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Influence of forest stand age on soil water repellency and hydraulic conductivity in the Mediterranean environment

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Abstract

The hydrological response of forest soil in the Mediterranean environment is characterised by high runoff and erosion rates, mainly due to low infiltration and high repellency of soils. However, little literature exists about the effects of forest ages on soil water repellency (SWR) and hydraulic conductivity (SHC). This study evaluates these hydrological parameters in five *Pinus nigra* Arn ssp. *Salzmannii* stands of different ages in Central-Eastern Spain; one of these stands, unmanaged, was chosen as reference system. SWR (measured in terms of water drop penetration time, WDPT) and SHC as well as the main physico-chemical properties and surface characteristics of soils were surveyed in forty-five plots. Water infiltration was higher in the older stands (including the older and unmanaged forest) and lower (by over 60%) in the more recent pine forests. Four of the studied stands did not show water repellency; only the more recent plantation showed a slight SWR. The differences in SHC among the forest ages were mainly driven by the organic matter (OM) and nutrient contents of the soils as well as by the bulk density and quantity of dead wood. SWR was similar among the plots (despite significantly differences in WDPTs), although having variable OM contents.

Considering these differences in soil properties, SHC and SWR were simply predicted for each forest stand using on dbRDA models and the following soil properties: (i) OM and total nitrogen contents of soil (for SHC and SWR); (ii) dead wood and bulk density (for SHC); and (iii) clay content and the percentage of bare soil (for SWR). Overall, this study has showed that, when a new forest stand is planted, decreases in water infiltration, with subsequent increases in runoff generation capacity) of the soils, can be expected. Conversely, no water repellency is likely to affect new pine plantations.

Keywords: forest stand; water infiltration; soil water repellency; organic matter; tree age; soil properties.

List of abbreviations

SHC = soil hydraulic conductivity

SWR = soil water repellency

SWC = soil water content

PNUM = unmanaged forest stands of 100-120 years old *Pinus nigra* Arn. ssp *salzmannii*

PN I = *Pinus nigra* Arn ssp. *Salzmannii* stands ranging 80-100 years old

PN II = *Pinus nigra* Arn ssp. *Salzmannii* stands ranging 60-79 years old

PN III = *Pinus nigra* Arn ssp. *Salzmannii* stands ranging 20-39 years old

PN IV = *Pinus nigra* Arn ssp. *Salzmannii* stands ranging 1-19 years old

RC = rock cover of soil

VC = vegetation cover of soil

BSC = bare soil cover

DWC = dead wood cover on soil

SaC = sand content of soil

SiC = silt content of soil

ClC = clay content of soil

BD = bulk density of soil

EC = electrical conductivity of soil

OM = organic matter of soil

TN = total nitrogen of soil

AL = active limestone of soil

WDPT = Water Drop Penetration Test
ANOSIM = Analysis of Similarities
PERMANOVA = Multivariate Permutational Analysis Of Variance
MDS = non-metric Multi-Dimensional Scaling
MDA = Multi-Dimensional Axis
RELATE = comparative (Mantel-type) tests on similarity matrices
DISTLM = Distance-Based Linear Modelling
dbRDA = distance-based Redundancy Analysis
AICc = Akaike Information Criterion

1. Introduction

Soil hydrology in forest ecosystems is the result of several and complex processes, which are driven by a number of environmental and anthropogenic factors (e.g., climate, soil dynamics, vegetation, fauna, afforestation) (Hewlett, 1982; Pike et al., 2010). An important role in governing the hydrological response of a forest soil is played by both plant characteristics and forest management operations. Plant species and structure can alter many physical, chemical and biological processes of soils (Grayston and Prescott, 2005; Lucas-Borja et al., 2010; Thoms et al., 2010), determining often noticeable changes in the related properties. For instance, the amount and composition of soil organic matter (OM), which is one of the most important indicators of forest soil status and functionality, is strictly linked to the plant dynamics; moreover, the OM quality and quantity are related to sustained productivity, biodiversity, and other ecosystem services (Grigal and Vance, 2000; Zornoza et al., 2015; Lucas-Borja et al., 2016). The OM of forest soils derives from litterfall and root input, while losses are the result of microbial degradation, eluviation, solution losses, and erosion, creating a balance between OM accumulation and loss (Entry and Emmingham, 1998). Among the factors influencing soil functionality and characteristics of forests, the tree age may be a key factor in governing the soil hydrology, since old forests have a mature and stable soil, resulting in high content of OM (Van Leeuwen et al., 2015; Lozano-García et al., 2016; Lucas-Borja et al., 2016). Furthermore, the forest management operations play noticeable effects on the general properties of soils. For instance, different studies have demonstrated that afforestation and deforestation and thinning as well as forest structure and tree stand composition may alter the nutrient storage and the physico-chemical and microbiological soil properties (Entry and Emmingham, 1998; Mund and Schulze, 2006; Jandl et al., 2007; Lucas-Borja et al., 2012; 2016). Both forest plant age and management, driving the characteristics of soil and litter of forest, can induce noticeable changes in the hydrological properties of soil (Neary et al. 1999).

The soil changes are of fundamental importance in the Mediterranean forest ecosystems, as these areas are characterized by frequent and intense rainstorms, often generating high-magnitude flash floods (Fortugno et al., 2017). Moreover, the soils of the Mediterranean Basin are generally shallow with low aggregate stability, and organic matter and nutrient contents (Cantón et al., 2011). Due to the combination of these climate and soil characteristics, the Mediterranean forests are prone to excessive runoff and soil erosion rates (Zema et al. 2020a; 2020b). Since the hydrological processes generating water runoff in Mediterranean soils are dominated by the infiltration-excess mechanism (Lucas-Borja et al., 2018), a deep understanding of water infiltration and physical parameters that influence this process is needed, one of which is the soil hydraulic conductivity (SHC), which can be low in many Mediterranean soils. A very low SHC may expose the forest soils to intolerable rates of surface runoff and soil erosion (Robichaud and Waldrop 1994). Moreover, SHC can be further decreased by soil water repellency (SWR), which very often affects the Mediterranean forest soils (Cerdà and Doerr, 2007; Stoof et al., 2011; Van Dam et al., 1990; Imeson et al., 1992; Flury et al., 1994; Plaza-Álvarez et al., 2019).

Forest soils with low SHC and high SWR may be subjected to high runoff and erosion generation in the Mediterranean areas, if rainfall exceeds the surface detention of soil infiltration-excess (Doerr et al., 2000). High runoff and erosion rates lead to heavy environmental on-site (e.g., soil loss, landslides) and off-site (e.g., transport of polluting compounds, damage of urban infrastructures) impacts. Therefore, a detailed knowledge of SWR and SHC is very important to control and mitigate the hydrological risks and other environmental hazards (Lucas-Borja et al., 2018; Plaza-Álvarez et al., 2018). Understanding the SWR and SHC dynamics is thus of fundamental importance in the Mediterranean forest ecosystems, which are subject to many threats (e.g., wildfire, biodiversity lost, drought), in addition to the hydrological risks.

