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Journal:	*Soil Science Society of America Journal*
Manuscript ID	S-2015-12-0447-OR
Manuscript Type:	Papers on Original Research
Keywords:	Soil physical quality, Soil water retention

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ACKNOWLEDGMENTS

This work was carried out under the research project "Development of innovative models for multiscale monitoring of ecosystem services indicators in Mediterranean forests (MiMoSe)", funded by the FIRB 2012 program of the Italian Ministry of Education, University and Research (Grant: RBFR121TWX_004, Research Unit of the University of Palermo). The investigation was outlined by V. Bagarello, S. Cullotta, M. Iovino and F. Maetzke. The soil characteristics were mainly investigated by V. Bagarello, G. Baiamonte, M. Iovino and V. Palmeri and most of the experimental activity was carried out by this last author. The forest characteristics were mainly investigated by S. Cullotta, G. Gugliuzza, D.S. La Mela Veca, F. Maetzke and S. Sferlazza. All authors contributed to analyze the results and to write the paper.

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ABSTRACT

Soil physical quality (SPQ) can be assessed by different experimental methodologies and criteria and the optimal/critical values or ranges for SPQ indicators are still approximate. Sampling soils with minimal anthropic pressures should allow improvements in SPQ assessment. Different experimental methodologies and criteria were applied to sample a Mediterranean oak forest and pasture land, in Sicily, with a varying degree of anthropic disturbance. Soil water retention was determined in the laboratory and the field, using the BEST (Beerkan Estimation of Soil Transfer parameters) procedure of soil hydraulic characterization. Capacity based indicators, the *S* index, and location and shape parameters of the pore volume distribution function were calculated for assessing SPQ. With the laboratory data, only the criterion using the capacity based indicators suggested that SPQ increased as external pressures decreased. Therefore, this criterion appeared to be more reliable than the other tested criteria in the sampled environment. The field method was more prone to suggest good conditions and less able to signal differences between plots as compared with the laboratory method. A forest soil with a good SPQ has an ability to store and provide water to plant roots similar to, but it is more aerated than, a good agricultural soil. Developing BEST for SPQ assessment is advisable since parameters descriptive of the soil water transport properties, can be collected with a single experiment. Simultaneous characterization of dendrometric and soil parameters at other sites is recommended to explore the relationships between SPQ indicators and characteristics of the forest cover.

INTRODUCTION

Soil physical quality (SPQ) denotes a well-established concept, especially with reference to agricultural soils, since it refers primarily to the soil's strength and fluid transmission and storage characteristics in the root zone. An agricultural soil with a good physical quality is strong enough to maintain good structure and hold field crops upright but also weak enough to allow optimal proliferation of crop roots, soil flora and soil fauna (Reynolds et al., 2007). Soils with good physical quality also have the ability to store and transmit water, air, nutrients and agrochemicals in ways which promote both maximum crop performance and minimum environmental degradation (Topp et al., 1997). Assessment of SPQ may imply many measurements, i.e. organic matter content, dry bulk density, water retained at different pressure heads, hydraulic conductivity, aggregate stability (e.g., Reynolds et al., 2002, 2009; Dexter, 2004; Pulido Moncada et al., 2015b).

Many investigations on SPQ were carried out on agricultural soils because there is the need to establish what happens with different agronomic practices (e.g., Keller et al., 2007; Moebius et al., 2007; Reynolds et al., 2007; Fernández-Ugalde et al., 2009; Gląb et al., 2009; Chakraborty et al., 2010; Arthur et al., 2011; Bamberg et al., 2011; Li et al., 2011; Stavi and Lal, 2011; Iovino et al., 2013; Reynolds et al., 2014, 2015; Baiamonte et al., 2015). Moreover, guidelines of practical interest have been developed with specific reference to these soils (e.g., Reynolds et al., 2009), and this circumstance has stimulated SPQ assessment in agricultural environments notwithstanding that optimal/critical values or ranges for SPQ indicators are still approximate (Reynolds et al., 2007). However, SPQ has also been assessed under other land uses, including forest and pasture. In some cases, only these soils were sampled. For example, Agnese et al. (2011) established a SPQ comparison between these two land uses since forest and pasture soils can be expected to differ by their physical and hydraulic properties but these differences could not imply that SPQ is compromised in a particular plot. In other investigations, non-agricultural soils were considered in conjunction with agricultural soils. For example, both cropland soils and never cropped or cultivated virgin soil under native trees and grasses were sampled by Reynolds et al. (2009, 2014) since the latter soil was considered to provide a benchmark for comparison purposes. The optimal/critical values or ranges for SPQ indicators developed for agricultural soils were also used in non-agricultural environments. This choice is not free from some uncertainty. For example, using optimal values developed for agricultural soils could perhaps be considered sound for grazing plots since some form of external pressure due to anthropic activities occurs both in agricultural and pasture soils. However, these pressures are expected to be reduced in forest plots, and particularly in undisturbed forest stands. Therefore, there is the need to establish if optimal/critical values or ranges for SPQ indicators developed with reference to agricultural soils can also be used in other contexts. Developing the reasoning by Reynolds et al. (2009, 2014), a possible strategy is sampling forest/pasture plots characterized by different degrees of disturbance and attempting to establish if the usual approaches signal a deterioration of the SPQ with increasing levels of disturbance. These investigations may also allow improvements in the optimal/critical values or ranges for SPQ indicators.

Soil water retention is central in determination of SPQ and different criteria can be applied to treat water retention data. For example, SPQ can be assessed using capacity based indicators such as macroporosity, matrix porosity, air capacity, plant available water capacity, relative water capacity (e.g., Reynolds et al., 2002, 2007; Topp et al., 1997). Another approach is based on the so-called *S*-index by Dexter (2004), that represents the magnitude of the slope of the soil water desorption curve at the inflection point when the curve is expressed as gravimetric water content versus natural logarithm of pore water tension head. A more recent approach calculates several location and shape parameters of the pore volume distribution function, that is deduced from the water retention curve (Reynolds et al., 2009). In many investigations on SPQ assessment by soil water retention characteristics, a single criterion was applied. For example, capacity based indicators were exclusively used by Reynolds et al. (2002, 2007, 2014, 2015) and Agnese et al. (2001) whereas only the S theory was applied by Kutlu and Ersahin (2008) and Li et al. (2011). Both criteria were used in other investigations (Chakraborty et al., 2010; Arthur et al., 2011; Iovino et al., 2013; Gląb, 2014), and all the available criteria (capacity based indicators, S-index, pore volume distribution function) were used by Reynolds et al. (2009) and Pulido Moncada et al. (2015a). A dependence of the SPQ assessment on the applied criterion was suggested in these last investigations. Reynolds et al. (2009) concluded that a suite of eight indicators should be used in conjunction with an optimal pore volume distribution and water release curve for quantifying the physical quality of rigid to moderately expansive agricultural soils and Pulido Moncada et al. (2015a) also agreed that S cannot be used as a unique indicator. Clearly, these conclusions raise several issues, including the reasons why different approaches provide different results and what approach should be preferred in practice. Establishing comparisons among alternative criteria in different environments is necessary to improve SPQ assessment by water retention data.

These last data can be obtained with different experimental methods both in the laboratory and the field. In the laboratory, it is rather common to use the hanging water column apparatus (Burke et al., 1986) for high pressure heads, h, and the pressure plate apparatus (Dane and Hopmans, 2002) for low h values. Relatively simple methods can now be applied to obtain a complete soil hydraulic characterization in the field. In particular, Lassabatère et al. (2006) proposed to estimate the water retention and hydraulic conductivity curves with the Beerkan Estimation of Soil Transfer parameters (BEST) procedure, using an infiltration experiment with a zero pressure head on a circular soil surface and a few basic soil physical determinations (particle size distribution, PSD, bulk density, and initial and final water content). This procedure appears promising to simply yield a reasonably reliable soil hydraulic characterization but applying BEST in an uncalibrated form implies the possibility of a non-perfect correspondence between laboratory measured and field predicted water retention (Aiello et al., 2014; Bagarello et al., 2014b). In addition, the performances of the BEST water retention model depend on the soil textural characteristics (Bagarello and Iovino, 2012). Therefore it seems plausible to presume that SPQ assessment can also vary with the applied experimental methodology to determine soil water retention characteristics. However, little has been done with reference to the link between SPQ assessment and the applied methods for obtaining the soil water retention curve.

The general objective of this investigation was to compare different experimental methodologies and SPQ assessment criteria in a Mediterranean forest and pasture land. Soil physical and hydraulic properties were determined in a grazing plot and in an oak coppice stand where different structural features of the forest cover were generated by silvicultural felling practices at different times. The specific objectives were to: i) compare different criteria to assess SPQ on the basis of the laboratory measured soil water retention curve; and ii) testing the suitability of the BEST procedure of soil hydraulic characterization to reproduce a laboratory based SPQ assessment.

MATERIALS AND METHODS

Field site

The study site was located in Sicily, on the Madonie mountains, in a forest stand mainly composed by holms and pubescent oaks. The forest (A1, A2, A3, A4) and pasture (A5) sampling plots were located in the meso-mediterranen vegetation belt, at an altitude of about 1000 m a.s.l., with more than 1000 mm of precipitation per year. These sampling plots were established on north-eastern slopes. Forest plots were characterized by coppice stands in different dynamic stages (i.e. rotation-age) according to the past silvicultural felling-age. In particular, felling occurred in 2013 for plot A1, 2009 for plot A2, 1993 for plot A3 and 1973 for plot A4 (**Table 1**). **Fig. 1** shows the site and the location of each sampling plot.

Sampling and calculation of dendrometric and structural parameters

The survey of the sampling plots was carried out in 2014. For the characterization of the forest cover, the diameter at breast height (D_{bh}) > 3 cm and the tree height (H) were measured for all living trees present in each sampling plot. All shoots D_{bh} were measured on each stool. Using these basic data, the following structural characteristics were calculated for each sampling plot: stem density (shoots ha^{-1}) and stool density (stools ha^{-1}), mean tree diameter (D_m, in cm) and mean tree height (H_m, in m), basal area (G ha^{-1}) and frequency distribution of trees with respect to D_{bh} (5 cm classes) and H (5 m classes). The number of individuals in each size class for D_{bh} and H was calculated on the stand density of each plot (number of individuals per hectare). The total basal area (G in m^2) from all the shoots for each individual (stool) was calculated too. The whole shoot volume (V in m^3) was calculated using mathematical models developed for the Italian National Forest Inventory (MAF-ISAFA, 1985) and the Sicilian Regional Forest inventory (Hofmann et al., 2011).

Forest canopy cover, also known as canopy coverage or crown cover, is defined as the proportion of the forest floor covered by the vertical projection of the tree crowns (values from 0 to 100 %) (Jennings et al. 1999). This index can influence soil properties since tree crowns reduce kinetic energy of water by precipitation at ground level. Moreover, the forest crown cover was detected by using the Stand Visualization System (SVS) software (McGaughey, 1997) that generates graphic images depicting stand conditions, displaying overhead, profile and perspective views of a forest stand.

Soil sampling and calculation of soil hydraulic and physical parameters

Each plot was sampled in the months of May to July of 2014. For a given plot, 20 undisturbed soil cores (0.05 m in height by 0.05 m in diameter) were collected at the 0 to 0.05 m and 0.05 to 0.10 m depths in 10 randomly selected points. Ten disturbed soil samples (0-0.10 m depth) were also collected. The undisturbed soil cores were used for laboratory determination of the initial volumetric soil water content, θ_i (m^3m^{-3}), i.e. the soil water content at the time of sampling, and the dry soil bulk density, ρ_b (Mg m^{-3}). The disturbed soil was used to determine the particle size distribution (PSD) and the clay (*cl*), silt (*si*) and sand (*sa*) percentages according to the USDA standards (Gee and Bauder, 1986). The organic carbon, *OC* (%), content was measured by the Walkley-Black method on seven samples and it was converted to organic matter, *OM* (%), content using the factor of conversion of 1.72. The fraction of water stable aggregates, *WSA*, was determined by the wet aggregate stability test (Kemper, 1965; Kemper and Rosenau, 1986) on five samples according to the procedure by Baiamonte and Crescimanno (1999).

