

RESEARCH ARTICLE

SOIL PHYSICAL QUALITY ESTIMATION APPLYING THE BEST-PROCEDURE: A CASE STUDY UNDER CONTRASTING SOIL MANAGEMENT

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ABSTRACT

The BEST-procedure was applied to estimate the soil physical quality (SPQ) of a marginal soil managed with no tillage for a long time or shallow tilled from a few days. Six soil indicators, directly or indirectly obtained from BEST, were used to account for the modifications due to the hydrostatic and hydrodynamic soil properties, that specifically were: bulk density, saturated hydraulic conductivity, macroporosity, air capacity, plant available water capacity and relative field capacity. The guidelines of literature were considered to evaluate the optimal values of such indicators and mean SPQ values were used to compare the effects of contrasting soil management (freshly tilled soil vs undisturbed soil). The long-term untilled soil showed a tendency towards physical degradation and, for this, it was more prone to compaction and, consequently, water erosion during intense rainfall events. However, the results highlighted that a relative improvement was possible by means of surface soil tillage because, as a matter of fact, tillage improved the soil properties in both hydrodynamic and hydrostatic terms. The study confirmed the diagnostic ability of the BEST procedure to estimate the soil physical quality for comparison purposes. More generally, the procedure may be suggested to evaluate the SPQ in a relatively simple, easy and fast way, and appropriately evaluate the land use sustainability of large areas.

KEYWORDS

Soil management; soil physical quality; soil water retention; BEST-steady; capacity-based indicators; soil bulk density; saturated hydraulic conductivity

1. INTRODUCTION

Soil quality (or soil health) can be defined as “the continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, maintain the quality of air and water environments, and promote plant, animal, and human health” (Doran et al., 1996). The soil physical quality (SPQ) of agricultural soils is evaluated mainly with reference to the mechanical and hydraulic characteristics of the layer explored by the roots. In particular, the upper soil layer is of great practical interest, as it plays a key role in agronomic and environmental processes such as seeds germination, rooting of seeds, aggregation of soil particles, impact of tillage, erosion and surface crust formation, aeration, infiltration and runoff (Topp et al., 1997; Reynolds et al., 2002).

SPQ can be determined using “capacitive” indicators obtained from the soil water retention curve such as, for example, air capacity, plant available water capacity, relative field capacity (Topp et al., 1997; Reynolds et al., 2007) or the S-index which represents the slope of the curve retention at its inflection point (Dexter, 2004). More recently, Reynolds et al. (2009) proposed a criterion for determining the SPQ based on the comparison between the experimentally determined soil porosity distribution curve and an “optimal” curve. On the other hand, the water transfer towards the deeper soil layers is mostly due to the hydraulically interconnected pore system, and/or due to the larger pores size (mesopores and macropores) (Cameira et al., 2003). As a consequence, the determination of “dynamic” soil physical indicators, such as the saturated hydraulic conductivity, can provide complementary information on SPQ of agricultural soils (Castellini et al., 2014). Regardless of the indicator used, however, the

judgment on the SPQ presupposes the comparison between the measured value and one (or more) reference values (Topp et al., 1997; Reynolds et al., 2002; Dexter, 2004; Reynolds et al., 2007; Dexter and Czyz, 2007; Reynolds et al., 2009).

A lot of methods are suggested to obtain the soil water retention curve. For instance, in common practice are used the sand-box or hanging water column apparatus (Burke et al., 1986), pressure plate apparatus (Dane and Hopmans, 2002) or evaporation method (Wind, 1968). Due to soil spatial variability, however, such direct measurements of soil water retention are expensive and time consuming; also, since they require quite complex measurement devices and skilled operators, make them practically unfeasible at the scale of irrigation district (Sinowski et al., 1997). Consequently, a great effort has been made in soil sciences, especially during the last decades, to develop relatively easy, robust, and inexpensive methods for soil hydraulic determination (Castellini and Iovino, 2019; Castellini et al., 2021a).