A large body of literature exists on SHC and SWR of Mediterranean forests under a variety of pedological, climatic and management conditions (e.g., Wittenberg et al., 2011; Neris et al., 2013; Inbar et al., 2014). Relationships between fires and soil repellency after fire have been also deeply studied in different forest ecosystem (Doerr et al., 2020; Plaza-Álvarez et al., 2018). Conversely, the influence of plant age and management operations of forests on soil hydrology and its driving parameters have been less explored, particularly in the very sensitive Mediterranean forest ecosystems. While the influences of soil properties on infiltration and water repellency of forests have been deeply studied (e.g., DeBano and Rice, 1973; Wahl et al., 2003; Martínez-Zavala and Jordán-López, 2009; Lucas-Borja et al., 2019, for SHC, and Buczko et al., 2002; Mataix-Solera and Doerr, 2004; Cesarano et al., 2016; Plaza-Álvarez et al., 2018, for SWR), there is a lack of studies that quantify the changes in SHC and SWR across a chrono-sequence of forest stands. This is important when new forest populations are planted, because the expected changes in soil hydrology may increase the forest aptitude to generate water runoff and soil loss. Thus, the relations between the soil properties in forest stands of different age and subject or not to management operations deserve deeper investigations. For instance, in older forest stands a higher SHC is expected compared to the new plantations, due to the higher quantity and better quality of organic matter (Jarvis et al. 2013; Lucas-Borja et al., 2016; Olorunfemi and Fasinmirin, 2017). However, the SWR, which increases with the organic matter content (Cesarano et al., 2016; Plaza-Álvarez et al., 2018), could make the topsoil more and even strongly repellent. A better knowledge of the relationships between SHC and SWR on one side, and forest age and soil properties on the other side may suggest the adoption of the most suitable measures for runoff control and soil conservation in Mediterranean forests.

To fill this gap, this study evaluates SWR and SHC in four forest stands of *Pinus nigra* Arn. ssp *salzmannii* with different age, managed throughout a period of 100 years, and in a control stand that has not been managed for 100-120 years old in Castilla-La Mancha (Central-Eastern Spain). We hypothesize that the soil properties as well as SWR and SHC are influenced by forest age. In other words, the age of each stand play different effects on the most important properties of soils (e.g. soil microclimatic conditions, soil organic matter and plant litter accumulation), which, in their turn, alter water repellency and infiltration of these Mediterranean forests. By demonstrating how forest stand age can have important effects on the hydrological characteristics of soils, we want to give land managers insights on the choice of the most suitable land use planning in view of facing the high runoff and erosion rates typical of the Mediterranean areas.

2. Material and methods

2.1. Study area

The study area is located in "Los Palancares y Agregados" forest, inside the largest natural reserve of Castilla-La Mancha (18,078 ha, Central-Eastern Spain, Figure 1) (Lucas-Borja et al., 2012; 2016). This forest covers about 4900 ha (40º01´50´´N; 1º59´10´´W) at an average elevation of 1200 m above sea level and consists of 85 compartments. According to the Kottek et al. (2006) classification, the climate of this area is Mediterranean humid (Csa). The mean annual temperature is 11.9 ºC, with a mean lowest temperature of the coldest month equal to -0.5 ºC and a mean highest temperature of the hottest month equal to 30.5 ºC. The mean annual precipitation is 595 mm, of which only 99 mm occurring in summer.

The soils of this area are classified as Entisols, according to the USDA soil taxonomy (Soil Survey Staff, 1999), with a sandy clay loam texture. The study area is dominated by mixed or monospecific forests of Spanish black pine (*Pinus nigra* Arn. ssp *salzmannii*), Holm oak (*Quercus ilex* L.), Portuguese oak (*Quercus faginea* Lam) and Spanish juniper (*Juniperus thurifera* L.). The herbaceous and shrub vegetation is characterized mainly by *Juniperus oxicedrus* L., *Rosa* sp., *Eryngium campestre* L., *Geranium selvaticum* L., *Centaurea paniculata* L., and *Plantago media* L. This type of forest ecosystem is included in the European Union endangered habitats, a listing of natural habitats requiring specific conservation measures (Resolution 4/1996 by the Convention on the Conservation of European Wildlife and Natural Habitats) and in the Protected Areas listing of the government of Castilla La Mancha (2/2001, Official Diary of Castilla La Mancha Nº 8). The forest management plan was the shelterwood method, which was applied since 1895 with a shelter-phase of 20 years and a rotation period of 100 years. The shelterwood method has remained equal ever since, which means that several classes of tree age have been generated in approximately 120 years in the 85 compartments. The regeneration method in both mixed and pure even-aged Spanish black pine stands consists of a uniform opening of the canopy without soil preparation. The main effort of this forest management plan aims at increasing forest standing stock and transforming age-heterogeneous stands into even-aged.

2.2. Experimental design

The forest under age-class management is characterised by a sequence of relatively homogenous, even-aged stands, once the rotation period (100 years) is completed. As the management operations in "Los Palancares and Agregados" forest started at the end of the 19th century, it was possible to select different compartments and age stands, ranging from 100 years old to 1 year old.

In May 2019, twelve compartments, each one of about 50 ha, were randomly selected in the study site, considering three compartments in each forest stand of the following ages:

(i) "PN I" (age 100–80 years).
(ii) "PN II" (age 79–60 years).
(iii) "PN III" (age 39–20 years).
(iv) "PN IV" (age 19–1 years).

Three other compartments ("PNUM"), 80 to 120 years old and without any anthropogenic influence (that is, forest management), were selected as "control" stand. The main forest and soil characteristics of each tree age level, which have been obtained from the current forest management plan developed by Castilla La Mancha Forest Service in 2005, are summarized in Table 1. All compartments had a main tree species (*Pinus nigra ssp. salzmannii*), with different density, basal area and height, but similar herbal and shrubs species composition. These forests have been growing under the same climatic conditions during the last century and are comparable in terms of soil (both type and texture), aspect (flat area) and slope (< 5%) (Table 1).

In each of the fifteen compartments, three plots, each one covering an area of 3 x 3 square metres, were identified, to measure SHC and SWR, and the physico-chemical soil properties (total of 45 plots). The distance between plots was greater than 500 m, in order to consider the plots as independent.

2.3. Measurement of soil properties and covers

The soil properties were measured on three soil samples at each plot. After manually removing the litter, the samples were collected in the surface layer (at a depth of 5 cm). This depth was chosen since the effects of tree species (through litter dynamics) should be stronger compared to the deeper layers. Each sample consisted of six sub-samples, each of 0.2 kg, which were mixed to obtain a composite sample. After removing plant residues for soil sampling, the samples were sieved at 2 mm) and then kept at 3 °C before the analyses, which were carried out one week after soil sampling.

The soil texture (sand, silt and clay contents, in percentage) was analysed using the soil survey laboratory methods suggested by NRCS (1996). The bulk density (BD) was calculated on triple samples per plot, as the weight of soil in a given volume of a core extracted from the surface soil using a small cylinder. The electrical conductivity (EC) and pH were measured, using a Crison conductivimeter and pH meter, respectively, in a 1/5 (w/v) aqueous extract. Soil organic matter (OM) was determined by oxidation with K_2CrO_7 in an acid medium and titration of the excess dichromate with $(NH_4)_2Fe(SO_4)_2$ (Yeomans and Bremner 1989). Total nitrogen (TN) was measured using Kjeldhal's method as modified by Bremner and Mulvaney (1982). The phosphorous content (P) was determined after sample digestion with nitric perchloric acid, by ICP spectrometry. The limestone (AL) content was measured according to Della Porta et al (2003).

Moreover, in each plot, three longitudinal transects were identified to measure the areal covers of vegetation, dead matter, rock and bare soil (hereinafter "soil covers", in %) using touch lengths in each transects, which was 3-m long.

