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Effects of stand composition and soil properties on water repellency and hydraulic conductivity in Mediterranean forests

Demetrio Antonio Zema[1], John T. Van Stan II[2], Pedro Antonio Plaza-Alvarez[3], Xiangzhou Xu[4], Bruno Gianmarco Carra[1], Manuel Esteban Lucas-Borja[3,*]

[1] "Mediterranea" University of Reggio Calabria, Department "AGRARIA", Località Feo di Vito, I-89122 Reggio Calabria (Italy)

[2] Applied Coastal Research Laboratory, Georgia Southern University, Savannah, GA, (United States of America)

[3] Castilla La Mancha University, School of Advanced Agricultural and Forestry Engineering. Department of Agroforestry Technology and Science and Genetics, Campus Universitario s/n, E-02071, Albacete (Spain)

[4] Institute of Environmental and Water Resources, School of Hydraulic Engineering, Dalian University of Technology 2, Ling Gong, Ganjingzi, Dalian, 116024, China.

Corresponding author: ManuelEsteban.Lucas@uclm.es

Running ahead: Water repellency and hydraulic conductivity in Mediterranean forests

Keywords: Organic matter, mixed forest, soil texture, water infiltration, hydrophobicity.

Abstract

This study evaluates soil hydraulic conductivity (SHC) and water repellency (SWR) in three mixed forest stands in relation to site plant and soil characteristics. The studied forest stands were: i) *Pinus nigra* Arn. ssp *salzmannii* and *Quercus ilex*; ii) *Pinus nigra* Arn. ssp *salzmannii* and *Juniperus Thurifera*; iii) *Pinus nigra* Arn. ssp *salzmannii, Quercus ilex* and *Juniperus Thurifera.* A 100-120 years old *Pinus nigra* Arn. ssp *salzmannii* stand, not subjected to any management practice was also chosen as control. The hydrological variables, physico-chemical properties and surface characteristics of soils were surveyed. Soil water infiltration was higher in *Pinus* + *Juniper* mixed forest, and *Pinus* + *Quercus* + *Juniper* mixed forests compared to unmanaged *Pinus* stands. None of the studied forest stands shows a high level of repellency. Only a slight repellency (in unmanaged stands dominated by pines) or moderate repellency (in soils with *Pinus* and *Juniper*) were evident, while soils with *Pinus* and *Quercus* were not repellent. Differences in SHC among the forest species were driven primarily by the soil texture and associated structure , and secondarily by soil organic matter and associated SWR. The latter was mainly due to organic matter content of the soils, but others of the soil physico-chemical properties and covers analysed were found as influencing parameters to discriminate SWR among mono-specific and mixed forest stands. While SHC at the studied forest stands could be predicted using organic matter as well as sand and clay contents of the soil, SWR is the result of several hydrological and physico-chemical parameters of Mediterranean forest soils.

Keywords: forest stand; water infiltration; soil structure; organic matter; forest biodiversity; soil properties.

List of abbreviations

SHC = soil hydraulic conductivity
SWR = soil water repellency
PN+QI = forest stand of *Pinus nigra* Arn. ssp *salzmannii* and *Quercus ilex*
PN+JT = forest stand of *Pinus nigra* Arn. ssp *salzmannii* and *Juniperus thurifera*
PN+QI+JT = forest stand of *Pinus nigra* Arn. ssp *salzmannii, Quercus ilex* and *Juniperus Thurifera*
PNUM = unmanaged forest stands of 100-120 years old *Pinus nigra* Arn. ssp *salzmannii*
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
SWC = soil water content
BD = bulk density of soil
EC = electrical conductivity of soil
OM = organic matter content of soil
TN = total nitrogen of soil
WDPT = Water Drop Penetration Test
PERMANOVA = Multivariate Permutational Analysis Of Variance
ANOSIM = Analysis Of Similarities
NMDS = Non-metric Multi-Dimensional Scaling
DISTLM = Distance-Based Linear Modeling
dbRDA = distance-based Redundancy Analysis