Almost twenty years ago now, Lassabatère et al. (2006) proposed a strong experimental procedure with the acronym BEST (Beerkan Estimation of Soil Transfer parameters). It allows the simultaneous determination of the main hydraulic properties of the soil, i.e. water retention curve, i.e. the relationship between volumetric water content, θ , and soil pressure head, h , and hydraulic conductivity function, i.e. the relationship between hydraulic conductivity of the soil, K , and θ (or h). Specifically, BEST makes use of the analytical infiltration model proposed by Haverkamp et al. (1994) and, based on the assumption that $\theta(h)$ and $K(\theta)$ are expressed by certain empirical relationships, it returns the unknown model's parameters from a pedotransfer function and from a simple field

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infiltration experiment under saturated soil conditions. The van Genuchten (1980) model with the condition of Burdine (1953) is used for the water retention curve and the Brooks and Corey (1964) relationship for hydraulic conductivity function. The available alternative algorithms developed to analyze field infiltration data can be found in the review by Angulo-Jaramillo et al. (2019), while the method efficiency was detailed reported in several investigations (Castellini et al., 2021a).

Cropping systems and agronomic practices, i.e., crops rotation, soil tillage, may deeply modify the physical and hydraulic properties of the soil. Consequently, they can modify also the SPQ (Castellini et al., 2021a). Some investigations were aimed at evaluating BEST ability to assess the SPQ for agricultural and forest environments. For example, in the investigation by Di Prima et al. (2018), the SPQ of a Spanish orchard under three different soil management, i.e., no-tillage using herbicides, conventional tillage under chemical farming, no-tillage under organic farming, was estimated; such evaluation considered common indicators such as soil bulk density, organic carbon content, or structural stability index, were considered in conjunction with capacitive indicators estimated by BEST. The findings showed that independent and BEST-derived indicators yielded comparable information, suggesting their ability to distinguish SPQ among contrasting soil management. More recently, Castellini et al. (2021b) applied the multi-height beerkan run methodology to detect the mechanical impact of water pouring height on the soil physical quality of a loam soil under minimum tillage and no tillage. They applied BEST-steady algorithm to estimate the soil water retention curve and considered three SPQ indicators, i.e., macroporosity, air capacity and relative field capacity (Castellini et al., 2021b). Overall, the relationships detected were plausible from a soil physics point of view. No-tilled soil showed to be more resilient than tilled one. Authors concluded that the study was useful to quantifying soil degradation effects, due to intense rainfall events, under different soil management practices in the Mediterranean environment (Castellini et al., 2021b).

The main goal of this investigation was to study the SPQ of a relatively coarse soil submitted to a contrasting soil management, namely, undisturbed for a long time (i.e., no-tilled, NT) and tilled shallowly (i.e. minimum tillage, MT). At this aim, the BEST retention curve was applied with the objective to estimate some SPQ indicators including macroporosity (P_{mac}), air capacity (AC), plant available water capacity ($PAWC$) and relative field capacity (RFC) from the soil water retention. Two other SPQ variables considered as input or output from BEST-procedure, i.e., respectively bulk density (r_b) and saturated hydraulic conductivity (K_s), were also considered to account for the compaction and permeability of the soil. The soil management induced effects on porous medium were evaluated in agreement with literature guidelines.