For each plot, 20 infiltration runs of the BEST (Lassabatère et al., 2006) type were carried out at randomly chosen sampling points using a ring with an inner diameter of 0.15 m, inserted to a depth of about 0.01 m to avoid lateral loss of the ponded water. A known volume of water (150 mL) was poured in the cylinder at the start of the measurement and the elapsed time during infiltration was measured. When the amount of water had completely infiltrated, an identical amount of water was poured into the cylinder, and the time needed for water to infiltrate was logged. Following Lassabatère et al. (2006), the procedure was repeated 15 times (total applied water volume = 2250 mL) to deduce an experimental cumulative infiltration, I (L), vs. time, t (L), relationship including the near steady-state phase. The BEST experiment was used to determine the parameters of the van Genuchten (1980) relationship for the water retention curve and the Brooks and Corey (1964) relationship for the hydraulic conductivity function:

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

$$m=1-\frac{k_m}{n} \qquad (1b)$$

$$\frac{K(\theta)}{K_s}=\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^\eta \qquad (2a)$$

$$\eta=\frac{2}{m\times n}+2+p \qquad (2b)$$

where θ (L^3L^{-3}) is the volumetric soil water content, h (L) is the soil water pressure head, K (L T^{-1}) is the soil hydraulic conductivity, n, m and η are shape parameters, k_m is a user index (Haverkamp et al., 2005), p is a tortuosity parameter, and h_g (L), representing the inflection point of the water retention curve, θ_s (L^3L^{-3}, field-saturated soil water content), θ_r (L^3L^{-3}, residual soil water content) and K_s (L T^{-1}, field-saturated soil hydraulic conductivity) are scale parameters. In BEST, θ_r is assumed to be zero and the Burdine's (1953) model is considered for the water retention curve, meaning that $k_m = 2$, $n > 2$ and $p = 1$. In the following, eq.(1) with $\theta_r = 0$ and $m = 1-2/n$ was denoted as the vGB (B = Burdine) model. The h_g scale parameter is determined by the K_s and soil sorptivity, S (L $T^{-0.5}$), estimates obtained from the measured infiltration process (Lassabatère et al., 2006). The Beerkan infiltration run was analyzed by the BEST-steady algorithm (Bagarello et al., 2014a) since it is simple to be applied and also because it was expected to yield a higher success percentage of the infiltration runs, implying more experimental information, as compared with other possible algorithms. In particular, Di Prima et al. (2015) showed that the BEST-slope (Lassabatère et al., 2006) and BEST-intercept (Yilmaz et al., 2010) algorithms can fail more frequently than

BEST-steady. Following Mubarak et al. (2009), BEST was applied by assuming $\theta_s = \phi$ since this choice allowed us to simplify experimental procedures, also taking into account that access to the sampling plots was rather difficult and only possible by feet. The BEST experiment at a given sampling point was considered successful when it allowed a complete soil hydraulic characterization for that sampling point (Lassabatère et al., 2006). Soil physical quality (SPQ) indicators were calculated from each estimated soil water retention curve. In particular, air capacity, AC (m^3m^{-3}), plant available water capacity, $PAWC$ (m^3m^{-3}), relative field capacity, RFC (-), and macroporosity, P_{MAC} (m^3m^{-3}), were calculated using eqs.(1) to (4) by Reynolds et al. (2009). **Table 2** summarizes the meaning of each indicator considered in this investigation and also lists suggested criteria to evaluate SPQ. Saturated hydraulic conductivity of matrix pores, K_m ($L\ T^{-1}$), was also estimated using eqs.(1) and (2) since it represents another SPQ parameter according to Topp et al. (1997), in addition to K_s. In particular, K_m was set equal to $K(h = -0.1$ m) since the corresponding soil water content represents the saturated volumetric water content of the soil matrix (Reynolds et al., 2009).

Water retention was also measured in the laboratory. Water retained at high pressure heads ($h \geq -1.5$ m) was determined on 10 replicated soil cores randomly collected from the surface soil layer, after removing the visible litter and other organic matter, in stainless steel cylinders (inner diameter = 0.08 m, height = 0.05 m). For low pressure heads ($h \leq -3$ m), 10 replicated samples, obtained by packing sieved soil in rings having an inside diameter of 0.05 m and a height of 0.01 m to the mean ρ_b value of the undisturbed cores, were used. The experimental methodologies described in detail by Bagarello and Iovino (2012) were also applied in this investigation to obtain volumetric water retention data for h values of -0.05, -0.1, -0.2, -0.4, -0.7, -1.0, -1.2, -3.37, -10.2, -30.6 and -153.0 m. For each sampling location, eq.(1) was fitted to the data to determine the unknown parameters. The fitting was performed by an iterative nonlinear regression procedure, which finds the values of the optimised parameters by minimizing the sum of squared residuals between the model and the data. This procedure was applied using the SOLVER routine of Microsoft Excel software (Microsoft Company, Redmond, WA, USA). The fitting performance of the theoretical model to the measured water retention data was evaluated for a given sampling point by calculating the sum of the squared residuals, SSR. Both the van Genuchten-Mualem (vGM) formulation, with an optimized θ_r (i.e., not forced to be equal to zero) and $k_m = 1$ in eq.(1b), and the vGB models were fitted to the data. The AC, $PAWC$, RFC and P_{MAC} indicators were calculated by using the parameters for both the vGM and vGB models fitted to the laboratory water retention data. Moreover, the pore volume distribution function was characterized according to Reynolds et al. (2009). In particular, the median, d_{median} (L), modal, d_{mode} (L) and mean, d_{mean} (L) location parameters and the standard deviation, SD, skewness, SK, and kurtosis, KU, shape parameters were calculated using the fitted vGM model and eqs.(14) to (19) by Reynolds et al. (2009). Finally, eqs.(7a) and (9a) by these last Authors were used to calculate the S SPQ index by Dexter (2004).

Data analysis

For each variable considered in this investigation (cl, si, sa, ρ_b, OM, WSA, AC, $PAWC$, RFC, P_{MAC}, d_{median}, d_{mode}, d_{mean}, SD, SK, KU, S, θ_i, K_s, K_m), a given dataset was summarized by calculating the mean, M, and the associated coefficient of variation, CV. Arithmetic means were generally calculated since characterization of an area of interest for SPQ assessment is generally based on arithmetic averages of individual determinations (Reynolds et al., 2009; Pulido Moncada et al., 2015a). Geometric means were calculated for K_s and K_m since a log-normal distribution generally describes hydraulic conductivity of saturated and near-saturated soil better than a normal distribution (Lee et al., 1985; Mohanty et al., 1994). For comparing mean values, untransformed and ln-transformed data were used for the normally and the ln-normally distributed variables, respectively.

Initially, the five plotas were compared with reference to the basic soil properties (*cl*, *si*, *sa*, ρ_b, *OM*, *WSA*) using the Tukey Honestly Significant Difference (THSD) test at $P = 0.05$. A preliminary SPQ assessment of each plot was carried out by considering ρ_b and *OM*, that represent commonly used SPQ indicators, using the available evaluation criteria (**Table 2**).

The impact of using different approaches to assess SPQ on the basis of the laboratory measured water retention was tested. The capacity based indicators (*AC*, *PAWC*, *RFC*, P_{MAC}), the pore-volume function characteristics (d_{median}, d_{mode}, d_{mean}, *SD*, *SK*, *KU*) and the *S* index by Dexter (2004) were considered. For each indicator, the THSD test was applied to statistically compare the five sampling plots and a SPQ assessment was made with each approach. This comparison was made to check consistency between alternative approaches, that could not occur (Reynolds et al., 2009; Pulido Moncada et al., 2015a). Developing this topic is important to reduce the risk to make an erroneous assessment of SPQ at a site of interest due to a possible weakness of the applied approach.

To better understand the performances of the applied approaches, the relationships between different laboratory determined SPQ indicators were examined. In particular, the relationship between *S* and d_{median}, d_{mode} and d_{mean} was established to see if *S* increased, as expected, with the characteristic pore sizes. The relationship between *S* and ρ_b was also tested because de Jong van Lier (2014) recently suggested that, as a relative indicator of SPQ, *S* does not have additional value over bulk density or total porosity. The relationship between *AC* and *RFC* was finally investigated since both these indicators depend on the same variables, i.e. θ_s and θ at $h = -1$ m ($\theta_{-1\text{m}}$). Therefore, it was advisable to establish if, for a given θ_s and $\theta_{-1\text{m}}$ data pair, the SPQ was consistently good (or poor) according to both indicators.

A comparison of the SPQ indicators obtained by BEST (K_s, K_m, *AC*, *PAWC*, *RFC*, P_{MAC}) in the five sampled plots was carried out with the THSD test and the SPQ was also assessed on the basis of the field data.

A comparison between the laboratory and the field assessment of SPQ was then made to check if a similarity between the two experimental methodologies was detectable. The comparison was focused on water retention, since it was obtained with both methodologies. An F test and a two-tailed t test ($P = 0.05$) were used to compare the two estimates (laboratory, field) of a given capacity based indicator (*AC*, *PAWC*, *RFC*, P_{MAC}) for each plot. Taking into account that BEST assumes the vGB model, the indicators calculated by fitting this model to the laboratory water retention data were also considered to establish a field vs. laboratory comparison. Consequently, the relative ability of the vGB and vGM formulations of the van Genuchten (1980) model to fit the laboratory water retention data was tested by establishing comparisons between these two formulations in terms of both *SSR* and error of the θ predictions. Linear regression analysis procedures were then used to compare the two estimates of the *AC*, *PAWC*, *RFC* and P_{MAC} indicators.

RESULTS AND DISCUSSION

Main dendrometric and structural aspects

The mean values of all measured and derived stand attributes were reported in **Table 3** for each forest plot. Moving from plot A1 to plot A4, the complexity and closure of the forest stands increased. The increase of most of the dendrometric and structural parameters was due to the age of stems (shoots) from the last coppice felling (**Table 1**). For example, the crown cover index showed a progressive increase from 34% in plot A1 to 97% for plot A4.

Similarly, the basal area (*G*) and the volume (*V*) of all shoots and standards increased moving from A1 to A4 sampling plots (**Table 3**).

Vice versa, parameters regarding the density of stools and shoots decreased from A1 to A4 plots, due to the normal plant competition for space and light through time, from the younger and smaller shoots (A1) to the older and larger ones (A4).

Fig.2 clearly shows the dendrometric differences and structural aspects among the sampling plot by the frequency distribution of shoots with respect to diameter at brest hight (D_{BH}). In an overview, the recently cut A1 (in 2013) and A2 (2009) plots showed similar figures, with a lot of new shoots in the smaller diameter class and few standards and trees in the greater ones. The other two sampling plots, A3 and A4, are characterized by a typical bell-shaped frequency distribution of a mature coppice with a progressive reduction of total shoots density.

Basic soil properties

The forest plots A1 to A4 were established at a small distance from each other, i.e. by not more than 600 m, suggesting a pedological uniformity of the site, and they had relatively similar mean steepness values, varying from 48% (A4) to 59% (A3) (**Table 4**). Therefore, land cover characteristics represented the main factor of difference among these plots. Plots A3 and A4 did not differ significantly by any basic soil property (**Table 4**), suggesting that possible soil alteration effects due to tree cutting did not last for more than 20 years.