1. Introduction

The Mediterranean climate is 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). The combination of these climate and soil characteristics can make Mediterranean areas prone to excessive runoff and high soil erosion rates (Zema et al., 2020a; Zema et al., 2020b). Since soil hydraulic conductivity (SHC) can be low in these soils, the hydrological processes generating runoff and erosion on Mediterranean soils tend to be dominated by the infiltration-excess mechanism (Lucas-Borja et al., 2018). The hydrology of Mediterranean soils may also be affected by soil water repellency (SWR) (Cerdà & Doerr, 2007), which is primarily determined by the accumulation of long-chain organic compounds in/around soil particles. SWR can stimulate land degradation processes by reducing the affinity of soil and water, thereby triggering a reduction in soil fertility and increasing soil and water losses (Keesstra et al., 2017). SWR can reduce the infiltration capacity of soils and increase surface runoff, resulting in soil erosion and the transport of entrained pollutants (e.g. Imeson et al.,, 1992; Ritsema et al., 1993; Ritsema et al., 1997; Shakesby et al., 1993). SWR can, thereby, reduce SHC (e.g. Imeson et al., 1992; Plaza-Álvarez et al., 2019; Van Dam et al., 1990), causing Hortonian infiltration-excess overland flow during intense storms (Doerr et al., 2000).

Due to the synergistic effects of high SWR and low SHC, infiltration rates of Mediterranean soils can be several orders of magnitude lower than would be expected (DeBano, 1971; Doerr et al., 2003; 2000), with heavy environmental on-site (e.g., soil loss, landslides) and off-site impacts (e.g., transport of entrained pollutants, damage of urban infrastructures). Therefore, the relationship between SWR and SHC is very important to control and mitigate the hydrological risks and the related environmental hazards (Lucas-Borja et al., 2018; Plaza-Álvarez et al., 2018; Di Prima et al., 2018). Moreover, soil hydraulic and hydrological properties in forests are noticeably influenced by disturbances (Bormann & Klaassen, 2008; Lucas-Borja et al., 2019; Lucas-Borja et al., 2019; Di Prima et al., 2020), such as human management. Understanding SWR and SHC dynamics is thus of fundamental importance in the Mediterranean forest ecosystems, which are subject to many disturbances (e.g., wildfire, biodiversity lost, drought) in addition to the hydrological risks.

Variability in SHC across forest ecosystems can be substantial (1-10^3 mm h^{-1}, Carlyle-Moses et al., 2018, and references therein); moreover, forest soils have been observed to span the full range of SWR, from negligible to extreme repellency (Mao et al., 2019). Generally, forest species (including their litter), and the physico-chemical and microbial community characteristics of the soil appear to drive SWR and SHC variability (Neary et al., 1999). These characteristics and the related physical, chemical and biological processes have been widely investigated across Mediterranean ecosystems using various approaches (e.g., Martín & Vila, 2012; Pausas et al., 2004; Sardans & Peñuelas, 2013). Especially in Mediterranean forests, SHC and SWR have been deeply explored under a variety of pedological, climatic and management conditions (e.g., Inbar et al., 2014; Neris et al., 2013; Wittenberg et al., 2011). Less attention has been paid to the interactive influence of forest species and soil characteristics on SWR and SHC in Mediterranean forests. An improved knowledge of these vegetation-soil-infiltration relationships may yield valuable insights into the hydrological processes of these delicate ecosystems and help improve management strategies for runoff control and soil conservation.

To fill this gap, this study evaluates SHC and SWR in four 100-year-old forest stands, containing tree species that are common in the Mediterranean region -*Pinus nigra* Arn. ssp *salzmannii* and *Quercus ilex* (PN+QI); *Pinus nigra* Arn. ssp *salzmannii* and *Juniperus thurifera* (PN+JT); *Pinus nigra* Arn. ssp *salzmannii, Quercus ilex* and *Juniperus thurifera* (PN+QI+JT), and in a 100-120 years old *Pinus nigra* Arn. ssp *salzmannii* stand of Castilla-La Mancha (Central-Eastern Spain) - not subject to any management operations - in relation to the plant and soil characteristics. The study aims at identifying the soil properties that mainly drive the SHC and SWR in the investigated forest species. To these aims, we hypothesize that soil texture and organic matter may play a fundamental role in driving these important hydrological parameters of forest soils.