2. MATERIALS AND METHODS

2.1 Field Site

This investigation was carried out at the experimental field of the Council for Agricultural Research and Economics, Research Center for Agriculture and Environment, CREA-AA of Bari, Italy (Castellini et al., 2021c). The field site is in the Mediterranean region with warm temperate climate, and hot and dry summer. According to the USDA classification, the investigated soil was a loam, with 43.2 and 17.2% of sand and clay, respectively. An experimental area of a few hundred square meters was selected in order to compare two alternative soil management conditions, i.e., no-tilled and conventional tilled soil (NT and CT, respectively). For each soil management (NT and CT), twelve sampling points were randomly selected, and 24 beerkan experiments in total were carried out (Castellini et al., 2021c). Beerkan experiments were conducted using thirty volumes of water of 200 mL each. Briefly, each of the thirty water volumes was repeatedly poured into the cylinder, establishing a height of water of about 1 cm, and the time needed for complete infiltration was logged. The procedure was repeated up to the thirtieth volume, and experimental cumulative infiltration, $I(t)$, and infiltration rate $q(t)$, was thus deduced. Field experiments started in April and ended in August and no significant precipitation occurred in the months of the investigation. Therefore, the experiments were conducted under almost dry soil conditions. For in-depth information on the measurement site, please refer to Castellini et al. (2021c).

2.2 BEST-Procedure And Soil Physical Quality Estimation

The BEST procedure by Lassabatere et al. (2016) was applied to estimate the soil water retention curve. For each of the 24 sampling points was determined: i) soil bulk density (r_b), using soil cores of 10 cm in height by 5 cm in diameter, ii) soil porosity, and therefore, saturated soil water content, estimated from r_b considering a mean particle density of 2.65 g

cm⁻³, as usual for this procedure, iii) gravimetric soil water content at the time of infiltration run, using the soil sample collected for r_b determination, and iv) percentages of clay, silt, and sand, according to the USDA classification.

Briefly, the BEST-method uses the van Genuchten (1980) model with the Burdine (1953) condition for the water retention curve (Equations 1 and 2), and the Brook and Corey (1964) model for hydraulic conductivity (Equations 3 and 4):

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

$$m = 1 - \frac{1}{n} \quad (2)$$

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

$$\eta = \frac{2}{m \cdot n} + 2 + p \quad (4)$$

where θ (L³L⁻³) is the volumetric soil water content, h (L) is the soil water pressure head, K (L T⁻¹) is the unsaturated soil hydraulic conductivity, n (> 2), m and (η) are shape parameters, p is a tortuosity parameter set equal to 1 following Burdine's (1953) condition, while h_g (L), θ_s (field saturated soil water content; L³L⁻³), θ_r (residual soil water content; L³L⁻³), and K_s (field saturated hydraulic conductivity; L T⁻¹) are scale parameters. In BEST, θ_r is assumed to be zero, while θ_s was calculated from r_b using the well-known relationship: $\theta_s = 1 - r_b / 2.65$. Shape parameters, which are texture-dependent, are estimated from particle-size analysis and soil bulk density measurement, assuming a shape similarity between the particle-size distribution and the water retention curve (Haverkamp et al., 2006).

The pedotransfer function by Minasny and McBratney (2007) was applied to estimate the shape parameters from mean values of clay, silt and sand percentages measured at each sampling site (Castellini et al., 2021c). BEST-steady algorithm (Bagarello et al., 2014) was adopted to analyze the field infiltration data. The scale parameter of the soil water retention curve, h_g is estimated by the equation:

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

where S (L T^{-1/2}) is the soil sorptivity and c_p is a coefficient dependent on n and m according to equation 6b by Lassabatere et al. (2006).

The soil water retention curve estimated by BEST-steady was used to calculate three soil physical quality indicators, namely, macroporosity, P_{mac} (cm³ cm⁻³), air capacity, AC (cm³ cm⁻³), plant available water capacity, $PAWC$ (cm³ cm⁻³) and relative field capacity, RFC (-):

$$P_{mac} = \theta_s - \theta_{10} \quad (6)$$

$$AC = \theta_s - \theta_{100} \quad (7)$$

$$PAWC = \theta_{100} - \theta_{15300} \quad (8)$$

$$RFC = \frac{\theta_{100}}{\theta_s} \quad (9)$$

where θ_{10} , θ_{100} and θ_{15300} represent the volumetric water content corresponding to $h = -10$, -100 and -15300 cm.