An effect of tree cutting was detectable by comparing the most natural plots (A3 and A4) with those more recently disturbed (A1 and A2). The soil at these last plots was denser, poorer in organic matter and with less water stable aggregates than the former plots, but tree cutting effects on ρ_b, *OM* and *WSA* were statistically negligible. On the other hand, the plot disturbed six years ago (A2) had significantly more sand and less clay than the most natural plots (A3 and A4) and a similar result was also detected with reference to the more recently disturbed plot (A1), although in this last case differences were smaller and not significant. Taking into account the closeness of the four plots to one another and particularly of plots A1 and A3 (**Fig.1**), soil textural differences likely represented a consequence of tree cutting. Soil of plot A2 remained exposed for the longest time to the direct action of rainfall and it was also affected by some loss or weakening of stabilizing agents since re-establishment of a vegetative soil cover was rapid but not immediate (i.e., a couple of years). Therefore, soil erosion phenomena were particularly favored in this plot (e.g., Dissmeyer and Foster, 1981) and probably they determined removal of fine and easily transportable soil particles. The data collected in the plot A1 were consistent with this interpretation since they suggested that these phenomena started to occur soon after tree cutting.

The pasture plot A5 was established in a flatter zone (slope steepness = 27%, **Table 4**) than the forest plots. Therefore, pasture and forest plots were compared to establish if the documented land use effects on soil characteristics (e.g., Archer et al., 2013; Hassler et al., 2011) remained detectable in relatively heterogeneous conditions, i.e. in neighboring areas that did not differ exclusively by land use. This comparison has practical interest since morphological heterogeneity is the rule rather than the exception in natural environments (e.g., Germer et al., 2010).

Soil of plot A5 had more clay and silt, less sand and it was more compacted as compared with soil of the forest plots (**Table 4**). Moreover, the pasture soil had less organic matter than the soil of the most undisturbed forest plots (A3 and A4) but a similar fraction of water stable aggregates as compared with the other plots. The higher content in fine particles could be due to pedological differences, taking into account that plot A5 was relatively far from the other areas (i.e. approximately 600 m from plot A4 and 1200 m from plots A1-A3, **Fig.1**). However, the differences between the pasture and the forest plots could also be a consequence of the erosion processes at the sampled site. In plot A5, runoff rates were expected to be relatively low due to the relatively small steepness, and this circumstance likely promoted some deposition of the fine sediments eroded in the steeper areas. Even the differences between organic matter and compaction levels were likely due to differences in land use. For example, a decrease in organic matter content was a plausible implication of the absence of litter and, therefore, a reduced biomass accumulation. Moreover, ρ_b is expected to increase in the passage from clay to sandy soils (Hillel, 1998) but, at the sampled site, the highest ρ_b values were measured on the soil with the highest *cl* content and the lowest *sa* content. This circumstance induced us to exclude an exclusively textural interpretation of the detected differences for ρ_b that instead were consistent with the documented effect of deforestation, pasture installation and cattle trampling, determining soil compaction and hence increase in bulk density (e.g., Chauvel et al., 1991; Martinez and Zinck, 2004; Germer et al., 2010). Therefore, this investigation suggested that land use effects on basic soil properties were also detectable in a relatively heterogeneous condition.

In general, the five plots had a poor SPQ according to the existing criteria since they were too rich in organic matter and had too small ρ_b values (**Table 5**), with the only exception of soils of plots A1 and A5 having an optimal soil bulk density. Taking into account that these two plots also had an *OC* content only slightly higher than 6% (6.3-7.7%), this preliminary analysis suggested that the soil characteristics at the sampled site approached those of a good agricultural soil (Reynolds et al., 2009) when some form of anthropic pressure occurred.

Determining soil physical quality by laboratory measurement of water retention

Soil physical quality indicators

A soil sample collected in the plot A2 was excluded from the analysis since a large stone was found to be embedded in the soil volume after measuring water retention at high pressure heads. Therefore, a total of 49 experimentally determined water retention curves were considered in this analysis.

Statistically similar results were obtained in the four forest plots for AC, $PAWC$, RFC and P_{MAC}, suggesting a similar SPQ (**Table 6**). The pasture plot also had a $PAWC$ value similar to those of the forest plots. However, lower AC and P_{MAC} values and higher RFC values were detected for plot A5 as compared with one or more forest plots. Differences were particularly clear, i.e. they were detected for the three indicators, with reference to the A4 vs. A5 plots comparison. Therefore, soil's ability to store and provide water to plant roots did not vary at the sampled site regardless of any factor of difference (land use, slope steepness) but soil of the most undisturbed forest plots was better than soil of the pasture plot due to the improved root zone aeration and soil's ability to quickly drain excess water and facilitate root proliferation. Even this result supported the conclusion that, at the sampled site, the expected land use effects (Archer et al., 2013; Hassler et al., 2011) remained detectable in relatively heterogeneous morphological conditions.

Even with the location and shape parameters approach, statistically similar results were generally obtained for the four forest plots with the only exception of a d_{median} value greater for plot A4 than plot A2 (**Table 6**). Two of the six considered indicators (d_{mode} and SD) also indicated a statistical similarity between the forest and the pasture plots. However, the other four indicators (d_{median}, d_{mean}, SK, KU) consistently suggested differences between the pasture plot and one to three forest plots. In particular, soil of plot A5 had smaller pores, a larger excess of small pores relative to a lognormal distribution and a less leptokurtic distribution (Reynolds et al., 2009) as compared with soil of the most natural forest plots (A3, A4).

The *S* index values were similar in the four forest plots, and a smaller *S* was obtained for the A5 plot as compared with the most natural A3 and A4 plots (**Table 6**).

Therefore, the three tested approaches yielded a similar information, i.e. a similarity of the considered indicators for the four forest plots and a difference between the pasture and the forest plots. This result, that leaves optimal values or ranges out of consideration, suggested a similarity of the three approaches in terms of their ability to distinguish between different conditions. Consequently, the choice of the approach to be applied for discrimination purposes could be based on the specific information of interest. For example, capacity based indicators could be used if two soils have to be compared in terms of their ability to store water and air (e.g., soil X has the same plant available water capacity but a larger macroporosity as compared with soil Y). Location and shape parameters could be preferred if the intention is to describe the soil pore system (e.g., larger pores and a wider range in pore diameters occurs in soil X than in soil Y). Finally, the *S* index appears usable to discriminate synthetically between two areas (e.g., soil X better/poorer than soil Y).

<u>*Soil physical quality assessment*</u>

The capacity based indicators (AC, $PAWC$, RFC, P_{MAC}) suggested in general a satisfactory SPQ at the sampled site since ideal, good or intermediate (in other words, not definitely poor) conditions were detected in 15 of the 20 cases (four indicators × five sampled plotas; **Table 5**). The best SPQ was detected in the A1, A2 and A4 forest plots in which the conditions were good/ideal/optimal for three of the four considered indicators. SPQ was slightly poorer in the forest plot A3, since *RFC* denoted water limited conditions and macroporosity was intermediate. The pasture plot had the worse SPQ since three indicators denoted poor conditions. A completely different assessment of the SPQ was made with the location and shape parameters since, in this case, the SPQ was generally non-optimal (**Table 5**). The most natural plot A4 had the poorest SPQ whereas the best conditions among the five plots were recognized for the pasture plot A5. Finally, the *S* index by Dexter (2004) suggested a very good SPQ for all sampled plots (**Table 5**).

Reasonably, soil at the sampled site was not heavily disturbed, particularly in the most natural forest plots where anthropic pressures were absent or minimal. In the more recently cut forest plots and in the pasture plot, some soil disturbance certainly occurred but presumably it was not very noticeable since cutting was performed only once and in a short time, and the presence of many pasture zones in the sampled environment suggested a limited pressure by livestock specifically in plot A5. Consequently, a good or at least a satisfactory SPQ was generally expected together with a better quality in the most natural forest plots than the pasture and the cut forest plots, considering that virgin soils should provide benchmarks for comparison purposes (Reynolds et al., 2009, 2014). According to this reasoning, the location and shape parameters criterion was the worst criterion since the SPQ was poor in general and better where external pressures were more noticeable. The performance of the *S* index criterion was satisfactory only in part, because the SPQ was always very good, but without any distinction between the plots. An inability of the *S* index criterion to distinguish between areas in terms of their SPQ was also detected in a recent investigation by Pulido Moncada et al. (2015b). The best approach to assess SPQ at the sampled site appeared to be that making use of the capacity based indicators since it suggested a satisfactory SPQ in general and better conditions in zones where anthropic and livestock pressures were minimal.

Taking into account that the currently available optimal values or ranges of the considered SPQ indicators were developed with particular reference to agricultural soils (Reynolds et al., 2009), this analysis should be viewed as no more than an attempt to establish if the five sampled soils had a physical quality similar to that expected in a physically good agricultural soil. Data on other forest soils should probably be collected to develop specific

SPQ assessment criteria for these soils. According to this investigation, the *PAWC*, *AC* and P_{MAC} evaluation criteria reported in **Table 2** seem to be usable for both agricultural and forest soils. In comparison with a good agricultural soil, a good forest soil has a larger ability to store air relative to the soil's total pore volume (i.e., lower optimal *RFC* values) and it also has a lower bulk density and a higher organic matter content. Attempting to further develop this reasoning, it could also be noted that, although $AC \geq 0.14$ m^{3}m^{-3} denotes good SPQ conditions (**Table 2**), *AC* values of 0.26-0.37 m^{3}m^{-3} were considered too high by Reynolds et al. (2002). Therefore, it could also be suggested that more root zone aeration (i.e., a higher *AC* value) should be expected in a good forest soil than in a good agricultural soil.

Relationships between soil physical quality indicators

The inconsistency between the SPQ assessment carried out with the *S* and the location and shape parameters criteria mainly occurred because large values of *S* denote a large presence of large structural pores (microcracks, cracks, biopores and other macrostructures; Dexter, 2004) but too much large pores denote poor conditions according to Reynolds et al. (2009). This situation is illustrated in **Fig.3** showing, for the 49 soil samples of this investigation, that *S* clearly increased with both d_{median} and d_{mean} (less with d_{mode} since an R^2 value of 0.09 was obtained in this last case). Therefore, large pore sizes denoted good conditions according to Dexter (2004) and poor conditions according to Reynolds et al. (2009).

The *S* index decreased with ρ_b according to a statistically significant exponential relationship (R^2 = 0.82; **Fig.4**). This result was seemingly in line with the suggestion by de Jong van Lier (2014) that, as a relative indicator of SPQ, *S* has no additional value over ρ_b. An implication of this suggestion is that the latter parameter could replace *S* in SPQ investigations, with obvious experimental advantages. However, a monotonic relationship between *S* and ρ_b indicates an inconsistency in the use of these two indicators for SPQ assessment on the basis of the currently applied assessment criteria (**Table 2**). According to Dexter (2004) and Dexter and Czyz (2007), SPQ improves as S increases. In this investigation, however, high S values were associated with low ρ_b values, lower than those defining the optimal range of soil bulk densities for SPQ assessment (Reynolds et al., 2009). Therefore, a very good SPQ according to the S index was associated with a poor SPQ according to the measured ρ_b. In other terms, S could maybe be replaced by ρ_b but the point is that the two indicators give a contrasting information on SPQ.

The RFC and AC indicators were strongly correlated to one another (**Fig.5a**) which was plausible given that both indicators were expressive of the difference between θ_s and $\theta_{-1\text{m}}$. Therefore, at least one of the two indicators could be considered practically superfluous in SPQ assessment notwithstanding that they have a different physical meaning (**Table 2**). In addition, the suggested criteria to discriminate between good ($AC \geq 0.14$ m^{3}m^{-3}; $0.6 \leq RFC \leq 0.7$) and poor conditions were not fully consistent. In particular, it was noted that an RFC value varying between 0.6 and 0.7 implied an AC value that did not increase indefinitely (**Fig.5b**). Moreover, the range of AC values yielding optimal values of RFC varied with θ_s (e.g., 0.11-0.14 m^{3}m^{-3} for θ_s = 0.36 m^{3}m^{-3} and 0.14-0.18 m^{3}m^{-3} for θ_s = 0.46 m^{3}m^{-3}). Fixing an upper limit for AC could be reasonable since it is not very realistic to presume that the SPQ increases indefinitely with soil aeration.

