi:10.1111/sum.12137

Castellini, M., L. Giglio, M. Niedda, A.D. Palumbo, and D. Ventrella. 2015. Impact of biochar addition on the physical and hydraulic properties of a clay soil. Soil Tillage Res. 154:1–13. doi:10.1016/j.still.2015.06.016

Castellini, M., M. Iovino, M. Pirastru, M. Niedda, and V. Bagarello. 2016. Use of BEST procedure to assess soil physical quality in the Baratz Lake catchment (Sardinia, Italy). Soil Sci. Soc. Am. J. 80:742–755. doi:10.2136/sssaj2015.11.0389

Castellini, M., S. Di Prima, and M. Iovino. 2018. An assessment of the BEST procedure to estimate the soil water retention curve: A comparison with the evaporation method. Geoderma 320:82–94. doi:10.1016/j.geoderma.2018.01.014

Castellini, M., and M. Iovino. 2019. Pedotransfer functions for estimating soil water retention curve of Sicilian soils. Arch. Agron. Soil Sci. doi:10.1080/03650340.2019.1566710

Cournane, F.C., R.W. McDowell, R.P. Littlejohn, and L.M. Condron. 2011. Effects of cattle, sheep and deer grazing on soil physical quality and phosphorus and suspended sediment losses in surface runoff. Agric. Ecosyst. Environ. 140:264–272. doi:10.1016/j.agee.2010.12.013

Cullotta, S., V. Bagarello, G. Baiamonte, G. Gugliuzza, M. Iovino, D.S. La Mela Veca, et al. 2016. Comparing different methods to determine soil physical quality in a Mediterranean forest and pasture land. Soil Sci. Soc. Am. J. 80:1038–1056. doi:10.2136/sssaj2015.12.0447

Dane, J.H., and J.W. Hopmans. 2002. Water retention and storage: Laboratory. In: J.H. Dane and G.C. Topp, editors, Methods of soil analysis. Part 4. Physical methods. SSSA, Madison, WI. p. 688–692.

Ferrara, R.M., G. Mazza, C. Muschitiello, M. Castellini, A.M. Stellacci, A. Navarro, et al. 2017. Short-term effects of conversion to no-tillage on respiration and chemical-physical properties of the soil: A case study in a wheat cropping system in semi-dry environment. Ital. J. Agrometeorol. doi:10.19199/2017.1.2038-5625.047

Francaviglia, R., A.M. Carroni, P. Ruda, M. Salis, P. Bazzoffi, S. Carnevale, et al. 2015. Environmental effectiveness of GAEC cross-compliance Standard 3.1 'Ploughing in good soil moisture conditions' and economic evaluation of the competitiveness gap for farmers. Ital. J. Agron. 10. doi:10.4081/ija.2015.10.s1.695.

Iovino, M., M. Castellini, V. Bagarello, and G. Giordano. 2016. Using static and dynamic indicators to evaluate soil physical quality in a Sicilian area. Land Degrad. Dev. 27:200–210. doi:10.1002/ldr.2263

Karlen, D.L., C.A. Cambardella, J.L. Kovar, and T.S. Colvin. 2013. Soil quality response to long-term tillage and crop rotation practices. Soil Tillage Res. 133:54–64. doi:10.1016/j.still.2013.05.013

Kiani, M., G. Hernandez-Ramirez, S. Quideau, E. Smith, H. Janzen, F.J. Larney, and D. Puurveen. 2017. Quantifying sensitive soil quality indicators across contrasting long-term land management systems: Crop rotations and nutrient regimes. Agric. Ecosyst. Environ. 248:123–135. doi:10.1016/j.agee.2017.07.018

Körschens, M. 2006. The importance of long-term field experiments for soil science and environmental research– a review. Plant Soil Environ. 52(special issue):1–8.

Lachenbruch, P.A. 1975. Discriminant analysis. Hafner, New York.