The impact of soil management on SPQ assessment was conducted on the basis of literature indications (Topp et al., 1997; Reynolds et al., 2002; Dexter, 2004; Reynolds et al., 2007; Reynolds et al., 2009), and SPQ values were classified as optimal when the average values for the considered indicators fell within the ranges, as reported in Table 1.

For each main variable considered in this investigation (Table 1), a given dataset was summarized by calculating the arithmetic mean and the associated coefficient of variation, and variables were assumed to be normally distributed, with the exception of K_s that was log-normally distributed, as commonly suggested in the literature (among others, Castellini et al., 2013).

Table 1: Optimal values of SPQ indicators considered in the investigation.

	units	Optimal values
r_b	g/cm ³	0.9 - 1.2
K_s	cm/d	81 - 204
P_{mac}	cm ³ /cm ³	0.04 - 0.10
AC	cm ³ /cm ³	0.14 - 0.26
$PAWC$	cm ³ /cm ³	0.15 - 0.20
RFC	-	0.6 - 0.7

The statistical significance of the SPQ indicators was tested by calculating the confidence intervals for the average values ($p = 0.95$) (Iovino et al., 2016). A given indicator was considered indicative of a very good, or very poor, quality when its confidence interval was completely inside, or outside, the range of optimal values (Table 1). When the calculated confidence interval included an extreme value of this range, the SPQ was classified good if the mean value of the considered indicator fell inside the optimal range and poor if it fell outside this range. By this approach, a different statistical confidence could be attributed to the mean values of

the selected indicators even if they were obtained by a relatively small number of replicate samples. A two tailed t -test was used to establish the statistical significance of the differences between two mean values at $p = 0.05$ (Iovino et al., 2016).

A flow chart of the procedural steps for SPQ estimation, from field measurements to data analysis and final judgment on the soil quality of compared soil management, is shown in Figure 1.

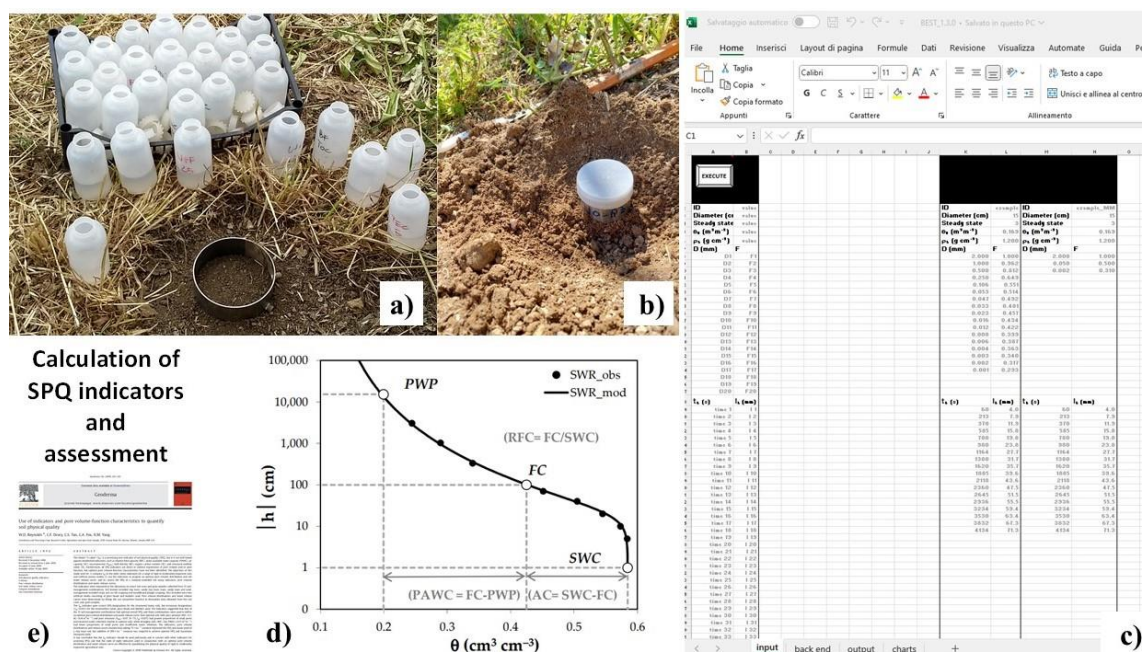


Figure 1: Flow chart of the procedural steps to estimate the SPQ: a) beerkan infiltration, b) soil sampling, c) run the BEST-steady algorithm, d) calculate soil indicators, e) evaluate the SPQ following the guidelines of literature.