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 management units. According to the Köppen-Geiger classification, the climate of the study 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.

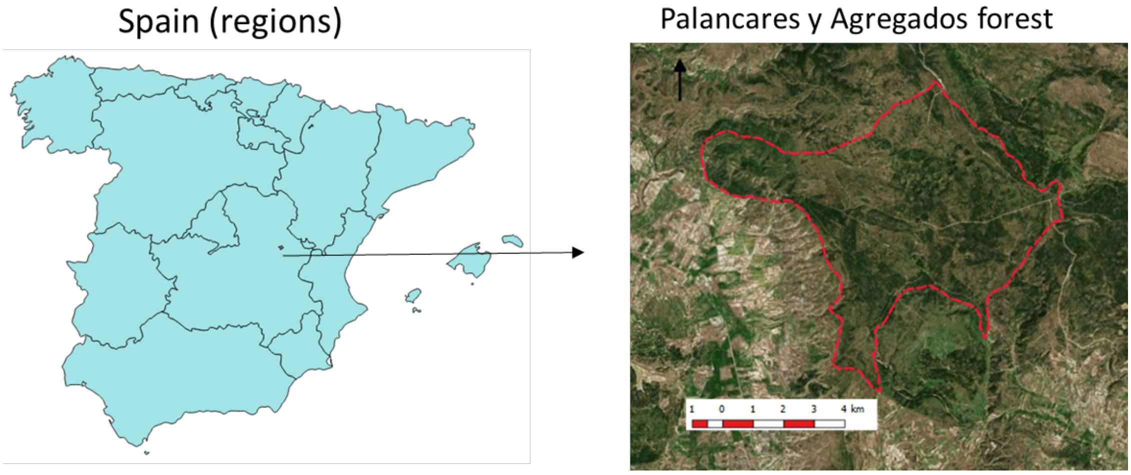


Figure 1 - Location of the "Los Palancares y Agregados" forest (Castilla La Mancha, Spain).

The soils of this area are classified as Entisols, according to the USDA soil taxonomy (Soil Survey Staff, 1999), with clay loam or loam texture. The study area is dominated by mixed natural 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 list 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 list of the government of Castilla La Mancha (2/2001, Official Diary of Castilla La Mancha Nº 8). The forests have been managed since 1895 using the shelterwood method with a shelter-phase of 20 years and a rotation period of 100 years. This shelterwood management practice has been continually practiced to date, which means that several classes of tree age have been generated in approximately 120 years across the management units. 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 stands.

2.2. Experimental design

In May 2019, nine plots, each of 50 ha, were selected according to the forest area management plan (Lucas-Borja et al., 2016) of the studied forest:

i) three plots mainly covered by *Pinus nigra* Arn. ssp *salzmannii* and *Quercus ilex* (hereinafter indicated as PN+QI);

ii) three plots of *Pinus nigra* Arn. ssp *salzmannii* and *Juniperus thurifera* (PN+JT);

iii) three plots of *Pinus nigra* Arn. ssp *salzmannii, Quercus ilex* and *Juniperus thurifera* (PN+QI+JT).

Three smaller reference plots, each one of about one hectare, were also considered, mainly covered by unmanaged forest stands of 100-120 years old *Pinus nigra* Arn. ssp *salzmannii* (PNUM). The stand structural characteristic across the study plots were as follows: (i) PN+QI plots had a basal area and tree height of 21–28 m^2/ha and 20–25 m, respectively; (ii)- PN+JT stands had basal area of 20–26 m^2/ha and tree height of 21–24 m ; (iii) basal area was 22–27 m^2/ha and tree height was 20–23 m for PN+QI+JT stands; (iv) PNUM plots showed a basal area and tree height of 80–82 m^2/ha and 35–40 m, respectively. All forest stands have been growing under the same climatic conditions during the last century and are comparable in terms of aspect and slope (flat area or slope of 2-5% in all plots). The stands were near-natural, without a distinct anthropogenic impact on their structure in the last three decades, and all tree ages were over 100 years. All plots presented the same understory herbal and shrubs species composition. A more detailed description of vegetation and soil at the different sites can be found in Lucas-Borja et al. (2012; 2016). In each of the management units, three plots covering an area of 9 m^2 (3 m x 3 m squares) were identified, to measure SHC and SWR, and the physico-chemical soil properties (total of 36 plots). The distance between plots was greater than 300 m, to consider the plots as independent.