All criteria should simultaneously be applied to assess physical quality in the environments sampled by Reynolds et al. (2009) but, according to this investigation, simultaneous use of all criteria may yield hardly interpretable results in forest and pasture soils. A SPQ assessment varying with the applied approach (capacity based indicators, location and shape parameters, S index) and the relationships between SPQ indicators detected in this investigation suggested that physical quality assessment of forest and pasture soils by criteria essentially developed for other land uses should be considered with a certain caution and there is the need to improve these criteria. Presumably, the focus should be put on the capacity based indicators because each indicator has a clear meaning with respect to soil functions, that can easily be understood by practitioners and farmers. Other reasons are the encouraging performance of these indicators in forest and pasture soils, the possibility to reduce the number of the considered indicators and/or that to modify optimal ranges to improve consistency between different indicators.

Determining soil physical quality by hydraulic parameters obtained in the field

Soil physical quality indicators

The mean soil water content at the time of the beerkan infiltration experiment, θ_i, varied between 0.134 and 0.265 m^3m^{-3} and the soil was significantly wetter in the plot A4 than in the other plots (**Table 7**). The ratio between the means of θ_i and the corresponding porosity estimated from the dry soil bulk density measurements (**Table 4**) varied from 0.24 (plot A5) to 0.38 (plot A4). Particularly for this plot, the ratio was higher than the suggested upper limit of θ_i/θ_s for an accurate application of the BEST procedure ($\theta_i/\theta_s \leq 0.25$; Lassabatère et al., 2006). However, more recent findings indicated that BEST can be applied in initially wetter soil conditions ($\theta_i > 0.25\times\theta_s$) without an appreciable loss of accuracy in the predictions (Di Prima et al., 2015). Therefore, the initial soil water content was not considered to affect the reliability of the predicted soil hydraulic parameters.

BEST-steady yielded successful results, i.e. a complete soil hydraulic characterization, at 12 to 20 sampling points for a given plot (success rate percentages ranging from 60 to 100%; **Table 7**). Failure of the soil characterization procedure at some locations occurred when the cumulative infiltration curve did not show the expected concavity, that is necessary to obtain positive estimates of both steady-state infiltration rate and intercept of the steady-state expansion of cumulative infiltration and hence meaningful estimates of the soil hydraulic parameters (Bagarello et al., 2014a). Soil water repellency is known to be a phenomenon that could explain patterns in infiltration rates that are not explained by the traditional theory (e.g., Lassabatère et al., 2012). Probably, soil hydrophobicity affected the results of this investigation since more organic matter in the soil implies more probability of water repellency (e.g., Jarvis et al., 2008) and a relatively strong inverse relationship was detected between the success rate percentages and the soil organic matter content (coefficient of determination, R^2 close to 0.8). An *OM* content not exceeding 11% did not cause failure in the BEST-steady procedure. In any case, the lowest number of successful data for a plot was large enough to obtain a reliable soil hydraulic characterization according to existing guidelines (Reynolds et al., 2002).

The saturated soil hydraulic conductivity was significantly higher in the most natural forest plots (A3 and A4) than the disturbed forest plots (A1 and A2), and the pasture plot (A5) yielded intermediate K_s values between these two extremes (**Table 7**). Therefore, soil disturbance due to pasture or cutting trees determined a decrease of the mean conductivity by a factor that was not too high, since it did not exceed 4.4 and considering that higher factors of difference (i.e., 5.9-10.0) were reported for other forest vs. pasture comparisons (e.g., Zimmermann et al., 2006; Hassler et al., 2011). This investigation was in line with the conclusion by these last Authors that recover of K_s from pasture up to pre-pasture levels is a slow process (more than eight years) since plots where trees were cut 6-7 years before soil sampling had lower conductivities than the most undisturbed plots. The means of K_s calculated for each plot were better correlated with variables expressive of soil structure (ρ_b, *OM*, *WSA*; $0.28 \leq R^2 \leq 0.73$) than with textural variables (*cl*, *si*, *sa*; $0.002 \leq R^2 \leq 0.16$) and the single statistically significant relationship suggested an increase of K_s with *OM*. This result was plausible and it suggested reliability of BEST predictions since K_s is known to be related to soil structure (Lassabatère et al., 2006) and other Authors have reported that *OM* should be expected to be positively correlated with K_s (Rawls et al., 2005).

The saturated hydraulic conductivity of the matrix pores did not differ among the sampled plots (**Table 7**). In part, this similarity was due to the very high variability of the individual data, inducing some skepticism in the representativeness of the means. In any case, K_m did not differ very much at the sampled site, since the maximum factor of difference between two plots was equal to 3.6. The difference, K_p (L T^{-1}), between K_s and K_m, i.e. the macropore saturated hydraulic conductivity (Watson and Luxmore, 1986; Timlin et al., 1994) is expected to be one to four orders of magnitude greater than K_m (Beven and Germann, 1982; Topp et al., 1997). In this investigation, the K_p values calculated from the means of K_s and K_m were 16 to 162 times higher than the corresponding values of K_m, i.e. they were in line with the literature suggestions. The highest K_p/K_m ratios ($\geq$ 136) were detected in the A3 and A4 plots and this ratio did not exceed 68 in the other plots. This result suggested that macropore flow should be expected to be particularly noticeable in the most natural plots. Soil disturbance due to tree cutting or trampling by livestock determines a decrease of macropore flow but it has a lower impact on matrix flow. This result was consistent with the recent finding by Niemeyer et al. (2014) that a forest soil had eight times more preferential flow paths than a pasture soil.

Statistically similar results were obtained in the four forest plots for *AC*, *PAWC*, *RFC* and P_{MAC} (**Table 7**). The pasture area had *RFC* and P_{MAC} values similar to those of the forest plots. However, lower *AC* and *PAWC* values were detected for plot A5 as compared with one or two forest plots.

Soil physical quality assessment

The saturated soil hydraulic conductivity and the capacity based indicators obtained with BEST suggested in general a satisfactory SPQ at the sampled site since ideal, good or intermediate conditions were detected in 22 of the 25 cases (five indicators × five sampled plots, **Table 5**; 18 cases out of 20 by only considering the four capacity based indicators). Signs of poor conditions were only detected in the forest plots A2 and A4 (water limited conditions) and in another forest plot (A3, too high K_s values).

Comparing laboratory and field experimental methodologies

The assessment of SPQ made with the capacity based indicators revealed a similarity between the laboratory and the field methodologies since the SPQ at the sampled site was satisfactory in both cases. This result was encouraging from a practical point of view since the BEST procedure, being experimentally simpler and faster than laboratory measurement of soil water retention, can be applied to intensively sample an area of interest.

However, an important difference was that, contrary to the laboratory data, the field methodology did not suggest any appreciable difference in SPQ between the forest and the pasture plots. The judgment was the same with the two experimental methodologies (e.g., good in both cases) for nine of the 20 established comparisons (45% of the total, **Table 5**). Assuming a conceptual similarity between good and ideal with reference to $PAWC$ and between optimal and intermediate for P_{MAC}, since the SPQ was non-poor in both cases, a similar judgment was made in 15 cases. According to a two-tailed t test ($P = 0.05$), the laboratory and the field measured values of a given indicator at a sampled plot were not statistically different in 12 cases (60% of the total). The similarities were clearer in the forest plots (not significant differences for 12 out of 16 comparisons) than in the pasture plot (significant differences for all comparisons). Therefore, the laboratory and field approaches did not yield a perfectly equivalent information. In particular, the field method was more prone to suggest good conditions and less able to signal differences between plots as compared with the laboratory method.

The discrepancy between the two approaches was not surprising. In this investigation, BEST was applied in the simplest possible way, i.e. by setting θ_s = porosity and using standard values of the constants β and γ of the infiltration model, i.e. 0.6 and 0.75, respectively (Lassabatere et al., 2006). This choice was made taking into account that investigations on SPQ typically have a territorial character, implying the need to apply as much as possible simple experimental and analytical protocols to extensively sample soils. However, other recent investigations have suggested that a satisfactory correspondence between the laboratory and the field determined soil water retention values, that represent the starting point of the capacity based indicators calculations, needs an adaption of the BEST procedures such as the use of soil dependent constants of the infiltration model, shape parameters of the hydraulic characteristic curves estimated by the clay and sand percentages, and a more appropriate estimate of the field saturated soil water content (Gonzalez-Sosa et al., 2010; Nasta et al., 2012; Aiello et al., 2014; Bagarello et al., 2014b). Improvements in the BEST procedures that do not complicate soil hydraulic characterization appear possible such as, for example, an estimate of β and γ based on the measured soil particle size distribution, that is already an input in the currently applied procedure. These improvements can be expected to contribute to a more reliable SPQ assessment. As a matter of fact, performing an infiltration run in the field is generally simple and rapid which implies that many replicated runs can easily be carried out to characterize an area of interest. Another obvious reason of interest for the field procedure is that more SPQ indicators can be collected with BEST than with the laboratory measurement of the soil water retention curve since hydrodynamic parameters are only obtained in the former case.

With the capacity based indicators obtained by fitting the vGB model to the laboratory data, a statistical similarity between the laboratory and the field methodologies was detected in 9 cases out of 20 (i.e., less than the 12 cases for the standard procedure making use of the vGM model). Therefore, using a common water retention model reduced the similarities between the two experimental methodologies.

Higher *SSR* values were obtained with the vGB model than the vGM model in the 86% of the cases (**Fig.6a**) and the *SSR*(vGB)/*SSR*(vGM) ratio varied between 0.72 and 6.27, with a mean of 2.17 (median = 1.61) and a *CV* = 92.2%. The relative prediction errors, *RE*, varied from -32.3 to 23.2% for the vGB model and from -16.0 to 23.0% for the vGM model. In both cases, the highest absolute values of *RE* were associated with the smallest measured values of θ and they decreased, approaching nearly zero, as the measured soil water content increased (**Fig.6b**). With the vGB model, the absolute *RE* did not exceed 5% and 10% in the 75.3% and 89.4% of the cases, respectively. With the vGM model, these percentages increased to 85.2% and 97.2%, respectively. Similar results were obtained in other tests of the vGB model by Aiello et al. (2014) and Bagarello and Iovino (2012). Therefore, the vGM model reproduced the measured retention data better than the vGB model, probably as a consequence of the larger number of optimized parameters (four instead of three) and the lack of the constraint on θ_r for the vGM model. In particular, this last model allowed to reduce the risk to underestimate low values of θ, which instead was a more frequent occurrence with the vGB model (**Fig.6b**).

This investigation supported the conclusions by Haverkamp et al. (2005) that the van Genuchten (1980) equation provides a relatively poor description of retention data for dry conditions and that using more parameters in the optimization may improve data description by eq.(1). With reference to this last point, an optimized value of $\theta_r = 0$ was obtained with the vGM model in 15 of the 49 cases and, on average ($N = 49$), θ_r was equal to 0.068 m^3m^{-3} (*CV*

= 88.6%). The optimized θ_s values with this last model were smaller than the porosity, ϕ, in the 92% of the cases and the mean of θ_s/ϕ was equal to 0.90 (*CV* = 10.1%). Ratios between θ_s and ϕ close to that of this investigation are rather common in the literature (e.g. 0.85 in Mubarak et al., 2009 and 0.93 in Somaratne and Smettem, 1993). This last result supported the hypothesis that better estimating θ_s in the BEST procedure (i.e., not simply setting θ_s = porosity) could improve the performances of this approach, i.e. could allow to obtain water retention data closer to those obtained with standard laboratory methods.