2.4. *Measurement of SHC and SWR*

SHC and SWR were measured in three points, randomly selected for each plot, using a Mini-Disk Infiltrometer (MDI, Decagon Devices, Inc. Pullman, W.A.) and the Water Drop Penetration Test (WDPT, (Woudt 1959; Letey 1969) method. MDI infiltrometer is commonly used for field measurements, given its small size and easy handling (Robichaud et al., 2008a), while WDPT is a simple but reliable method to measure SWR (Doerr, 1998; Dekker et al., 2009). In more detail, the SHC measurements were carried out in unsaturated soil conditions according to the MDI technical manual and Robichaud et al (2008a, b). Shortly, the litter cover was removed by a small shovel, and the soil surface was cleaned using a brush, before the measurements. A cut was made at a depth of 1-2 cm, to prepare a horizontal surface for placing the infiltrometer. Then, the volume of water infiltrated in the device was measured every 30 seconds for no less than 10 min. SHC was estimated applying the equations proposed by Zhang (1997) to the infiltrometer records. Firstly, the measured cumulative infiltration values (I, [m]) were regressed against the measured time intervals (t, [s]) by equation (1):

$$I = C_1 t + C_2 t^{1/2} \quad (1)$$

where:

C_1 = coefficient related to soil hydraulic conductivity [m s^{-1}]
C_2 = coefficient related to absorption capacity [m $s^{-1/2}$].

Then, the SHC (k, [mm h^{-1}]) was calculated by the following equation:

$$k = C_1/A \quad (2)$$

"A" is a value corresponding to the Van Genuchten parameters (n and α) for a given soil type for the suction rate (h_0, -2 cm) and disk radius (2.25 cm) of the infiltrometer. According to n, α and h_0 values for the experimental soils, A was equal to 3.91 (Decagon Devices, Inc. Pullman, W.A.) (Devices 2013). As regards the SWR determination, WDPT measures the time that a drop takes to completely infiltrate into soil. In this study, 15 drops of distilled water were released, using a pipette, on the soil surface of a 1-m transect, to homogenize the changing soil conditions; the time necessary for drops to infiltrate completely into the soil was measured by a stopwatch. SWR was classified according to the values of WDPT as Bisdom et al (1993):

i) Non water-repellent or wettable soil (class 0, WDPT < 5 s).
ii) Slightly water-repellent soil (class 1, 5 < WDPT < 60 s).
iii) Strongly water-repellent soil (class 2, 60 < WDPT < 600 s).
iv) Severely water-repellent soil (class 3, 600 < WDPT < 3600 s); and
v) Extremely water-repellent soil (WDPT > 3600 s).

The latter class has on its turn three sub-classes:

v') Sub-class 4 (1 < WDPT < 3 h);

v") Sub-class 5 (3 < WDPT < 6 h); and

v"') Sub-class 6 (WDPT > 6 h).

The mean values of both SWR and SHC were calculated at the plot scale and used for the statistical analyses.

Finally, since SWR strictly depends on its water content (SWC, e.g., Dekker and Ritsema, 1994; Lichner et al., 2013; Vogelmann et al., 2013; Alagna et al., 2017), this property was measured simultaneously to SWR by a device, placed on the soil surface and connected to a data logger (UX120 4-channel Analog Logger, Onset HOBO, Massachussetts, USA).

2.4. Statistical analyses

The reciprocal relationships among the soil properties and covers (RC, VC, BSC, DWC, SaC, SiC, ClC, BD, pH, EC, OM, TN and AL) as well as their influence on SHC and SWR were evaluated adopting a combination of statistical techniques. First, the statistical differences in SHC or SWR measurements were determined by the multivariate permutational analysis of variance (PERMANOVA, Anderson, 2005), using the tree age (PNUM, PN I, PN II, PN III and PN IV) as factor. PERMANOVA tests the simultaneous response of one variable to one or more factors in an experimental design based on any resemblance measure, using permutation method. Before PERMANOVA, the soil properties and covers were log(x+1) transformed, whereas SHC and SWR data were square root transformed; the resemblance matrix was built using the Euclidean and Bray Curtis distance for soil properties and covers, and SHC or SWR data, respectively. No normality tests were applied, since PERMANOVA do not require sample normality. The sums of squares type were type III (partial) and the four-level factor was a fixed effect (tree age). The permutation method used was the unrestricted permutation of raw data and the number of permutations was 999. Then, the analysis of similarities (ANOSIM), described by Clarke (1993), was carried out for the soil properties and covers, and the multivariate resemblances were analysed, according to the tree age. Secondly, the non-metric Multi-Dimensional Scaling (MDS) and the

Kruskal stress formula (minimum stress of 0.01) were applied to the soil properties and covers, to evaluate the similarity level in the individual cases of the dataset. Thirdly, a DISTLM function (distance-based linear modelling) was developed to determine the relative importance of each soil property and cover on SHC and SWR variables. For the DISTLM routine, we applied "marginal" tests of the relationship between the response variable (SWR or SHC) and an individual variable (soil property or cover), in order to identify the independent variables that explain the variations in the soil samples. Following the marginal tests, "sequential" tests of individual variables were performed, in order to assess whether adding an individual variable contributes significantly to the explained variation of the response variable. Third, the distance-based redundancy analysis (dbRDA) was applied to SHC and SWR, to build a regression model against two new response variables ("axis" 1 and "axis" 2), using the soil properties and covers as input. The AICc (Akaike Information Criterion, (Akaike 1974)) criterion was adopted to select the best model and the step-wise procedure was followed to build the model. Finally, two multiple regression models were built between those soil properties and covers (independent variables "y") that were found to be most influencing SHC and SWR and the latter variables (each one assumed as dependent variable "y") plus the forest age. The explanatory capacity of the models (that is, its prediction accuracy) was measured by the coefficient of determination (r^2). For the statistical analyses the software PRIMER V7® with PERMANOVA add-on (Anderson et al., 2008), Statgraphics Centurion XVI® (StatPoint Technologies, Inc., Warrenton, VA, USA) amd XLSTAT version 2020 (Addinsoft, Paris, France) were used. A significance level of 0.05 was used, unless otherwise indicated.

3. Results

Vegetation cover was more developed in the younger forest stands (PN II, PN III and PN IV, from 54.4 ± 10.1% to 70.6 ± 9.50%) and lower in the older PN I and PNUM stands (31.7 ± 19.7% and 21.7 ± 5.0%). A small percentage of rocky soil was found in PN III (3.3 ± 5.0%) plots, which also showed the highest percentage of bare soil (17.8 ± 12.0%) among the stands. Dead wood was noticeable in PNUM (78.3 ± 5.0%), PN I (67.8 ± 19.2%) and PN II (65.0 ± 11.7%) plots and lower in the other forest plots (less than 24.4%) (Table 2).

Soil texture, prevalently sandy clay loam, showed slight differences among the plots, with lower sand content in PN III and PN IV forests stands (49.4 ± 1.2% and 49.0% ± 1.6%, respectively), which had higher clay contents (25.7 ± 2.5% and 27.5 ± 1.5%, respectively). The latter forest soils showed the lowest OM content (6.66 ± 1.2%), while the PNUM showed the highest OM (12.7 ± 1.11%). The highest TN content was detected in PN I soils (0.67 ± 0.04%) and the lowest in PN IV plots (0.28 ± 0.1%). The soils of PN IV stands were more compacted compared to the other forest plantations, as shown by the higher BD (1.79 ± 0.06 g/cm^3 against values between 1.40 ± 0.01 and 1.42 ± 0.02 g/cm^3 of PNUM and PN I soils, which were the less compact). Three forest soils were slightly acidic (PNUM, PN I and PN II, pH of 6.1 ± 0.4, 6.6 ± 0.6 and 6.3 ± 0.4, respectively), while the remaining plots were alkaline (pH = 7.9 ± 0.2, PN III, and 8.1 ± 0.3, PN IV). EC was in the range 0.21 ± 0.02 (PN II) to 0.27 ± 0.02 (PN I) mmhos/cm. Finally, the AL content was variable between 4.84 ± 0.37% in PN III forests and 5.48 ± 0.24% in PNUM plots (Table 2).