3. RESULTS

Infiltration rate against cumulative infiltration, carried out from beerkan experiments under NT and CT, was reported in Figure 2. Overall, a decreasing trend between infiltration rate, i_r , and cumulative infiltration, I , was detected, in agreement with theory of the infiltration process (Castellini et al., 2021c). Some infiltration runs at the NT plot (Figure 2a), however, showed anomalous trends, as i_r was nearly constant from the

beginning of the run or it increased with I . Therefore, such infiltrations were not considered in the subsequent analysis to avoid development of a heterogeneous dataset, i.e., to include in the data analysis both consistent and inconsistent runs with the classical infiltration theory; moreover, since BEST-steady is expected to yield invalid results when the intercept of the straight line fitted to the last portion of the cumulative infiltration curve is null or negative (Castellini et al., 2021c), the reduction of the data set appeared necessary.

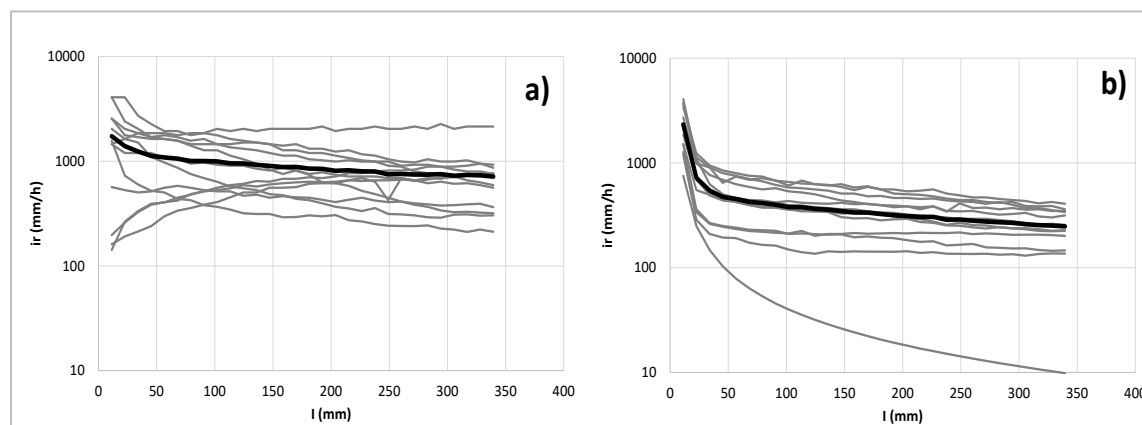


Figure 2: Infiltration rate vs cumulative infiltration (i_r vs I) carried out under no-tillage (a) and conventional tillage (b). Note that mean curves were represented with black lines.

Results of soil water retention curve obtained from BEST-steady were reported in Table 2 (i.e., model parameters) and the corresponding graphics were depicted in Figure 2. In general, saturated soil water content (θ_s) was lower under NT than CT (0.50 and 0.53 cm^3/cm^3 , respectively) as expected (Table 2). Relatively similar values were detected for the shape parameters of water retention curve (n , m and η), while higher discrepancies between soil management, NT vs CT, were detected in terms of scale parameter, since h_g changed between 185 and 118 mm as a mean (Table 2). Because the retention curves obtained under different soil management had different shapes, it is plausible that the SPQ indicators also highlight differences between NT and CT.