The vGM and vGB models yielded significantly correlated predictions of each considered indicator (*AC*, *PAWC*, *RFC*, P_{MAC}; **Table 8**) although data scattering was particularly noticeable for P_{MAC} (**Fig.7**). A linear regression line not different from the identity line according to the calculated 95% confidence intervals for the intercept and the slope was detected for *AC*, *RFC* and P_{MAC} but not for *PAWC*. Therefore, the water retention model fitted to the data cannot be considered irrelevant in terms of estimated SPQ indicators. In other terms, if an investigation making use of the vGB model is compared with another investigation based on the vGM model, an effect of the water retention model on the results of the comparison cannot be excluded. **Fig.8**, showing the differences, $diff_{\mathrm{CBI}}$, between the two estimates (vGB, vGM) of a capacity based indicator at a sampling point against *SSR*(vGB), suggested that this last parameter can be viewed as an index of the expected differences between the two estimates. If the vGB model fits well to the data, i.e. if *SSR*(vGB) is low, then the applied model does not influence appreciably the estimate of a given SPQ indicator. Detection of this influence presupposes a poor performance of the vGB model, i.e. high *SSR*(vGB) values.

This analysis had an obvious general importance, since it allowed to establish what formulation better described the water retention data for the sampled soils under the hypothesis that laboratory measurement of θ was free from any experimental error. It was also necessary to establish if the choice of the water retention model should be expected to influence the SPQ assessment. On the basis of this investigation, to reduce differences between the laboratory and the field calculations of the capacity based indicators, an improved fitting to the laboratory water retention data appears more important than using a common water retention model for the two experimental methodologies.

CONCLUSIONS

In this investigation, the expected land use effects on soil physical and hydraulic properties were found to be detectable notwithstanding that steepness was greater for the forest plots than the pasture plot. Moreover, soil properties were affected by land management practices in a morphologically homogeneous area were trees were cut on different dates. Therefore, a conclusion was that, at the sampled site, both land use and management practices influenced appreciably soil physical and hydraulic properties. This circumstance has to be taken into account in the development of soil sampling strategies aimed to interpret and/or simulate hydrological processes at the hillslope or watershed scale.

The three tested approaches to assess soil physical quality (SPQ) on the basis of the laboratory measured water retention (capacity based indicators, *S* index, location and shape parameters of the pore volume distribution function) showed a similar ability to discriminate between the two land uses. An implication of this result was that a single indicator, such as the *S* index, could be enough in practice if the objective of the investigation is to detected differences between SPQ attributes of different areas. However, the three approaches yielded a completely different assessment of the SPQ at the sampled site. This discrepancy was due to the applied criteria to express the judgment. Taking into account that never cropped and virgin soil is expected to have nearly optimal SPQ conditions and that pressure of anthropic nature can reduce SPQ, the most convincing criterion was found to be that developed for the capacity based indicators. This result is important from a practical point of view because, with the current procedures, only four water retention data points are necessary to establish the SPQ of an area of interest instead of the complete water retention curve required by the other criteria.

With the capacity based indicators criterion, the optimal/critical values or ranges for SPQ indicators developed with reference to agricultural soils appear approximately usable even for other land uses such as forest and pasture. More in particular, a forest soil with a good SPQ has an ability to store and provide water to plant roots similar to that of a good agricultural soil but the root zone is expected to be more aerated in the former case than the latter one. However, even the capacity based indicators approach needs improvements due to some inconsistencies in the SPQ evaluation criteria. Solving these problems could imply a simpler assessment of SPQ for an area of interest, i.e. based on a smaller number of indicators.

The soil organic matter content appears a good predictor of the expected performance (success, failure) of the BEST procedure for soil hydraulic characterization directly in the field. This procedure, applied in the simplest possible form also in terms of the used data analysis algorithm, and the more standard laboratory approach presented similarities in terms of SPQ assessment since it was found to be generally satisfactory in both cases. However, the field approach was more prone to signal good conditions and less inclined to detect differences between land uses. On the basis of the laboratory obtained water retention data, the water retention model used by BEST is not the most appropriate model at the sampled site. To reduce differences between the laboratory and the field calculations of the capacity based indicators, an improved fitting to the laboratory water retention data appears more important than using a common water retention model for the two experimental methodologies.

BEST appears susceptible of practical and theoretical improvements that should not imply much more complicate field and data analysis procedures. These improvements are also advisable to allow SPQ assessment of large areas. Larger sample sizes are expected to yield a more reliable information on the SPQ of a given area and the field procedure appears suitable to intensively sampling soil directly in the field with a practically negligible disturbance of the porous medium. Another advantage of developing BEST for SPQ assessment is that the procedure gives a complete soil hydraulic characterization. Therefore, other SPQ parameters, such as those descriptive of the hydrodynamic characteristics of the soil, can be collected with a single experiment.

In this investigation, simultaneous determination of dendrometric and soil parameters was carried out for four forest plots differing by felling age. Four plots located in a particular zone of the world are not enough to draw conclusions of general validity about the relationships between SPQ and characteristics of the forest cover. Simultaneous characterization of forest and soil at other sites is recommended to develop an international database usable at this purpose.

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FIGURE CAPTIONS

Fig. 1. Location of a) the study area and b) the sampling plots in the study area

Fig. 2. Frequency distribution of shoots in DBH classes

Fig. 3. Relationship between the S index and a) d_{median}, b) d_{mode}, and c) d_{mean}

Fig. 4. Relationship between the S index and the dry soil bulk density, ρ_b

Fig. 5. Relationship between relative field capacity, *RFC*, and air capacity, *AC*: a) experimentally determined relationship and b) determination of the *AC* values corresponding to optimal conditions in terms of *RFC*

Fig. 6. Comparison between the vGB (van Genuchten – Burdine) and vGM (van Genuchten – Mualem) water retention models: a) sum of squared residuals, *SSR*, and b) plot of relative errors, *RE*, against the measured soil water content, θ

Fig. 7. Comparison between the capacity based indicator estimates obtained by fitting the vGB (van Genuchten – Burdine) and vGM (van Genuchten – Mualem) water retention models to the laboratory data: a) air capacity, *AC* (m^3m^{-3}), b) plant available water capacity, *PAWC* (m^3m^{-3}), c) relative field capacity, *RFC* (-), and d) macroporosity, P_{MAC} (m^3m^{-3})

Fig. 8. Difference between the estimates of a given indicator (air capacity, *AC* in m^3m^{-3}, plant available water capacity, *PAWC* in m^3m^{-3}, relative field capacity, *RFC*, and macroporosity, P_{MAC} in m^3m^{-3}) obtained by fitting the vGB (van Genuchten – Burdine) and vGM (van

Genuchten – Mualem) water retention models to the laboratory data plotted against the sum of squared residuals for the vGB model, *SSR(vGB)*

Table 1. Main characteristics of the sampling plots

Sampling plot	**Surface area (m^2)**	**Stand structure**	**Tree composition**	**Year of felling**	**Age of new stools**
A1	1260	Coppice with standard	*Quercus ilex* *Q. pubesces* *Fraxinus ornus*	2013	1 year-old
A2	710	Coppice with standard	*Quercus ilex* *Q. pubesces* *Fraxinus ornus*	2009	6 year-old
A3	310	Coppice with standard	*Quercus ilex* *Q. pubesces* *Fraxinus ornus*	1993	20 year-old
A4	310	Coppice with standard	*Quercus ilex* *Q. pubesces*	1973	40 year-old
A5	1000	pasture	/	/	/

Table 2. Meaning of the considered soil physical quality indicators and suggested evaluation criteria

Indicator	**Meaning**	**Evaluation criterion**	**Reference**
Bulk density, ρ_b (Mg m^{-3})	Indicator of aeration, strength, and ability to store and transmit water	Optimal if $0.9 \leq \rho_b \leq 1.2$; intermediate if $1.2 < \rho_b \leq 1.30$; poor if $\rho_b > 1.30$ or $\rho_b < 0.9$; medium to fine textured soils	Reynolds et al. (2009)
Organic carbon content, *OC* (% by weight)	Strong indirect effects on soil physical quality	Optimal if $3 \leq OC \leq 5$; intermediate if $2.3 < OC \leq 3$ or $5 \leq OC < 6$; poor if $OC > 6$ or < 2.3	Reynolds et al. (2009)
Saturated soil hydraulic conductivity, K_s (mm h^{-1}),	Soil's ability to imbibe and transmit plant-available water to the crop root zone as well as drain excess water out of the root zone	Optimal if $18 \leq K_s \leq 180$; intermediate if $180 < K_s \leq 360$ or $3.6 \leq K_s < 18$; poor if $K_s > 360$ or < 3.6; humid climates	Reynolds et al. (2014)
Air capacity, *AC* (m^{3}m^{-3})	Root zone aeration	Good if ≥ 0.14 and limited if < 0.14; sandy loam to clay loam soils	Reynolds et al. (2009)
Plant available water capacity, *PAWC* (m^{3}m^{-3})	Soil's ability to store and provide water that is available to plant roots	Ideal if > 0.20; good if $0.15 \leq PAWC < 0.20$; limited if $0.10 \leq PAWC < 0.15$; poor if $PAWC < 0.10$	Reynolds et al. (2009)
Relative field capacity, *RFC* (-)	Soil's ability to store water and air relative to the soil's total pore volume	Optimal if $0.6 \leq RFC \leq 0.7$; water limited soil if $RFC < 0.6$; aeration limited soil if $RFC > 0.7$; rain-fed agriculture on mineral soils	Reynolds et al. (2009)
Macroporosity, P_{MAC} (m^{3}m^{-3})	Soil's ability to quickly drain excess water and facilitate root proliferation	Optimal if $P_{MAC} \geq 0.07$; intermediate if $0.04 \leq P_{MAC} < 0.07$; limited if $P_{MAC} < 0.04$	Reynolds et al. (2009)
d_{median} (μm)	Location parameter (central tendency) of the pore volume distribution	Optimal if $3 \leq d_{median} \leq 7$; non-optimal in the other cases	Reynolds et al. (2009)
d_{mode} (μm)	Location parameter (central tendency) of the pore volume distribution	Optimal if $60 \leq d_{mode} \leq 140$; non-optimal in the other cases	Reynolds et al. (2009)
d_{mean} (μm)	Location parameter (central tendency) of the pore volume distribution	Optimal if $0.7 \leq d_{mean} \leq 2$; non-optimal in the other cases	Reynolds et al. (2009)
SD	Spread of the pore volume distribution	Optimal if $400 \leq SD \leq 1000$; non-optimal in the other cases	Reynolds et al. (2009)
SK	Asymmetry of the pore volume distribution	Optimal if *SK* varying from -0.43 to -0.41; non-optimal in the other cases	Reynolds et al. (2009)
KU	Peakedness of the pore volume distribution	Optimal if $1.13 \leq KU \leq 1.14$; non-optimal in the other cases	Reynolds et al. (2009)
S	Slope of the gravimetric water content vs. natural logarithm of tension head at the inflection point	Very good if $S \geq 0.050$; good if $0.035 \leq S < 0.050$; poor if $0.020 \leq S < 0.035$; very poor if $S < 0.020$; temperate and tropical soils	Dexter and Czyz, 2007

Table 3. Main dendrometric parameters sampled in the forest areas

Area	Species	Number of stools ha^{-1}	Number of shoots ha^{-1}	Number of individuals ha^{-1} (%)	mean n. shoots per stool/ha	Number of standards ha^{-1}	D$_m$ (cm)	H$_m$ (m)	G ha^{-1} (m^{2}ha^{-1})	V ha^{-1} (m^{3}ha^{-1})
A1	*Q. ilex*	1200	18507	62.6	15	56	14.9	10.2	1.0	5.1
	Q.pubescens	380	2799	14.0	7	72	25.7	11.7	3.7	18.8
	F. ornus	1000	9144	23.4	9	80	13.9	10.4	1.2	6.8
	Total	**2580**	**30450**	**100,0**		**206.9**			**5.9**	**30.7**
A2	*Q. ilex*	1066	15216	61.5	14	113	21.0	12.7	3.9	18.6
	Q.pubescens	238	1170	6.9	5	141	35.7	13.5	14.1	69.4
	F. ornus	1000	10358	31.7	10	42	15.1	12.4	0.8	5.2
	Total	**2304**	**26744**	**100,0**		**297.1**			**18.8**	**93.1**
A3	*Q. ilex*	1210	4488	60.3	4		8.4	7.3	25.0	113.1
	Q.pubescens	95	255	3.4	3		16.8	8.1	5.6	24.8
	F. ornus	1050	2706	36.3	3		7.0	6.7	10.4	42.8
	Total	**2355**	**7448**	**100,0**					**41.0**	**180.6**
A4	*Q. ilex*	1496	3820	92.3	3		12.4	10.6	46.2	255.8
	Q.pubescens	286	318	7.7	1		24.6	13.8	15.2	82.2
	Total	**1783**	**4138**	**100,0**						**338.0**