In relation to the physico-chemical properties and covers of soils in the forest compartments, ANOSIM (providing a global R of 0.645 and a significance level of 0.05%) showed significant differences among all tree ages. In accordance with the ANOSIM results, MDS clearly grouped the five forest stands with different age in as many clusters, depending on the property and cover variables (Figure 2).

The importance of each property or cover of soil in clustering all tree levels is shown by the loading of each variable on the two axes, MDA1 and MDA2 (Table 3). A clear gradient between PN III and PN IV on one side, and PN I, PN II and PNUM on the other side is noticed along the first axis (MDA1). In more detail, while all sand and clay fractions of soil, OM, TN, BD and pH among the physico-chemical properties, and all soil covers significantly weighted on the axis one (loadings over 0.65), only the silt content of soil had a large effect on axis two (loadings over 0.60). This means that clusters of soils under the five forest stands were differentiated according to a combination of these variables. In particular, the soil cover and texture, and other important factors (e.g., OM, nutrients and soil compaction) drive the vegetation dynamics (Figure 2). It is worthy to notice that each of the two groups of clusters, those with soil sampled in PN III and PN IV as well as in PNUM, PN I and PN II plots, shared very similar values of these properties.

The mean values of SHC, in general very low (few millimetres per hour), were in the range 0.78 ± 0.002 mm/h (PN IV plots) to 4.39 ± 0.54 mm/h (PN III) (Figure 3a), whereas WDPT was between 3.05 ± 0.72 s (PNUM plots) and 55.2 ± 39.9 s (PN IV) (Figure 3b). According to the SWR classification adopted in this study, four forest soils were "wettable" or "non repellent" (PNUM, PN I, PN II and PN III), since WDPT was always lower than 60 seconds, while only PN IV plots showed a slight repellency (WDPT > 60 s). SWC was very similar among both the plots subjected to SWR measurements, which furthermore showed a very low variability (due to the same morphological conditions of the plots and physico-chemical properties and covers of soils). The mean values of SWC in the studied forest stands were 10.99 ± 0.26% (PNUM), 10.94 ± 0.19% (PN I), 10.79 ± 0.25% (PN II), 11.37 ± 0.26 (PN III) and 11.26 ± 0.21% (PN IV).

SHC and SWR were both significantly different (Pseudo-F= 121.54; P(perm) < 0.001 and Pseudo-F= 33.404; P(perm) < 0.001, respectively) among the tree ages according to PERMANOVA. In spite of the significant differences in WPDT values, no changes in SWR level (repellent vs wettable soil) were detected in forests of four tree ages (PNUM and PN I to PN III). In relation to the pairwise comparisons among tree ages, only the difference between PNUM and PN I was not significant (at $p < 0.05$) for SHC. Instead, all couples of tree ages were significantly different for SWR, except the difference between PN I and PN II (not significant at $p < 0.05$) (Table 4). Furthermore, no significant correlations between SHC and SWR ($R^2 < 0.18$), except for the PNUM forest stands, although the latter was not high ($R^2 = 0.44$) (Figure 4).

By applying the distance linear models (DISTLM), the marginal tests revealed that all the soil physico-chemical properties and covers significantly influenced SHC, except SiC, EC and AL for both SHC and SWR ($p < 0.05$), when those variables were considered as isolated (Table 4). The sequential tests indicated that the best distance linear model ($R^2 = 0.80$; AICs = 187.2) for predicting SHC consisted of DWC, TN, OM and BD, which explained more than 80% of the total variation of SHC (Table 5). A larger set of variables should be used in the best distance linear model ($R^2 = 0.77$, AICs = 246.29) for predicting SWR, and this set consists of ClC, OM, BSC and TN, explaining more than 78% of the total variation of SWR; soil pH can be removed from this set, loosing little variance explanation (less than 1%) (Table 5).

According to the variations (out of the fitted model and out of the total variation) explained by the axes of dbRDA, axis one (dbRDA1) explained almost all (99.3%) of the total variation the fitted model and 79.8% of the total variation of the variables for SHC, whereas the axis two (dbRDA2) explained only 0.7% of the fitted model and 0.6% of the total variation (Figure 5a). When dbRDA was applied to SWR, the axis one (dbRDA1) explained 98.9% of the fitted model and 7.57% of the total variation, whereas the axis two (dbRDA2) explained 1.1% of the fitted model and 0.8% of the total variation (Figure 5b). As for DISTLM model, DWC, TN, OM and BD were the soil properties that most influenced these two axes in the dbRDA model, used to predict SHC (although with variable loadings), while ClC, OM, BSC and TN heavily weighted on the two axes in the SWR prediction model (Figures 5a and 5b).
Finally, the multiple regression models to predict SHC and SWR from the most significant soil properties and covers identified by the marginal and sequential tests and forest age have the following expressions:

$$SHC = 2.405 \times 10^{-4} \times DWC - 0.586 \times TN + 8.308 \times 10^{-2} \times OMC + 0.917 \times BD + 0.235 \times FS\text{-}PN\ I - 0.893 \times FS\text{-}PN\ II - 2.192 \times FS\text{-}PN\ IV - 3.646 \times FS\text{-}PN\ V \quad (1)$$

and

$$SWR\ (WDPT) = -36.319 + 1.766 \times ClC + 0.141 \times OMC + 0.234 \times BSC - 3.196 \times TN + 4.902 \times FS\text{-}PN\ I + 6.326 \times FS\text{-}PN\ II + 28.727 \times FS\text{-}PN\ IV + 40.021 \times FS\text{-}PN\ V \quad (2)$$

where FS-PN I, FS-PN II, FS-PN IV and FS-PN V are categorical variables that assume the values of zero or one if according to the forest age (for instance, FS-PN II is zero if the forest is 30 years old and one if the forest is 70 years old). The measuring units of the independent and dependent variables are reported in Table 2. The explanatory capacity of the models is $r^2 = 0.860$ for SHC and $r^2 = 0.8607$ for SWR. Figures 6a and 6b, illustrating the accuracy of the predicted SHC and SWR compared to the measured values, show how almost all the predictions (except one soil sample of PN II) fall inside the 95% confidence interval (Figures 6a and 6b).

4. Discussions

Several studies have highlighted the importance of water infiltration in the hydrological response of forest soils, which is governed by the variability of SHC. On its turn, this hydrological property is strictly linked to the textural fractions, surface conditions and physico-chemical properties of soils (e.g., DeBano and Rice, 1973; Wahl et al., 2003; Martínez-Zavala and Jordán-López, 2009). Moreover, SWR is another key factor in driving the hydrological processes in forestland (Stoof et al., 2011), since this property may alter, often noticeably, the infiltration capacity of surface soil and increase its capacity to generate runoff. The forest soils of this study were characterised by the same dominant tree species (*Pinus nigra* Arn. ssp *salzmanni*) and rather homogenous geomorphological, ecological, physiographical and climatic conditions. These site-specific conditions allowed disentangling the effects of forest age and forest structure on the main soil properties and simultaneously on the SHC and SWR variability among a chrono-sequence of forest stands.

The positive development of multiple forest functions and complexity from years to decade can be a consequence of the natural development of forest ecosystems. Peterken (1996) demonstrated that the structural and functional forest complexity increases at higher tree stand ages. A large variation in tree dimension and basal area, the occurrence of large living trees and multi-layered canopy, a large amounts of deadwood, vertical multi-layering or the presence of gaps, which create an ecological niche for a wide range of species, are easily found in older forest stands (Sabatini et al., 2018). On this context, this structural and functional forest complexity may induce higher litterfall, nutrient content and soil organic matter accumulation on the forest floor (Lucas-Borja et al., 2016). Moreover, structural and functional forest complexity significantly re-routed vertical precipitation pathways by canopy interception, throughfall and stemflow, hence clearly affecting the water regulation function (Sun et al., 2006).