2.3. Measurement of soil properties and covers

Soil properties were measured on three soil samples at each plot. Soil sampling points were always more than three meters far from the nearest tree base. After manually removing the litter, the samples were collected in the surface layer (at a depth of 5 cm). This depth was chosen because (i) this is the initial interface for water-soil interactions and (ii) 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 200 g, which were mixed to obtain a composite sample. After removing plant residues for soil sampling, the samples were passed through a 2-mm sieve and then kept at 3 °C prior to the analyses, which were carried out one week after soil sampling. Soil texture (sand, silt, and clay contents in percentage, abbreviated as SaC, SiC, and ClC, respectively) was analyzed using the method of Guitian and Carballas (1976). Bulk density (BD) was calculated on triple samples per plot as the weight of soil in each volume of a core extracted by a small cylinder at a depth of 20-30 cm. 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 & Bremner, 1989). Total nitrogen (TN) was measured using Kjeldhal's method as modified by Bremner & Mulvaney (1982). Calcium carbonate content of limestone ($CaCO_3$) was measured according to Della Porta, Kenter, Bahamonde, Immenhauser, & Villa (2003).

In each plot, three longitudinal transects were identified to measure the percentage of areal covers of vegetation (VC), dead matter (DW), rock (RC) and bare soil (BS) (hereinafter "soil covers") using touch lengths in each transect, which was 3-m long. Depth, area and weight were excluded form the field measurements of soil covers, because litter characteristics are affected by seasonal variability as a response to other external factors (such as the wind and runoff); this variability may alter the significance of measurements. Moreover, the bare soil area may be considered as an indirect indication of litter influence on the hydrological variables, since litter is absent where the soil is bare.

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, 2013) and the Water Drop Penetration Test (WDPT) method (Letey, 1969; Woudt, 1959). The selected points were always more than three meters of distance from the nearest tree base. These measurement points were chosen at different distance from trees, in order to smooth the influence of this parameter on SHC and SWR, which has been evidenced in some studies (e.g., Madsen et al., 2008).

The MDI infiltrometer is commonly used for field measurements, given its small size and easy handling (Robichaud, Lewis, & Ashmun, 2008). The MDI test is an effective indirect technique to quickly assess the existence and degree of water repellency of soil, since sorptivity and early infiltration rates are good indicators of repellency (Robichaud et al., 2008; Lozano Baez et al., 2020; Williams et al., 2020). However, we preferred to rely on direct measurements of SWR, using the WDPT method, which is a simple but reliable procedure to measure SWR (Dekker et al., 2009; Doerr, 1998).

In more detail, the SHC measurements were carried out according to the MDI technical manual, and Robichaud et al., 2008a; 2008b). In summary, the litter layer on the small area of soil surface was removed by a small shovel. This area was leveled 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). Firstly, the measured cumulative infiltration values (I, [m]) were regressed against the measured time intervals (t, [s]) by equation (1):

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

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:

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

A is a value corresponding to the Van Genuchten parameters (n and α) for a given soil type to the suction rate (h_0, equal in this study to -2 cm) and disk radius (2.25 cm) of the infiltrometer. According to n, α and h_0 values for the experimental soils, the values of A were equal to 6.64 (clay loam soil of PNUM and PN + QI plots) and 6.27 (loam soil of PN + JT and PN + QI + JT plots) (Decagon Devices, 2013).

As regards the SWR determination in situ, 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 variable soil conditions; the time necessary for drops to infiltrate completely into the soil was measured by a stopwatch. Before measurement, the litter cover was removed, and the soil surface was cleaned using a brush.