Mean values of soil bulk density were comparable between soil management, as r_b was equal to 1.26 and 1.24 g/cm^3 as a mean, respectively under NT and CT; accordingly, such differences were not statistically different according to a *t*-test. Similarly, the hydrodynamic differences between soils were also not dissimilar, as the saturated

hydraulic conductivity, K_s was not different from a statistical point of view (Table 3). Regarding the capacity-based indicators, macroporosity and plant available water were similar between soils, while air capacity and relative field capacity was different, as conventional tilled soil showed higher AC and lower RFC values (Table 3).

The SPQ assessment was overall poor or very poor, regardless of soil management, except for the macroporosity (P_{mac}) that always very good. Intermediate results were obtained for the remaining indicators (Table 3). Specifically, with reference to NT and CT, r_b , K_s and PAWC was very poor or poor, AC was very poor or good, while RFC was poor and good (Table 3). Therefore, the soil under study was generally with relatively low physical soil quality. However, the impact of soil management on SPQ was detected because, regardless on soil indicator considered, soil tillage generally improved the soil quality (only P_{mac} remained unchanged), with the judgment that increased from NT to CT (Table 3).

Table 2: Mean and associated coefficient of variation (CV) of BEST parameters for soil water retention curve determination under no-tillage (NT) and conventional tillage (CT) soil management.

		θ_s (cm^3/cm^3)	n (-)	m (-)	$ h_g $ (mm)	η (-)
NT	Mean	0.505	2.152	0.071	185	16.156
	CV	0.041	0.001	0.014	0.203	0.012
CT	Mean	0.533	2.149	0.069	118	16.448
	CV	0.067	0.002	0.026	0.414	0.023

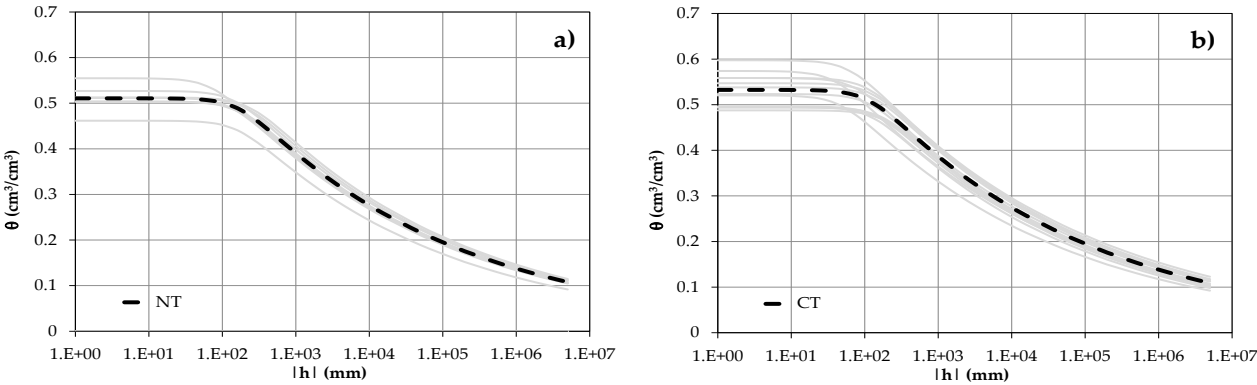


Figure 3: Soil water retention curve obtained under NT (a) and CT (b) soil management. Note that the average curve is highlighted in dashed lines.

Table 3: Mean (M) and associated coefficient of variation (CV) of SPQ indicators obtained under no-tillage (NT) and conventional tillage (CT) soil management.

	units	NT			CT			Optimal values	SPQ changes
		M	CV	SPQ	M	CV	SPQ		
r_b	g/cm^3	1.26	0.06	a - -	1.24	0.08	a -	0.9-1.2	Better
K_s	cm/d	0.029	0.51	a - -	0.020	0.35	a -	81-204	Better
P_{mac}	cm^3/cm^3	0.012	0.80	a + +	0.027	0.78	a + +	0.04-0.10	=
AC	cm^3/cm^3	0.123	0.19	a - -	0.151	0.21	b +	0.14-0.26	Better
PAWC	cm^3/cm^3	0.206	0.05	a - -	0.201	0.05	a -	0.15-0.20	Better
RFC	-	0.76	0.05	a -	0.72	0.06	b +	0.6-0.7	Better