In this study, SHC was the highest in the older forests (PNUM, PN I and PN II) and the lowest in the more recent stands (PN III and PN IV); averaging this difference among the two groups of forest stands (the older and the newer), the percent variation is 64%. The higher SHC in PNUM, PN I and PN II plots can be explained by the higher OM content of soil (about 50% more than in PN III and PN IV). OM increases improve the stability of aggregates and therefore the soil macro-porosity (Chenu et al., 2000; Devine et al., 2014). These differences in SHC are also reflected by the lower bulk density (on the average -45% compared to the mean value of PN III and PN IV), since a lower soil compaction facilitates water infiltration, which helps to reduce the runoff generation capacity of the forest soils (Lucas-Borja et al., 2018). Moreover, differences between managed and unmanaged stands may be related to harvesting operations and machinery soil influence. The pros (e.g., economic benefits, reduced fire susceptibility, increased worker safety and access) and cons (e.g., increased soil compaction, increased hydrologic responses, and short-term loss of habitat) of tree harvesting have been debated for years (Gomez et al., 2002; Lucas-Borja et al., 2020). More in detail, Lucas-Borja et al. (2020) demonstrated in the same forest area that harvesting operations generated higher soil compaction and lower plant cover in skidding affected plots, which could reduce water infiltration capacity.

Also SWR may have played a role on the SHC differences among the forest stands. All the plots, except those in the more recent forest stand, were non-repellent, although the differences in WPDT were significant; slight SWR was found in PN IV plots. Also Zavala et al. (2014) found a lower SWR in pine stands compared to other species (oaks and eucalypts), while other studies (Buczko et al., 2002; 2005; 2006; Bens et al., 2007) showed that SWR may be apparent especially at the mixed stands with coniferous. These contrasting findings suggest that SWR may be expected or not in *Pinus* stands, but, if present, it is of very low intensity.

Differently from SHC, the differences in SWR cannot be related to the OM content of the soil, as instead was found by some authors (e.g., Cesarano et al., 2016). For instance, Buczko et al. (2002) reported that soil OM and WDPT had positive and fair linear correlations each other, explained by the higher proportion of mor-type humus and greater thickness of the humus topsoil. More in general, significant positive relationships between SWR and OM of soil were reported in literature (e.g., Martínez-Zavala and Jordán-López, 2009; Olorunfemi and Fasinmirin, 2017; Plaza-Álvarez et al., 2018), particularly when the other soil physico-chemical properties are similar (Chenu et al., 2000; McKissock et al., 2002; Mataix-Solera and Doerr, 2004; Kajiura et al., 2012). Conversely, in this study, the higher is the SWR, the lower is the OM content of the soil and this relationship should be explained by factors other than OM quantity, derived from the decomposition of vegetation and litter. In general, many other studies have shown that soil content of OM alone could not fully account for the variability in SWR, but also the soil texture may be in some cases an influencing factor on SWR level. Presumably, changes in soil OM storage and quality caused by the different tree ages affected the WDPTs, however without inducing repellency, which in turn influenced the hydraulic properties of the experimental soils (Bens et al., 2007). In more detail, although the soil texture of the five forest stands was homogenous, the higher clay content of PN IV plots (the only forest stand showing SWR) may affect WPDT values. This in accordance with findings of Keiluweit et al. (2015), Bonanomi et al. (2013) and Cesarano et al. (2016), who found that clay content may increase in some cases WDPTs and thus SWR. Moreover, also plant litter can have been as a source of hydrophobic substances, since it is able to induce a small SWR with a different response depending on plant species (DeBano, 1981; Doerr et al., 2000; Olorunfemi et al., 2014; Cesarano et al., 2016).

Another important result of this study is the lack of significant correlations between SHC and SWR (except in unmanaged and older pine stands), as confirmed by the low and non-significant linear regressions. Instead, a negative correlation between SHC and SWR was found in (Olorunfemi and Fasinmirin 2017). The lack of correlation between these two hydrological parameters should be due to the fact that some soil properties and covers influence only SWR but not SHC and vice versa. For instance, while many soil cover parameters played a clear effect on SWR, the same influence was not as evident on SHC. Moreover, although SHC and SWR were simultaneously measured in the same point or, at least, very close points, also the different spatial variability of these parameters can have plaid a role on their separate dynamics.

The tree ages of these stands were clearly differentiated according to the variability of the physico-chemical properties and covers, as shown by the MDS biplot. Soil samples were arranged in two separated groups of clusters, one for the older three stands and another for the more recent pine trees, with a limited overlap among clusters. This clear separation was due to the variability of almost all soil properties and covers (except for active limestone, silt content and electrical conductivity of soils). This means that forest ages determined a temporal dynamics in the complex physico-chemical and biological processes acting in forest soils (Lucas-Borja et al., 2012; 2016). It should be noticed also an evident gradient in the axis one of MDS along the clusters of soil samples collected under the stands with different ages. This gradient was also generated by the small differences in texture fractions of soils, which strongly contributed to differentiate the forest soils despite the large similarity of soil sites.

The statistical analysis based on DISTLM routine highlighted that the same variables individually influence SWR and SHC, according to the tree ages. This result is in close accordance with the previous discussion, confirming that, among all the soil properties, the organic matter and total nitrogen contents of soil were key parameters in driving the hydrological characteristics of the studied forest soils. However, the synergistic effects among these properties or covers of soil cannot be neglected for both SHC and SWR, since these effects made the influence of some individual parameters (e.g., the sand content and vegetation cover) not significant on soil hydrological parameters. This was also shown by the multiregression model built using dbRDA, which was particularly accurate in explaining the variability of SHC or SWR among the different forest stands. This accuracy is proven by the high percentages (more than 80% for SHC and 75% for SWR) of the total variation of the soil properties and covers that is explained by the models. According to these models, the organic matter and nitrogen contents as well as the of the bulk density and dead wood cover of soils were the most meaningful variables in predicting SHC for the different forests stands; two of these variable (OM and TN) and the clay content and bare soil cover must be used to differentiate the SWR among the different forest ages. Also, in the biplots related to dbRDA, clear clusters were evident, discriminating forest soils with higher SHC (PN I and PNUM stands) from soils with the lower SHC (PN II, PN III and PN IV stands) as well as the different values of WDPTs among the compartments. In the study of Šimkovic et al. (2009), the results of multiple regression analysis showed that SWR in topsoil material is significantly controlled by organic carbon content (as in this study), while this investigation has shown that the differences among the forest stands were determined by other and more numerous soil properties. As regards SHC, also this analysis has demonstrated that OM content of soil (most influencing the axis one) created a noticeable gradient (and thus a clear difference) between the more recent and the older forest stands (the latter having higher OM and TN contents as well as dead wood amount and bulk density). In temperate forests, carbon and nitrogen in soils are bound together in organic matter and the accumulation of C and N in soil organic matter occurs through the same mechanisms, production of dead organic matter and microbial turnover. Thus, an accumulation of soil organic matter and litterfall occurred with stand age might then promote an accumulation of N. Finally, confirming other literature studies (e.g., Zavala et al., 2014; Cesarano et al., 2016), OM is an important parameter influencing WDPT among forests of different ages, although the direct influence of OM should be deepened in terms of quality.

The multiple regression models established between the most significant properties and covers of soils on one side as well as SHC and SWR on the other side according to the forest age have a very accurate prediction capacity for both the modelled variables. Since almost all the predictions of SHC and SWR are reliable, these models, which requires a low number of input parameters that furthermore are easy to be measured, may be used for predictions of these hydrological variables under future scenarios of climate changes, when modifications of soil properties are expected (e.g., reductions in organic matter or vegetal cover), which may influence both SWR and SHC (Lucas-Borja et al., 2019).