SWR was classified according to the values of WDPT as Bisdom, Dekker, & Schoute (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) with three sub-classes (class 4, 1 < WDPT < 3 h, class 5 (3 < WDPT < 6 h) and 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 and SHC by a device (Vegetronix VG400. accuracy of 2%, measurement range 0-50%), placed on the soil surface and connected to a data logger (UX120 4-channel Analog Logger, Onset HOBO, Massachusetts, USA).

2.4. Statistical analyses

The reciprocal relationships among the soil properties and covers (RC, VC, BS, DW, SaC, SiC, ClC, BD, pH, EC, OM, TN, C:N and $CaCO_3$) as well as their influence of 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 diversity level (PN+QI, PN+JT, PN+QI+JT and PNUM) as factors. 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 environmental and SHC or SWR data, respectively. The sums of squares type were type III (partial) and the four-level (tree diversity) factor was a fixed effect. The permutation method used was the unrestricted permutation of raw data and the number of permutations was 999. Then, an analysis of similarities (ANOSIM), described by Clarke (1993), was carried out for the soil properties and covers, and the multivariate resemblances were analyzed, according to the tree diversity level. Secondly, the Non-metric Multi-Dimensional Scaling (NMDS) and the Kruskal stress formula (minimum stress: 0.01) were applied to soil properties and covers, to evaluate the similarity level in the individual cases of the dataset. Thirdly, a comparative (Mantel-type) test on similarity matrices was developed, to assess the statistical relationships among soil properties and covers on one side, and SHC or SWR on the other side. Fourthly, a DISTLM function (distance-based linear modelling) was developed, to determine the relative importance of any soil properties and covers on SHC and SWR variables. For the DISTLM function, we developed "marginal" tests of the relationship between the response variable (SWR or SHC) and an individual variable (soil property or cover), to identify the independent variables that explain the variations in the soil samples. Following the marginal tests, "sequential" tests of individual variables were performed to assess whether adding an individual variable contributes significantly to the explained variation of the response variable. Finally, 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), built on the soil properties and covers. The AICc (Akaike, 1974) criterion was adopted to select the best model and the step-wise procedure was followed to build the model.

For the statistical analyses the software PRIMER V7® with PERMANOVA add-on (Anderson, 2005) and Statgraphics Centurion XVI® (StatPoint Technologies, Inc., Warrenton, VA, USA) were used. A significance level of 0.05 was used, unless otherwise indicated.

3. Results

Vegetation cover was the most developed in PNUM forest stands (70.0 ± 12.3%) and lowest in PN + QI plots (26.7 ± 12.3%); PN + QI + JT and PN + JT plots showed a vegetation cover of 30 ± 15% and 41.1 ± 19.0%, respectively. Soil texture, although being prevalently clay loam for PNUM and PN + QI plots and loamy for PN + JT and

PN + QI + JT plots, showed significant differences, with higher sand content in PN + JT and PN + QI + JT forests stands (49.4 ± 1.90% and 45.0% ± 2.02%, respectively), while the clay content was higher in PNUM and PN+QI soils (31.0 ± 1.63% and 29.59 ± 2.02%). The latter forest soils showed the highest OM content (24.5 ± 0.58%) and the PN + QI the lowest (9.27 ± 0.75%). The lowest TN content was detected PN + QI soils (0.38 ± 0.04%) and the highest in PN + JT (0.72 ± 0.11%). Based on the values of OM (converted to total carbon) and TN, the values of C:N were in the range 15.77 ± 1.34 (PN + JT stands) to 24.54 ± 0.75 (PNUM plots). The PN + QI + JT soils were more compacted compared to the other forest stands, as shown by the lower BD (1.36 ± 0.01 g/cm^3 against values between 1.51 ± 0.01 g/cm^3 1.53 ± 0.04 g/cm^3 and 1.70 ± 0.04 g/cm^3 for PNUM, PN + QI, and PN + JT, respectively). The soils were slightly acid (PNUM, pH = 6.31 ± 0.54) or close to the neutrality (pH between 7.10 ± 1.33 and 7.69 ± 0.43, for the other stands). EC was in the range 0.17 ± 0.05 (PN + QI + JT) to 0.24 ± 0.02 (PN + JT) mmhos/cm. Finally, while in the forest stands the $CaCO_3$ content was quite high (4.67 ± 0.59%, PNUM, and 4.84 ± 0.47%, PN + QI + JT), this percentage was 1.47 ± 0.35 in PN + QI forest plots (Table 1).