Table 4. Summary statistics of the basic soil properties at the five sampling areas

Variable	**Statistic**	**A1**	**A2**	**A3**	**A4**	**A5**
Slope steepness (%)	Mean	56.6	55.3	59.3	48.2	27.3
Clay (%)	N_s	10	10	10	10	10
	Mean	17.2ab	14.9a	22.0b	21.2b	29.5c
	CV (%)	23.0	41.9	8.2	14.2	23.0
Silt (%)	N_s	10	10	10	10	10
	Mean	37.5a	35.2a	34.5a	37.5a	43.7b
	CV (%)	15.3	12.9	5.8	8.7	9.9
Sand (%)	N_s	10	10	10	10	10
	Mean	45.3ab	49.9a	43.4b	41.2b	26.8c
	CV (%)	10.7	7.2	5.1	8.9	30.3
ρ_b (g cm^{-3})	N_s	20	20	20	20	20
	Mean	0.914a	0.892a	0.863a	0.785a	1.142b
	CV (%)	24.5	15.8	20.0	24.4	10.7
OM (%)	N_s	7	7	7	7	7
	Mean	13.3ab	13.1ab	16.8a	17.7a	10.8b
	CV (%)	24.3	20.9	26.6	28.0	12.0
WSA	N_s	5	5	5	5	5
	Mean	0.159a	0.131a	0.231a	0.248a	0.219a
	CV (%)	31.3	19.7	18.0	35.1	48.0

N_s = sample size; *CV* = coefficient of variation; ρ_b = dry soil bulk density; *OM* = organic matter content; *WSA* = fraction of water stable aggregates. For a given variable, means followed by the same letter are not significantly different according to the Tukey Honestly Significant Difference test ($P = 0.05$).

Table 5. Soil physical quality of the five sampling areas assessed by using different indicators and measurement methods of the hydraulic properties

Indicator	Method	A1	A2	A3	A4	A5
ρ_b	LAB	Optimal	Poor	Poor	Poor	Optimal
OC	LAB	Poor	Poor	Poor	Poor	Poor
K_s	BEST	Optimal	Optimal	Poor	Intermediate	Optimal
AC	BEST LAB	Good Good =	Good Good ≠	Good Good =	Good Good =	Good Limited ≠
PAWC	BEST LAB	Ideal Ideal =	Good Ideal ≠	Good Good =	Good Ideal =	Good Ideal ≠
RFC	BEST LAB	Optimal Optimal =	Water limited Optimal =	Optimal Water limited =	Water limited Water limited =	Optimal Aeration limited ≠
P_{MAC}	BEST LAB	Optimal Intermediate =	Optimal Intermediate ≠	Optimal Intermediate ≠	Optimal Optimal =	Optimal Limited ≠
d_{median}	LAB	Non-optimal	Non-optimal	Non-optimal	Non-optimal	Optimal
d_{mode}	LAB	Optimal	Optimal	Optimal	Non-optimal	Non-optimal
d_{mean}	LAB	Non-optimal	Non-optimal	Non-optimal	Non-optimal	Optimal
SD	LAB	Non-optimal	Non-optimal	Non-optimal	Non-optimal	Optimal
SK	LAB	Non-optimal	Non-optimal	Non-optimal	Non-optimal	Non-optimal
KU	LAB	Non-optimal	Non-optimal	Non-optimal	Non-optimal	Non-optimal
S	LAB	Very good	Very good	Very good	Very good	Very good

ρ_b = dry soil bulk density; *OC* = organic carbon content; K_s = saturated soil hydraulic conductivity; *AC* = air capacity; *PAWC* = plant available water capacity; *RFC* = relative field capacity; P_{MAC} = macroporosity; d_{median}, d_{mode} and d_{mean} = median, modal and mean equivalent pore diameter, respectively; *SD*, *SK* and *KU* = standard deviation, skewness and kurtosis, respectively, of the pore volume distribution function; *S* = soil physical quality index by Dexter (2004). LAB = laboratory method; BEST = field procedure of soil hydraulic characterization. The symbols "≠" or "=" indicate that, for a given area/indicator combination, the two datasets were or were not significantly different, respectively, according to a two-tailed t test ($P = 0.05$).

Table 6. Summary statistics of the indicators obtained for each sampling area by the laboratory measured water retention data

Suite of indicators	**Indicator**	**Statistic**	**A1**	**A2**	**A3**	**A4**	**A5**
Capacity based	AC (m^{3}m^{-3})	Mean	0.216ab	0.203ab	0.235b	0.302b	0.128a
		CV (%)	35.9	30.5	21.4	37.0	39.1
	PAWC (m^{3}m^{-3})	Mean	0.212a	0.239a	0.195a	0.200a	0.227a
		CV (%)	14.9	16.6	28.0	18.8	18.1
	RFC	Mean	0.627a	0.656a	0.593a	0.552a	0.774b
		CV (%)	15.8	13.0	11.0	18.5	10.6
	P_{MAC} (m^{3}m^{-3})	Mean	0.058ab	0.048ab	0.048ab	0.114b	0.031a
		CV (%)	88.5	96.5	58.2	94.0	81.8
Location and shape parameters	d_{median} (μm)	Mean	24.6ab	15.1a	34.6ab	54.0b	3.12a
		CV (%)	58.6	69.5	84.0	94.0	74.8
	d_{mode} (μm)	Mean	85.1a	78.8a	74.5a	250.5a	37.4a
		CV (%)	87.0	116.0	52.8	181.0	88.8
	d_{mean} (μm)	Mean	14.9ab	9.76ab	26.3b	30.6b	1.41a
		CV (%)	60.9	89.6	103.4	86.5	108.4
	SD	Mean	37.3a	234.6a	33.3a	48.6a	741.7a
		CV (%)	98.7	242.3	154.7	116.7	172.8
	SK	Mean	-0.320ab	-0.329ab	-0.286b	-0.333ab	-0.392a
		CV (%)	-18.0	-23.7	-27.0	-14.3	-13.6
	KU	Mean	1.153b	1.148ab	1.150b	1.153b	1.141a
		CV (%)	0.32	0.72	0.58	0.44	0.91
Dexter's theory	S	Mean	0.103ab	0.100ab	0.120b	0.129b	0.057a
		CV (%)	42.1	43.6	33.6	31.1	27.9

Sample size N_s =10 for areas A1, A3, A4 and A5 and N_s = 9 for area A2. *AC* = air capacity; *PAWC* = plant available water capacity; *RFC* = relative field capacity; P_{MAC} = macroporosity; d_{median}, d_{mode} and d_{mean} = median, modal and mean equivalent pore diameter, respectively; *SD*, *SK* and *KU* = standard deviation, skewness and kurtosis, respectively, of the pore volume distribution function; *S* = soil physical quality index by Dexter (2004). For a given variable, means followed by the same letter are not significantly different according to the Tukey Honestly Significant Difference test (*P* = 0.05).

Table 7. Summary statistics of the initial soil water content, θ_i, and the indicators obtained for each sampling area by the BEST procedure of soil hydraulic characterization

Variable	Statistic	A1	A2	A3	A4	A5
θ_i (m^3m^{-3})	N_s	20	20	20	20	20
	Mean	0.189a	0.182a	0.186a	0.265	0.134a
	CV (%)	50.3	40.6	26.0	19.4	24.5
K_s (mm h^{-1})	N_s	16	14	12	13	20
	Mean	93.0a	106.0a	412.9b	321.4bc	129.1ac
	CV (%)	154.1	91.1	90.4	163.1	122.6
K_m (mm h^{-1})	N_s	16	14	12	13	20
	Mean	5.53a	1.53a	2.54a	2.35a	3.11a
	CV (%)	338.6	36202.5	284.3	364.4	4253.8
AC (m^3m^{-3})	N_s	16	14	12	13	20
	Mean	0.244ab	0.284b	0.268ab	0.290b	0.223a
	CV (%)	17.1	25.6	12.6	17.0	25.2
PAWC (m^3m^{-3})	N_s	16	14	12	13	20
	Mean	0.205b	0.196ab	0.180ab	0.190ab	0.169a
	CV (%)	14.0	20.5	10.0	12.4	13.5
RFC	N_s	16	14	12	13	20
	Mean	0.624a	0.569a	0.612a	0.587a	0.610a
	CV (%)	10.3	19.4	7.9	10.6	14.0
P_{MAC} (m^3m^{-3})	N_s	16	14	12	13	20
	Mean	0.096a	0.137a	0.146a	0.155a	0.103a
	CV (%)	50.1	71.7	27.9	38.7	65.2

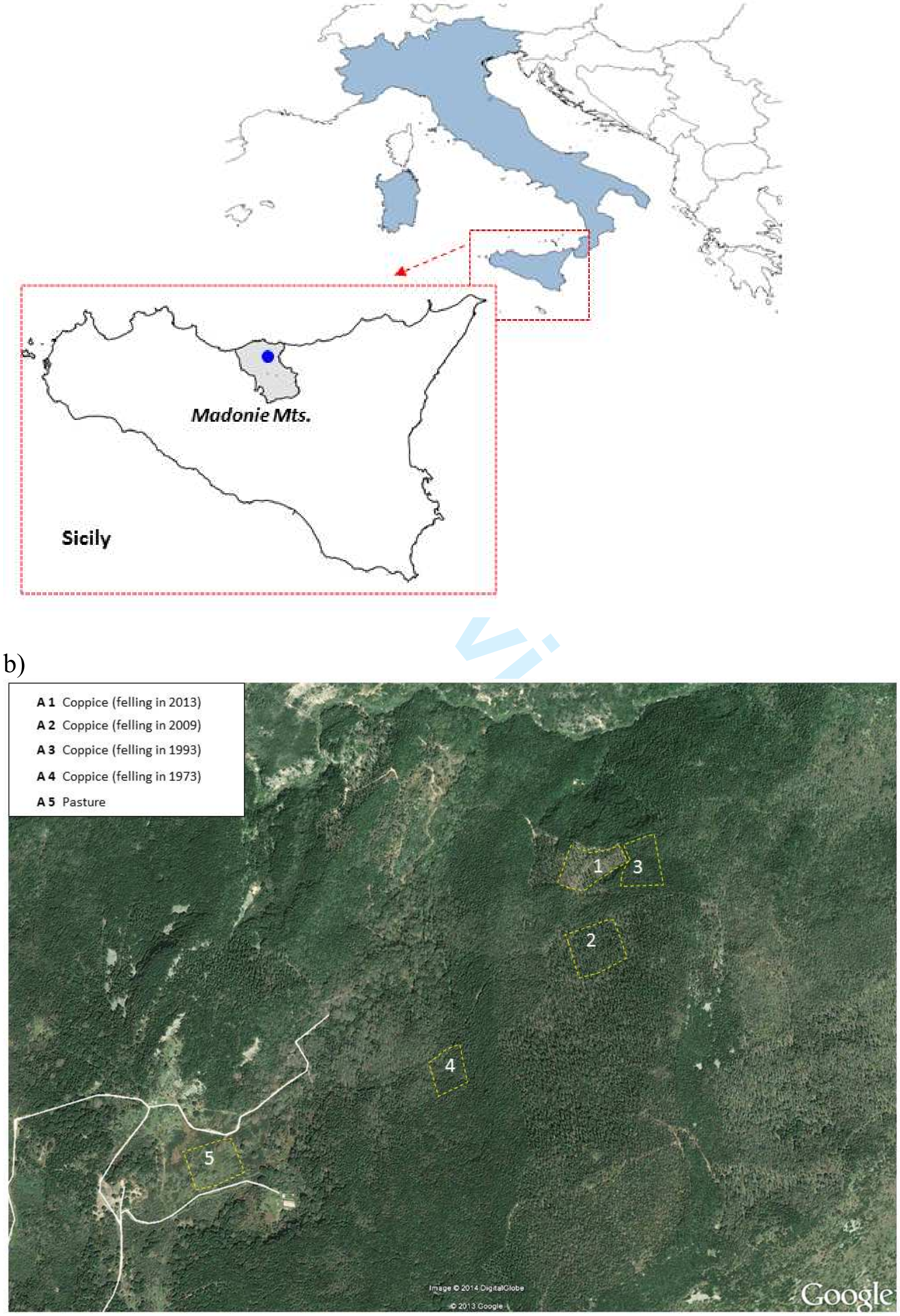
N_s = sample size; CV = coefficient of variation; K_s = saturated soil hydraulic conductivity; K_m = saturated hydraulic conductivity of matrix pores; AC = air capacity; $PAWC$ = plant available water capacity; RFC = relative field capacity; P_{MAC} = macroporosity. For a given variable, means followed by the same letter are not significantly different according to the Tukey Honestly Significant Difference test ($P = 0.05$).