Overall, together with the forest stand ability to cope with climate, our results should be considering to suggest proper management guidelines of Mediterranean forests. Mid to long-term studies related to different mixed species stand composition should be developed to fully understand SHC and SWR patterns. These findings provide a guideline for developing suitable forest management guidelines aiming to conserve the older forest stands, in which structural and functional forest complexity, soil organic matter and litter accumulation or higher levels or microbial activities clearly favour nutrient cycling, carbon stocks, water regulation, decomposition and wood production. This allows preserving the multiple forest actions, that is, forest health and functions for future generations.

Further research should evaluate whether and by what extent the changes in soil properties and the consequent variability of SHC and SWR across temporal gradients may affect other important species of the Mediterranean forests. Moreover, modelling approaches can be adopted to predict the effects of climate change across next decades on eco-hydrology of forest soils. For instance, decision support systems can be applied to artificial intelligence techniques (Manos et al., 2010; Bournaris et al., 2015), in order to give landscape planners useful indications about sustainable management practices of forest ecosystems.

5. Conclusions

This study has shown that water infiltration of soil is higher and its repellency is lower in the older forests compared to the more recent pine stands. The differences in SHC were attributed to the OM content of the soils, while their different texture presumably has played a minor role. Conversely and contrarily to what expected, the higher SWR shown by the more recent pine stands, characterised by lower OM content, may be attributable to different combination of soil properties and covers. The significant differences detected in several physico-chemical properties and covers of the forest soils under the studied chrono-sequence help to confirm our working hypothesis that SHC is influenced by forest age, but reject the statement that SWR characterises old pine plantations. Moreover, the accurate and meaningful multiregression models shows that few soil variables, different for each different forest age, are good predictors of both SHC and SWR, although several variables play significant effects as the product of the very complex processes driving the characteristics of forest soils.
Overall, the results of this study highlight that in new forest plantations water infiltration may decrease with increases in runoff generation capacity of the soils. Conversely, no water repellency (or very slight hydrophobicity in recent plantations) is expected in new pine stands.

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TABLES

Table 1 - Soil, climatic and stand characteristics of the experimental area of Los Palancares y Agregados forest (Castilla La Mancha, Spain).

Forest stand	**Forest characteristics**			**Tree characteristics**			**Shrub and herbal characteristics**		**Soil characteristics**	
	Age (years)	*Regeneration period*	*Main tree species composition*	*Density (trees ha^{-1})*	*Basal area (m^2 ha^{-1})*	*Height (m)*	*Vegetation cover (%)*	*Species composition*	*Slope (%) and aspect*	*Type and texture*
PNUM	80-120	No intervention	*Pinus nigra* ssp. *salzmannii*	1221-1129	49-55	35-40	35-40	*Crataegus monogyna L. Geranium selvaticum L., Cardus-cellus hispanicus L., Trifolium montanum L.*	< 5 and flat	Entisols Sandy clay loam
PN I	80-100	1895-1915		1017-823	28-38	15-20	25-35	*Genista scorpius L., Geranium selvaticum L., Cardus-cellus hispanicus L., Trifolium montanum L.*		
PN II	60-79	1915-1935		947-818	25-35			*Genista scorpius L., Eryngium campestre L., Geranium selvaticum L., Plantago media L.*		
PN III	20-39	1955-1975		1351-1007	18-25	12-15	25-30	*Genista scorpius L., Eryngium campestre L., Geranium selvaticum L., Plantago media L.*		
PN IV	1-19	1975-1995		1443-1371	12-21	1-10	15-20			

Table 2 - Mean and standard deviations of the main physico-chemical properties and covers of soil sampled in plots under four tree ages by pairwise test using Permutational multivariate analysis of variance (PERMANOVA) (Los Palancares y Agregados, Castilla-La Mancha, Spain).

Soil properties and covers		**Forest age**									
		PNUM		**PN I**		**PN II**		**PN III**		**PN IV**	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Soil covers	*RC (%)*	0.00 a	0.00	0.00 a	0.00	0.00 a	0.00	3.33 a	5.00	3.89 a	4.86
	VC (%)	21.67 a	5.00	31.67 ab	19.69	32.22 ab	13.25	54.44 bc	10.14	70.56 c	9.50
	BSC (%)	0.00 a	0.00	0.56 a	1.67	2.78 ab	4.41	17.78 b	12.02	12.22 b	8.33
	DWC (%)	78.33 a	5.00	67.78 a	19.22	65.00 ab	11.73	24.44 bc	12.36	13.33 c	8.29
Soil texture	*SaC (%)*	53.37 a	1.65	53.23 a	1.02	53.33 a	1.32	49.39 b	1.22	48.99 b	1.62
	SiC (%)	24.41 a	1.80	23.77 a	1.28	21.89 a	2.03	24.90 a	2.25	23.48 a	1.43
	ClC (%)	22.22 a	1.09	23.00 ab	0.87	24.78 abc	1.48	25.71 bc	2.52	27.53 c	1.52
Soil physical properties	*BD (g/cm³)*	1.40 a	0.01	1.42 a	0.02	1.53 ab	0.05	1.62 bc	0.04	1.79 c	0.06
	pH (-)	6.11 a	0.37	6.64 ab	0.55	6.34 a	0.35	7.90 bc	0.23	8.10 c	0.29
	EC (mmhos/cm)	0.23 ab	0.03	0.27 b	0.02	0.21 a	0.02	0.25 b	0.15	0.25 ab	0.10
Soil chemical properties	*OM (%)*	12.69 a	1.11	9.81 ab	2.21	9.50 abc	1.59	7.73 bc	1.32	6.66 c	1.17
	TN (%)	0.52 ab	0.05	0.67 b	0.04	0.57 ab	0.06	0.37 bc	0.03	0.28 c	0.05
	AL (%)	5.48 a	0.24	4.91 a	0.46	4.88 a	0.46	4.84 a	0.37	4.88 a	1.34

Note: different letters indicate statistically significant differences according to PERMANOVA tests (at $p < 0.05$). See the related list for the abbreviations.

Table 3 - Spearman correlations of physico-chemical properties and covers of soil samples collected in plots under four tree ages using multidimensional scaling (MDS) routine (Los Palancares y Agregados, Castilla-La Mancha, Spain).

Soil property/cover	**MDS1**	**MDS2**
RC	**0.613**	-0.413
VC	**0.816**	-0.060
BSC	**0.638**	0.214
DWC	**-0.915**	0.187
SaC	**-0.825**	0.035
SiC	0.070	**-0.668**
ClC	**0.755**	0.507
BD	**0.823**	0.214
pH	**0.895**	-0.074
EC	0.119	0.408
OMC	**-0.777**	-0.072
TN	**-0.840**	-0.022
AL	-0.399	0.409

Note: values in bold are significantly at p level < 0.05. See the related list for the abbreviations.

Table 4 - Comparison of SHC and SWR in plots under four tree ages by pairwise tests using Permutational multivariate analysis of variance (PERMANOVA) (Los Palancares y Agregados, Castilla-La Mancha, Spain).

Forest tree age	**SHC**		**SWR**	
	t	*P(perm)*	*t*	*P(perm)*
PNUM vs PN I	0.27	0.794	2.65	0.012
PNUM vs PN II	4.30	0.001	2.46	0.008
PNUM vs PN III	6.62	0.001	20.58	0.001
PNUM vs PN IV	25.49	0.001	21.50	0.001
PN I vs PN II	2.96	0.012	0.47	0.689
PN I vs PN III	5.80	0.001	6.75	0.001
PN I vs PN IV	19.47	0.001	7.52	0.001
PN II vs PN III	5.20	0.001	4.57	0.002
PN II vs PN IV	77.04	0.001	5.15	0.001
PN III vs PN IV	9.72	0.001	5.49	0.001

Notes: t = pseudo-t statistic; P(perm) = Permutation P value. See the related list for the abbreviations.