Table 1 - Main physico-chemical properties and covers (mean ± standard deviation) of soil sampled in plots under four tree diversity levels by pairwise test using Permutational multivariate analysis of variance (PERMANOVA) (Los Palancares y Agregados, Castilla-La Mancha, Spain).

Soil properties/covers		**FOREST STAND**			
		PNUM	**PN + QI**	**PN + JT**	**PN + QI + JT**
Covers	*RC (%)*	0.00 ± 0.00 a	14.44 ± 8.82 ab	10.00 ± 11.18 b	17.78 ± 17.16 b
	VC (%)	70.00 ±12.25 c	26.67 ± 12.25 a	41.11 ± 19.00 b	30.00 ± 15.00 ab
	BSC (%)	0.00 ± 0.00 a	15.56 ±11.30 a	36.67 ± 28.72 b	14.44 ± 11.30 c
	DWC (%)	27.78 ± 13.94 a	47.78 ± 23.33 b	15.56 ± 25.55 a	17.78 ±17.16 a
Texture	*SaC (%)*	36.93 ± 1.59 b	27.27 ± 1.71 a	49.44 ± 1.90 d	44.98 ± 2.02 c
	SiC (%)	31.38 ± 1.70 b	42.59 ± 2.52 c	26.49 ± 2.01 a	29.32 ± 3.37 b
	ClC (%)	31.04 ± 1.63 c	29.59 ± 2.02 c	22.20 ± 1.97 a	26.41 ± 1.89 b
Physical properties	*BD* (g/cm^3)	1.53 ± 0.04 b	1.51 ± 0.01 b	1.70 ± 0.04 c	1.36 ± 0.01 a
	pH (-)	6.31 ± 0.54 a	7.63 ± 0.88 b	7.69 ± 0.43 b	7.10 ± 1.13 b
	EC (mmhos/cm)	0.21 ± 0.03 ab	0.18 ± 0.06 a	0.24 ± 0.02 b	0.17 ± 0.05 a
Chemical properties	*OM (%)*	24.49 ± 0.58 d	9.27 ± 0.78 a	20.36 ± 0.90 c	14.82 ±1.18 b
	TN (%)	0.54 ± 0.09 b	0.38 ± 0.04 a	0.72 ± 0.11 c	0.52 ± 0.06 b
	C:N (-)	24.54 ± 0.75 b	16.40 ± 0.78 a	15.77 ± 1.34 a	15.82 ± 1.46 a
	$CaCO_3$ *(%)*	4.67 ± 0.59c	1.47 ± 0.35a	3.60 ± 0.54 b	4.87 ± 0.47 c

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

In relation to the physico-chemical properties and cover of soils in the forest plots, ANOSIM (providing a global R of 0.94 and a significance level of 0.001) showed significant differences among all tree diversity levels. In accordance to the ANOSIM results, the NMDS clearly grouped the four forest stands in as many clusters (Figure 2), depending on the soil physico-chemical and cover variables. The importance of each property or cover of soil in clustering all tree level is shown by the loadings of each variable on the two axes, NMDS1 and NMDS2 (Table 2).