4. DISCUSSION AND CONCLUSIONS

The impact of soil management on SPQ is an open topic to evaluate agro-environmental sustainability in the context of ongoing climate change (Qiao et al., 2022). However, SPQ determination is expensive, time consuming and there is a need to test new reliable and rapid soil property estimation procedures (Angulo-Jaramillo et al., 2019). In this investigation the BEST procedure was applied to quantify the impact of tillage on the SPQ of a marginal soil, i.e. a relatively coarse soil with relatively poor quality characteristics. Therefore, the work evaluated the SPQ improvements of freshly tilled soil as compared to a long-term undisturbed one. Except for macroporosity, the SPQ improved in all remaining cases, including bulk density, saturated hydraulic conductivity, air capacity, plant available water capacity and relative field capacity, suggesting that tillage has beneficial effects for degraded soils. The relative improvement was highlighted for soil density, hydrodynamic soil characteristics, as well as for the better capacity to retain water and air in an optimal ratio. For instance, the relative field capacity (RFC) improved (i.e., from NT to CT) by approaching the optimal value suggested for this indicator (i.e., 0.7), therefore, moving from a condition of relatively compacted soil towards a relatively better condition, since an almost optimal ratio between air and water into the soil for tilled soil was detected. RFC can be considered an indicator that summarizes the overall result obtained (Stellacci et al., 2021). A similar positive effect of soil tillage on SPQ detected by Iovino et al. (2016) for a marginal soil. They used both capacitive indicators, i.e. derived from the water retention curve, and

dynamic measurements, derived from tension infiltration experiments, to assess the soil physical quality of two agricultural areas of central Sicily, cropland and olive orchard, and two natural areas, grassland and managed woodlot plantation, potentially subject to soil degradation. The results showed that only the surface layer of the cropland site showed optimal SPQ while, both in the grassland and woodlot sites, SPQ was deteriorated also as a consequence of compaction because of grazing. They conclude that, in general, the physical quality was better in tilled than no-tilled soils.

From a methodological point of view, the soil quality determination corresponding to two different sampling points (for example, the comparison between two points from the same soil use or, alternatively, two points from two different soil uses) could provide inconsistent SPQ estimates, based on statistical significance or on the limits suggested in the literature for that given indicator. The data analysis methodology to estimate the soil quality applied by Iovino et al. (2016) and Castellini et al. (2014) allows a double evaluation and, therefore, obtaining a reliable and unambiguous assessment of SPQ. Consequently, it can be suggested as an alternative and relatively simple data analysis criterion, compared to the usual and more complex multivariate analyses.

The case study confirmed the real applicability of the BEST procedure for comparing the soil physical quality with the aim of evaluating the environmental sustainability of agro-environments in a relatively simple, easy and fast way. The studied soil, that was uncultivated for a long time, suggested a tendency towards physical degradation (unpublished data).

Consequently, it could be more prone to compaction and water erosion due to intense rainfall events (Castellini et al., 2021c). However, the results highlighted that a relative improvement was possible by means of surface soil tillage. The improvement of soil organic management, implementing for example organic amendments, can further improve the structure of the porous medium and increase its overall fertility.

A general recommendation from the case study suggests that an aprioristic soil quality assessment, i.e. only based on soil management, cannot be made, and ad-hoc (appropriately conceived) soil tillage may provide, in specific contexts, soil improvements when compared to undisturbed soil conditions. Therefore, further investigations on the physical quality of soils conventionally managed and/or soils suffering of various degrees of structural degradation are desirable in the future, both to further validate the adopted methodologies and to improve our knowledge on this topic.

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