Table 5 - Marginal tests of the relationship between the response variables (SWR or SHC) and an individual soil property under four tree ages using matched resemblance matrices (DISTLM) (Los Palancares y Agregados, Castilla-La Mancha, Spain).

Soil property/cover	**SHC**			**SWR**		
	Pseudo-F	*P*	*Prop.*	*Pseudo-F*	*P*	*Prop.*
RC	15.31	0.002	0.263	10.50	0.001	0.196
VC	41.29	0.001	0.490	33.48	0.001	0.438
BSC	17.61	0.001	0.291	36.11	0.001	0.456
DWC	96.42	0.001	0.692	55.89	0.001	0.565
SaC	46.66	0.001	0.520	43.11	0.001	0.501
SiC	0.21	0.661	0.005	0.12	0.782	0.003
ClC	31.74	0.001	0.425	47.50	0.001	0.525
pH	55.24	0.001	0.562	57.62	0.001	0.573
EC	0.45	0.508	0.010	0.14	0.764	0.003
OMC	43.47	0.001	0.503	42.84	0.001	0.499
TN	88.03	0.001	0.672	48.12	0.001	0.528
AL	2.28	0.129	0.050	2.92	0.1	0.064
BD	46.06	0.001	0.517	10.50	0.001	0.196

Notes: bold values show the soil properties and cover that significantly influence SHC and SWR; Pseudo-F = pseudo-F statistic, P = P value; Prop. = Proportion of the variability explained by the selected soil property/cover. See the related list for the abbreviations.

Table 6 – Sequential tests of the relationship between the response variables (SWR or SHC) and soil properties after fitting one or more variables together under four tree ages using matched resemblance matrices (DISTLM) (Los Palancares y Agregados, Castilla-La Mancha, Spain).

Soil property/cover	**SHC**					
	AICc	*Pseudo-F*	*P*	*Prop.*	*Cumul.*	*Res. DF*
+ DWC	200.24	96.42	0.001	0.692	0.692	43
+ TN	191.39	11.80	0.003	0.068	0.759	42
+ OMC	187.35	6.32	0.015	0.032	0.791	41
+ BD	187.2	2.47	0.098	0.012	0.804	40
Best solution	$R^2 = 0.804$			AICc = 187.2		
	SWR					
Soil property/cover	*AICc*	*Pseudo-F*	*P*	*Prop.*	*Cumul.*	*Res. DF*
+ pH	266.04	57.62	0.001	0.573	0.573	43
+ ClC	255.72	13.59	0.001	0.104	0.677	42
+ OMC	252.07	5.92	0.014	0.041	0.718	41
+ BSC	247.86	6.47	0.012	0.039	0.757	40
+ TN	247.02	3.17	0.056	0.018	0.775	39
- pH	246.29	1.72	0.179	0.010	0.765	40
Best solution	$R^2 = 0.765$			AICc = 246.29		

Notes: AICc = Akaike value for the model; Pseudo-F = pseudo-F statistic; P = P value; Prop. = Proportion of the variability explained by the selected soil property/cover; Cumul. = Cumulative proportion variability explained by the selected soil property/cover; Res. DF = Degrees of freedom of the residual model; + indicates that the variable is added to the model, while - indicates a variable removed from the model. See the related list for the abbreviations.

FIGURES

Figure 1 - Location of the “Los Palancares y Agregados” forest and images of the five pine stands (Castilla La Mancha, Spain).

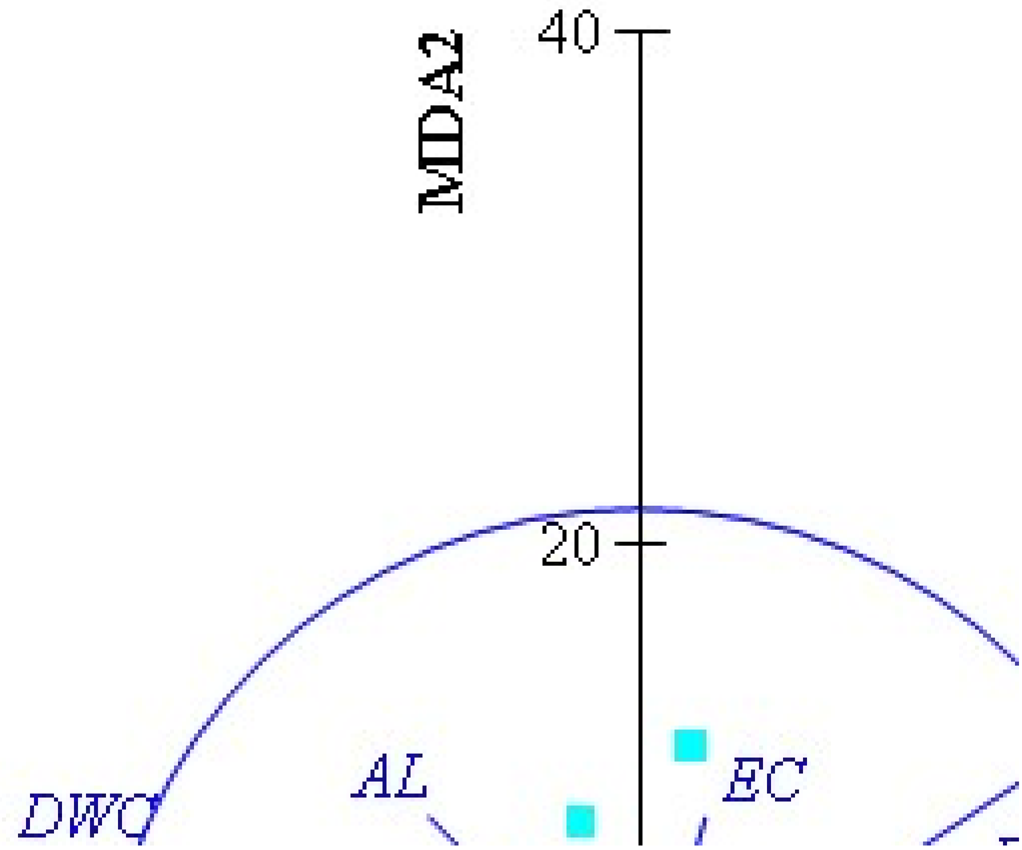

Figure 2 - Biplot of physico-chemical properties and covers of soil samples collected in plots under four tree ages using multidimensional scaling (MDS) routine (Los Palancares y Agregados, Castilla-La Mancha, Spain). See the related list for the abbreviations.