Table 8. Parameters of the regression between the estimates of different indicators obtained by fitting the vGB (van Genuchten – Burdine) and vGM (van Genuchten – Mualem) models to the laboratory water retention data

Indicator	vGB vs. vGM regression				
	Intercept	**Slope**	**R^2**	**95% confidence interval for the intercept**	**95% confidence interval for the slope**
AC (m^3m^{-3})	0.0006	0.9785	0.7021	-0.043 – 0.045	0.79 – 1.17
PAWC (m^3m^{-3})	0.0836	0.6769	0.6590	0.052 – 0.115	0.53 – 0.82
RFC	0.0105	0.9989	0.9217	-0.045 – 0.066	0.91 – 1.08
P_{MAC} (m^3m^{-3})	0.0082	0.8318	0.3713	-0.020 – 0.036	0.51 -1.15

Sample size for given indicator, $N_s = 49$. All coefficients of correlation, R, were significantly greater than zero according to a one-tailed t test ($P = 0.05$)

Figure 1



a)

b)

Madonie Mts.
Sicily
A 1 Coppice (felling in 2013)
A 2 Coppice (felling in 2009)
A 3 Coppice (felling in 1993)
A 4 Coppice (felling in 1973)
A 5 Pasture
1
3
2
4
5
Image © 2014 DigitalGlobe
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Google

Figure 2

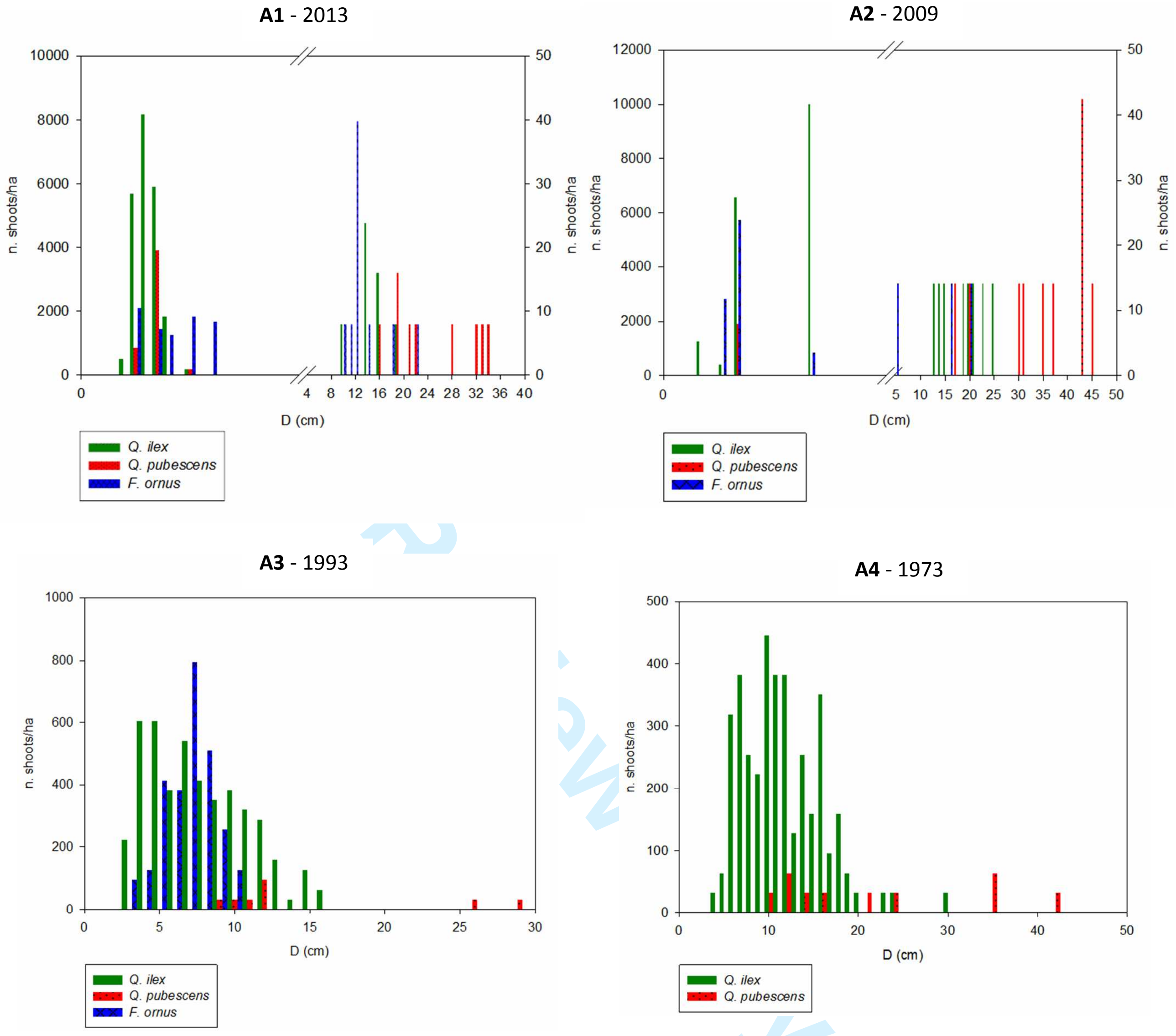
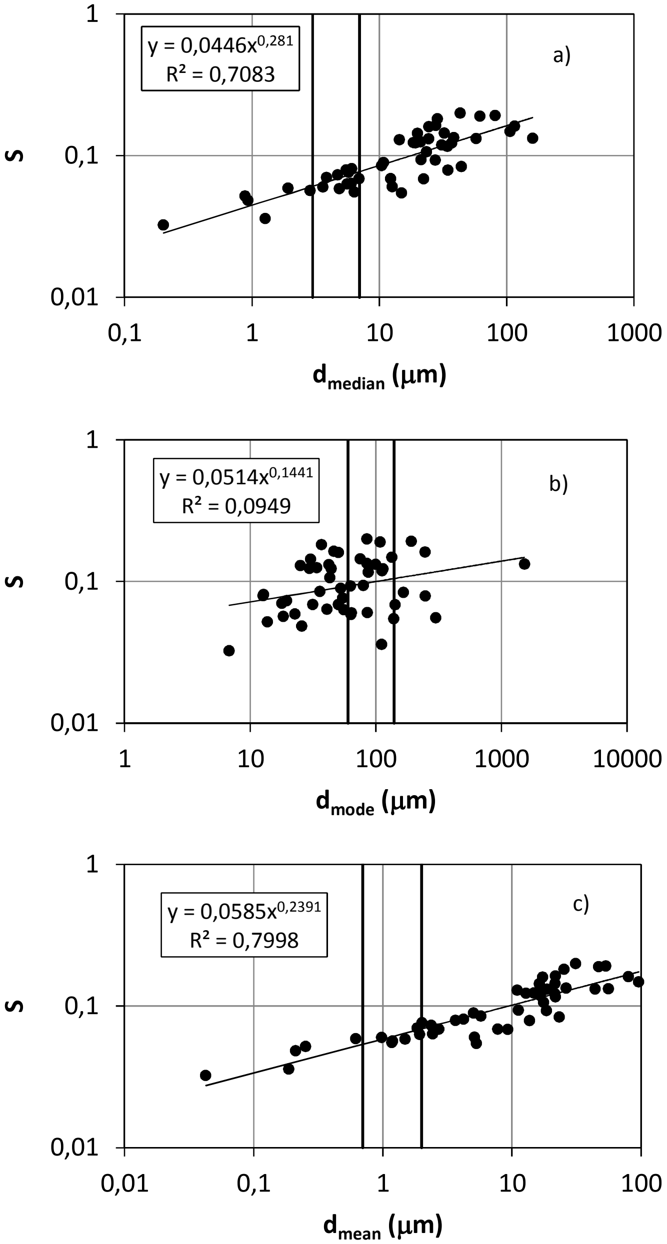

A1 - 2013
10000
8000
6000
4000
2000
0
50
40
30
20
10
0
n. shoots/ha
n. shoots/ha
0
4 8 12 16 20 24 28 32 36 40
D (cm)
Q. ilex
Q. pubescens
F. ornus
A2 - 2009
12000
10000
8000
6000
4000
2000
0
50
40
30
20
10
0
n. shoots/ha
n. shoots/ha
0
5 10 15 20 25 30 35 40 45 50
D (cm)
Q. ilex
Q. pubescens
F. ornus
A3 - 1993
1000
800
600
400
200
0
n. shoots/ha
0 5 10 15 20 25 30
D (cm)
Q. ilex
Q. pubescens
F. ornus
A4 - 1973
500
400
300
200
100
0
n. shoots/ha
0 10 20 30 40 50
D (cm)
Q. ilex
Q. pubescens

Figure 3



1
0,1
0,01
S
y = 0,0446x^{0,281}
R² = 0,7083
a)
0,1
1
10
100
1000
d$_{median}$ (µm)
1
0,1
0,01
S
y = 0,0514x^{0,1441}
R² = 0,0949
b)
1
10
100
1000
10000
d$_{mode}$ (µm)
1
0,1
0,01
S
y = 0,0585x^{0,2391}
R² = 0,7998
c)
0,01
0,1
1
10
100
d$_{mean}$ (µm)

Figure 4

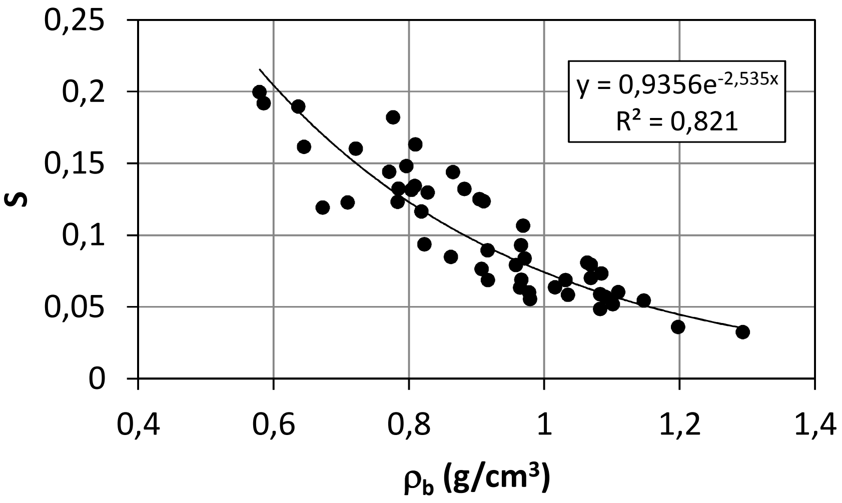

y = 0,9356e^-2,535x
R² = 0,821
S
0,25
0,2
0,15
0,1
0,05
0
0,4
0,6
0,8
1
1,2
1,4
ρb (g/cm³)