Miralles, I., R. Ortega, G. Almendros, M. Sánchez-Marañón, and M. Soriano. 2009. Soil quality and organic carbon ratios in mountain agroecosystems of south-east Spain. Geoderma 150:120–128. doi:10.1016/j.geoderma.2009.01.011

Peterson, G.A., D.J. Lyon, and C.R. Fenster. 2012. Valuing long-term field experiments: Quantifying the scientific contribution of a long-term tillage experiment. Soil Sci. Soc. Am. J. 76:757–765. doi:10.2136/sssaj2011.0413

Reynolds, W.D., B.T. Bowman, C.F. Drury, C.S. Tan, and X. Lu. 2002. Indicators of good soil physical quality: Density and storage parameters. Geoderma 110(1–2):131–146. doi:10.1016/S0016-7061(02)00228-8

Reynolds, W.D., C.F. Drury, X.M. Yang, and C.S. Tan. 2008. Optimal soil physical quality inferred through structural regression and parameter interactions. Geoderma 146(3-4):466–474. doi:10.1016/j.geoderma.2008.06.017

Reynolds, W.D., C.F. Drury, C.S. Tan, C.A. Fox, and X.M. Yang. 2009. Use of indicators and pore volume-function characteristics to quantify soil physical quality. Geoderma 152:252–263. doi:10.1016/j.geoderma.2009.06.009

Reynolds, W.D., C.F. Drury, X.M. Yang, C.S. Tan, and J.Y. Yang. 2014a. Impacts of 48 years of consistent cropping, fertilization and land management on the physical quality of a clay loam soil. Can. J. Soil Sci. 94:403–419. doi:10.4141/cjss2013-097

Reynolds, W.D., J.J. Schoenau, and C.F. Drury. 2014b. Scientific and practical benefits of long-term field studies. Can. J. Soil Sci. 94:253–254. doi:10.4141/cjss-2014-501

SAS Institute Inc. 2012. SAS/STAT software, release 9.3. SAS Institute Inc., Cary, NC.

Schuenemeyer, J., and L. Drew. 2011. Statistics for earth and environmental scientists. Wiley, Hoboken, NJ.

Soil Survey Staff. 2010. Keys to soil taxonomy. 11th ed. USDA–NRCS, Washington, DC.

Stellacci, A.M., A. Castrignanò, A. Troccoli, B. Basso, and G. Buttafuoco. 2016. Selecting optimal hyperspectral bands to discriminate nitrogen status in durum wheat: A comparison of statistical approaches. Environ. Monit. Assess. 188:199. doi:10.1007/s10661-016-5171-0

Thenkabail, P.S., E.A. Enclona, M.S. Ashton, and B. Van Der Meer. 2004. Accuracy assessments of hyperspectral waveband performance for vegetation analysis applications. Remote Sens. Environ. 91:354–376. doi:10.1016/j.rse.2004.03.013

Uddin, N., 2013. Consumer credit customers' financial distress prediction by using two-group discriminant analysis: A case study. Int. J. Economics Finance 5(6):55–66.

Uddin, N., S. Meah Md, and R. Hossain. 2013. Discriminant analysis as an aid to human resource selection and human resource turnover minimization decisions. Int. J. Bus. Manage. 8(17):153–169. doi:10.5539/ijbm.v8n17p153

Van Eerd, L.L., K.A. Congreves, A. Hayes, A. Verhallen, and D.C. Hooker. 2014. Long-term tillage and crop rotation effects on soil quality organic carbon, and total nitrogen. Can. J. Soil Sci. 94:303–315. doi:10.4141/cjss2013-093

van Genuchten, M.T. 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44:892–898. doi:10.2136/sssaj1980.03615995004400050002x

Ventrella, D., A.M. Stellacci, A. Castrignanò, M. Charfeddine, and M. Castellini. 2016. Effects of crop residue management on winter durum wheat productivity in a long term experiment in Southern Italy. Eur. J. Agron. 77:188–198. doi:10.1016/j.eja.2016.02.010

Zhou, Z.C., Z.T. Gan, Z.P. Shangguan, and Z.B. Dong. 2010. Effects of grazing on soil physical properties and soil erodibility in semiarid grassland of the northern Loess Plateau. Catena 82:87–91. doi:10.1016/j.catena.2010.05.005

Zornoza, R., J.A. Acosta, F. Bastida, S.G. Domínguez, D.M. Toledo, and A. Faz. 2015. Identification of sensitive indicators to assess the interrelationship between soil quality, management practices and human health. Soil (Gottingen) 1:173–185. doi:10.5194/soil-1-173-2015