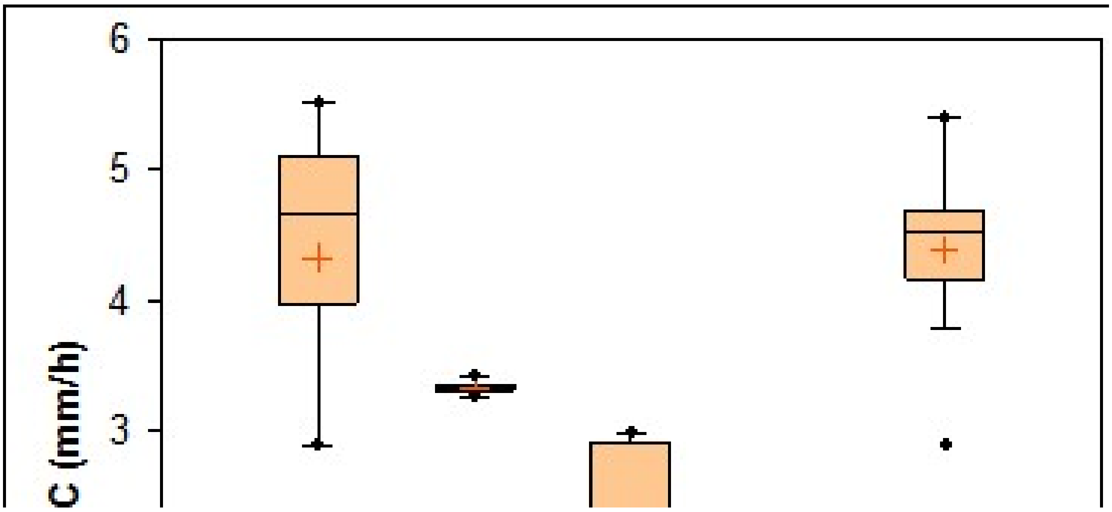

Figure 3 - Box-Whisker plots of SHC (a) and SWR (b) in forests under four tree ages (Los Palancares y Agregados, Castilla-La Mancha, Spain). See the related list for the abbreviations.

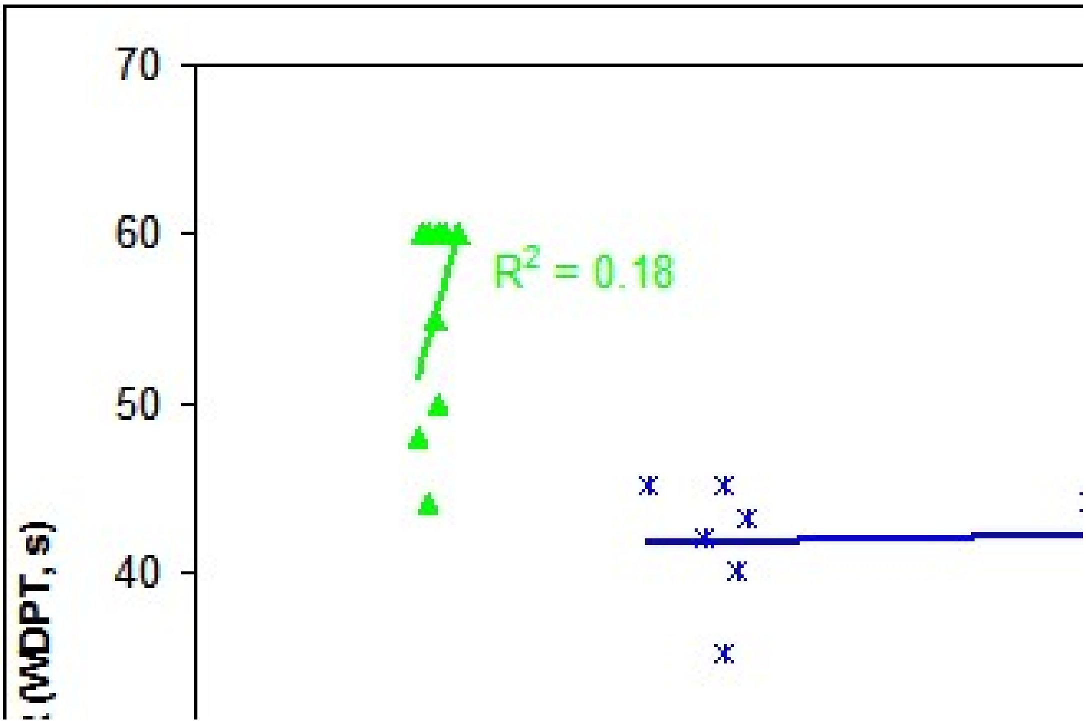

Figure 4 - Linear regressions between SHC and SWR in forest plots under four tree ages (Los Palancares y Agregados, Castilla-La Mancha, Spain). See the related list for the abbreviations.

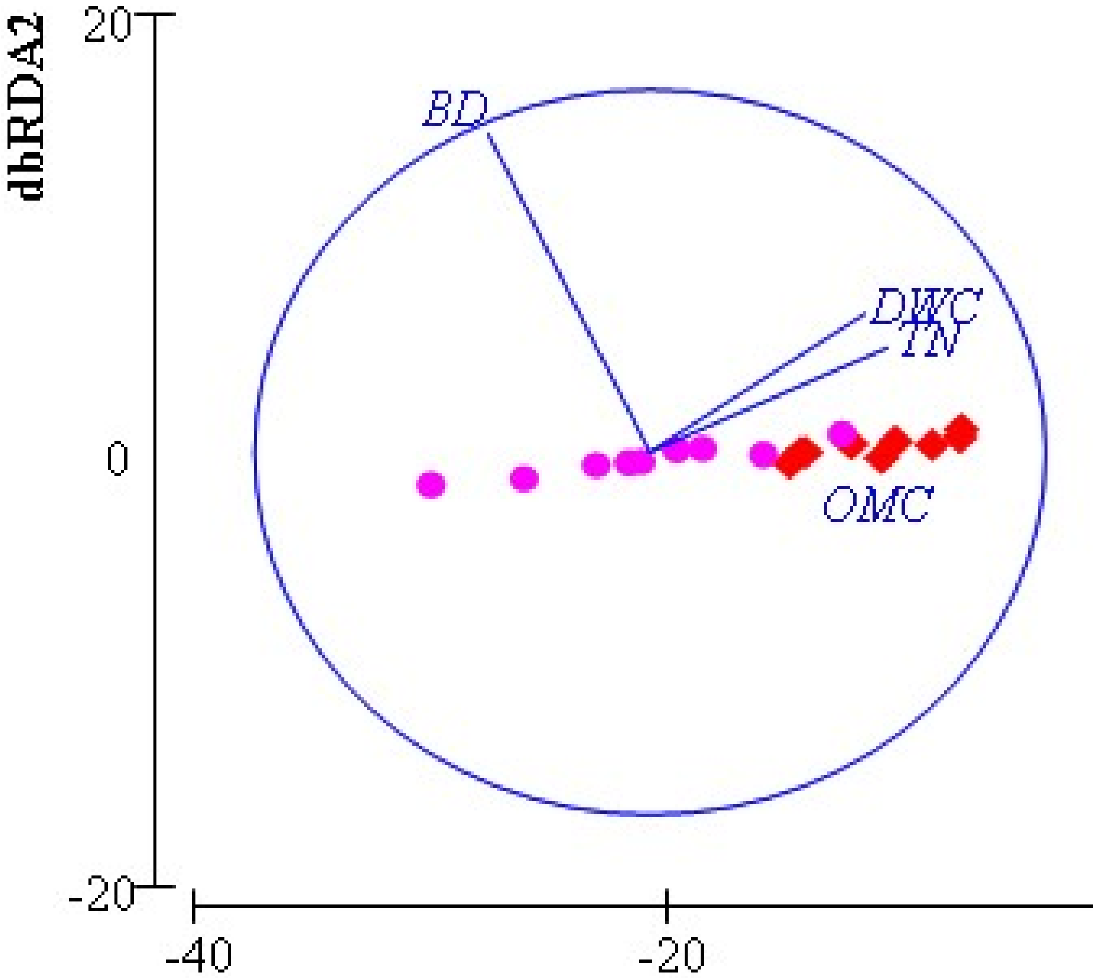

Figure 5 - Biplots of dbRDA applied to SHC (a) and SWR (b) of soils under four tree ages (Los Palancares y Agregados, Castilla-La Mancha, Spain). Abbreviations: RC: rock cover, VC: vegetation cover, BS: bare soil, DW: dead wood, SaC: sandy, SiC: silt, ClC: clay, BD: bulk density, EC: electrical conductivity, OM: soil organic matter and TN: total nitrogen). See the related list for the abbreviations.