Figure 5

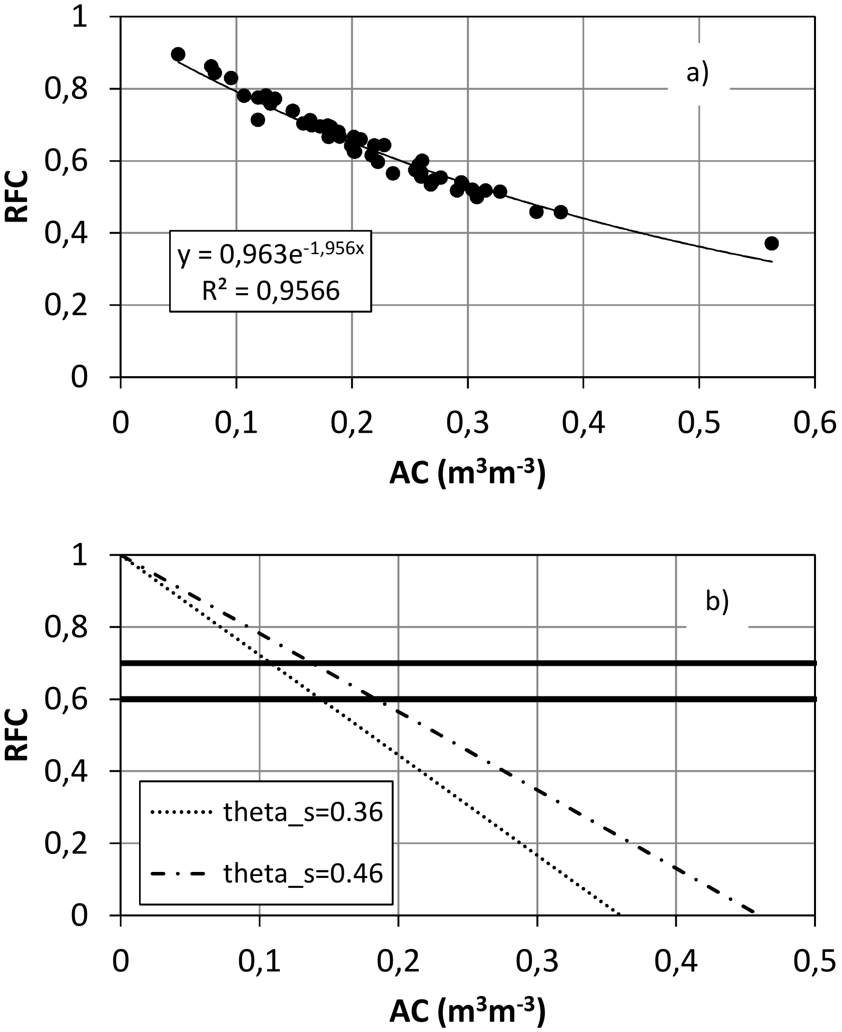

1
0,8
0,6
0,4
0,2
0
RFC
a)
y = 0,963e^-1,956x
R² = 0,9566
0
0,1
0,2
0,3
0,4
0,5
0,6
AC (m³m⁻³)
1
0,8
0,6
0,4
0,2
0
RFC
b)
theta_s=0.36
theta_s=0.46
0
0,1
0,2
0,3
0,4
0,5
AC (m³m⁻³)

Figure 6

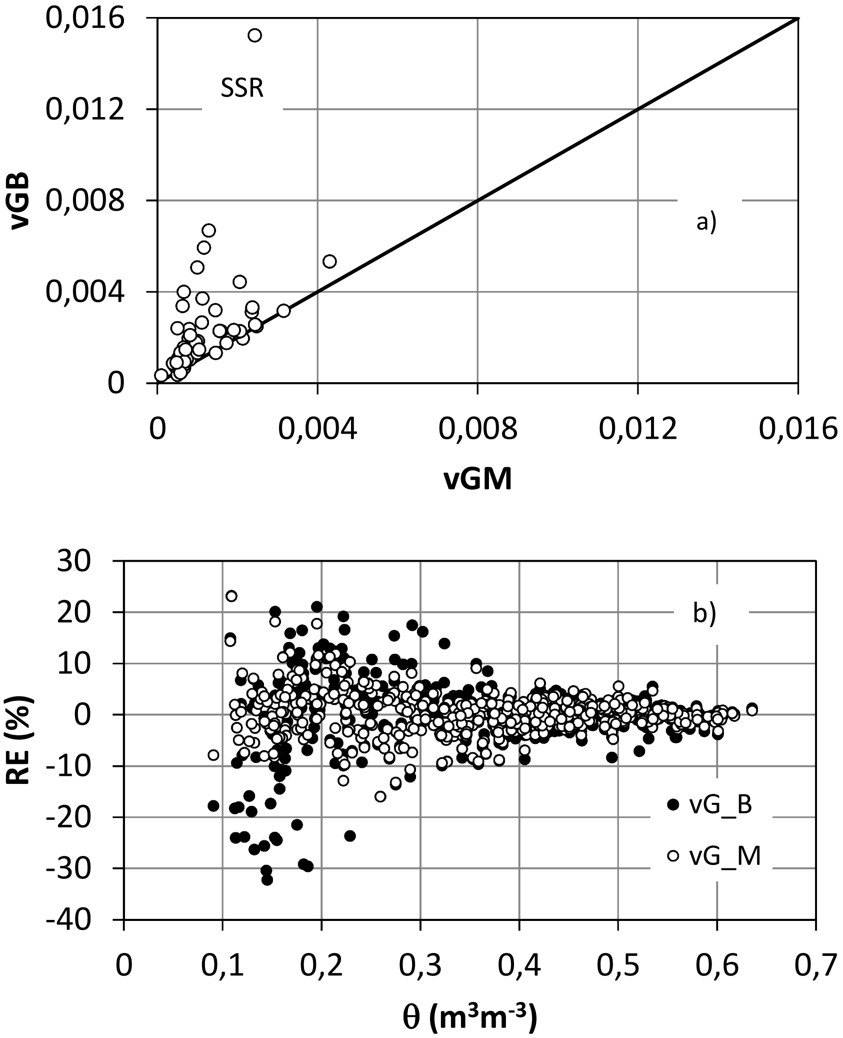

0,016
0,012
0,008
0,004
0
vGB
SSR
a)
0
0,004
0,008
0,012
0,016
vGM
30
20
10
0
-10
-20
-30
-40
RE (%)
b)
● vG_B
○ vG_M
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
θ (m³m⁻³)

Figure 7

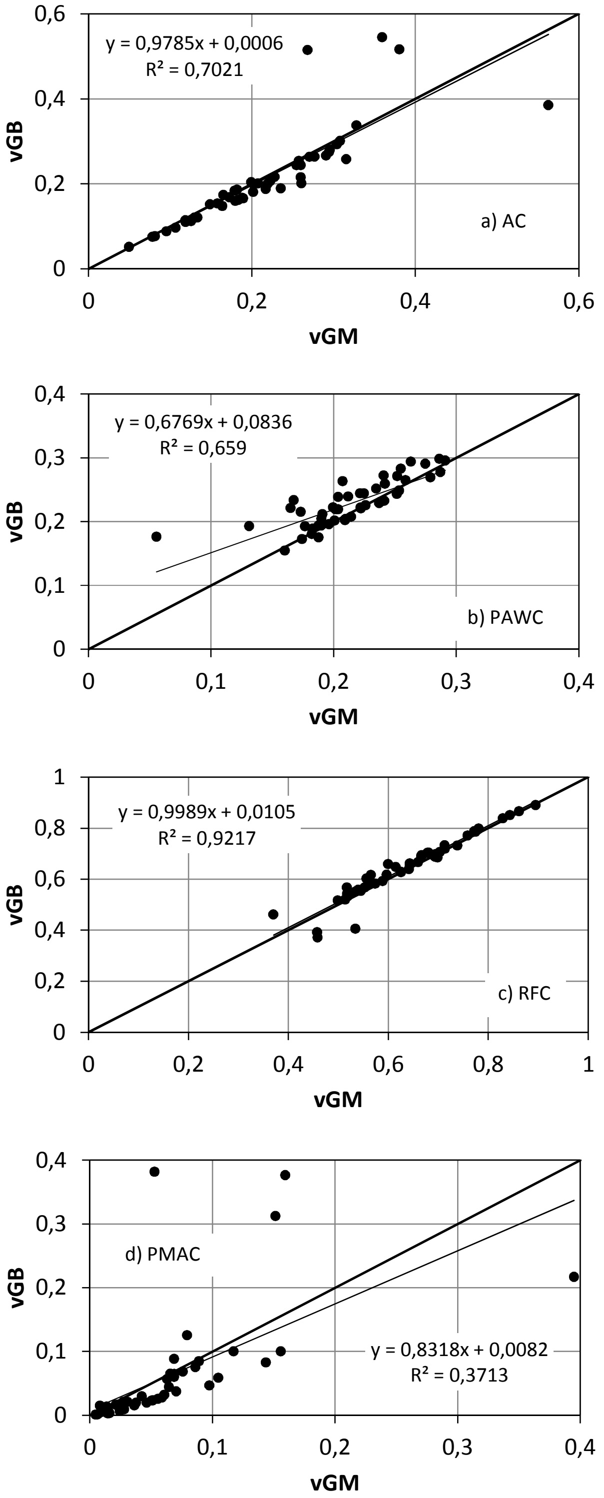
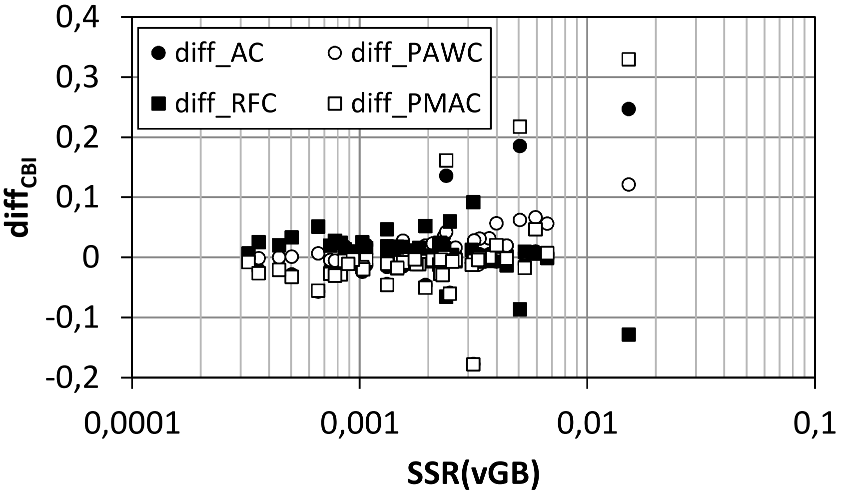

0,6
0,4
0,2
0
vGB
y = 0,9785x + 0,0006
R² = 0,7021
a) AC
0
0,2
0,4
0,6
vGM
0,4
0,3
0,2
0,1
0
vGB
y = 0,6769x + 0,0836
R² = 0,659
b) PAWC
0
0,1
0,2
0,3
0,4
vGM
1
0,8
0,6
0,4
0,2
0
vGB
y = 0,9989x + 0,0105
R² = 0,9217
c) RFC
0
0,2
0,4
0,6
0,8
1
vGM
0,4
0,3
0,2
0,1
0
vGB
d) PMAC
y = 0,8318x + 0,0082
R² = 0,3713
0
0,1
0,2
0,3
0,4
vGM

Figure 8


● diff_AC
○ diff_PAWC
■ diff_RFC
□ diff_PMAC
0,4
0,3
0,2
0,1
0
-0,1
-0,2
$diff_{CBI}$
0,0001
0,001
0,01
0,1
SSR(vGB)