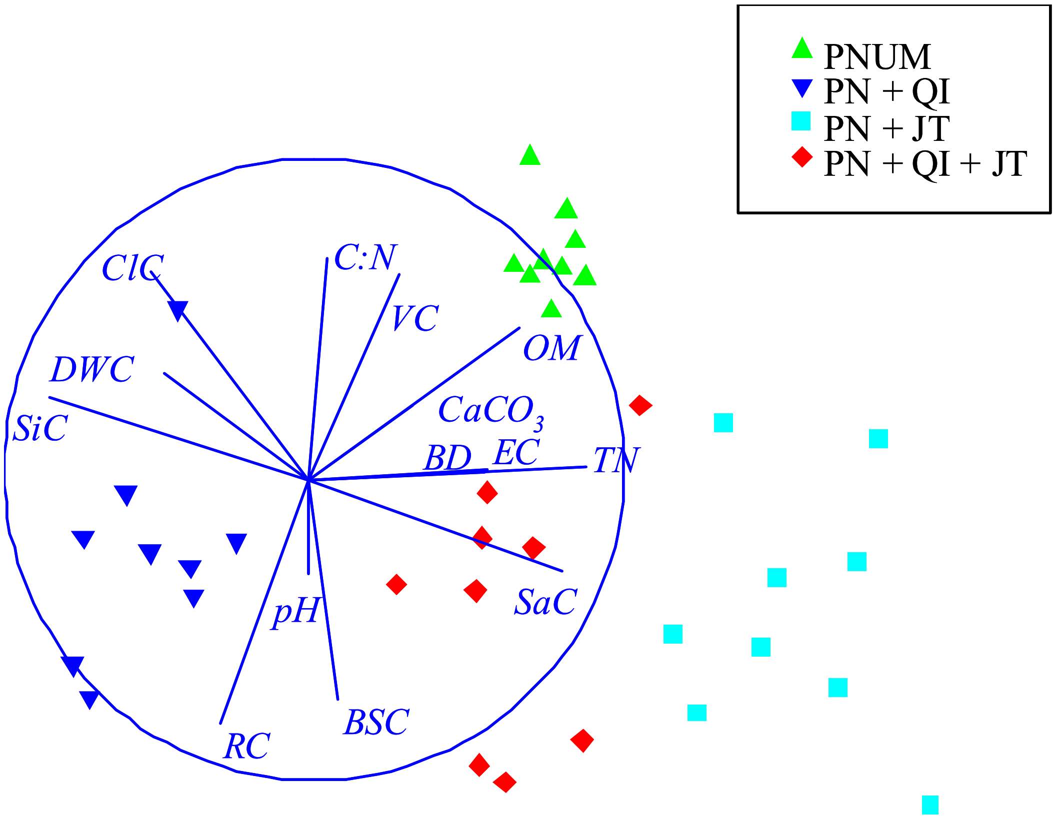


Figure 2 - Biplot of physico-chemical properties and covers of soil samples collected in plots under four tree diversity levels using nonmetric multidimensional scaling (NMDS) routine (Los Palancares y Agregados, Castilla-La Mancha, Spain). The stress value for the NMDS is 0.09. See the related list for the abbreviations.

In more detail, while the soil texture fractions (mainly SaC and SiC) as well as BD significantly weigh on the axis one (loadings over 0.80), most of the soil cover characteristics as well as OM and ClC have a large effect on axis two (loadings over 0.65). This means that clusters of soils under the four forest stands are differentiated according to a combination of these variables and, in particular, the soil texture mainly on axis one, and the soil covers and many important chemical properties on axis two.

Table 2 - Spearman correlations of physico-chemical properties and covers of soil samples collected in plots under four tree diversity levels using multidimensional scaling (MDS) routine (Los Palancares y Agregados, Castilla-La Mancha, Spain).

Soil property/cover	**NMDS axes**	
	axis 1	**axis 2**
RC	-0.285	-0.779
VC	0.292	0.666
BSC	0.097	-0.701
DWC	-0.459	0.347
SaC	0.818	-0.286
SiC	-0.829	0.272
ClC	-0.507	0.674
pH	0.005	-0.300
EC	0.567	0.026
OM	0.065	0.713
TN	0.334	0.239
C:N	0.576	0.041
CaCO3	-0.459	0.347
BD	0.900	0.050

Note: See the related list for the abbreviations.

The values of SHC were in the range 0.79 ± 0.04 mm/h (PNUM plots) to 11.4 ± 10.2 mm/h (PN + JT) (Figure 3a), whereas WDPT was between 2.3 ± 0.5 s (PN + QI plots) and 106 ± 23.4 s (PN + JT) (Figure 3b). According to the SWR classification adopted in this study, PN + QI and PN + QI + JT soils were classified as “wettable”, PNUM soil as “slightly repellent” and PN + JT soils as “repellent”.

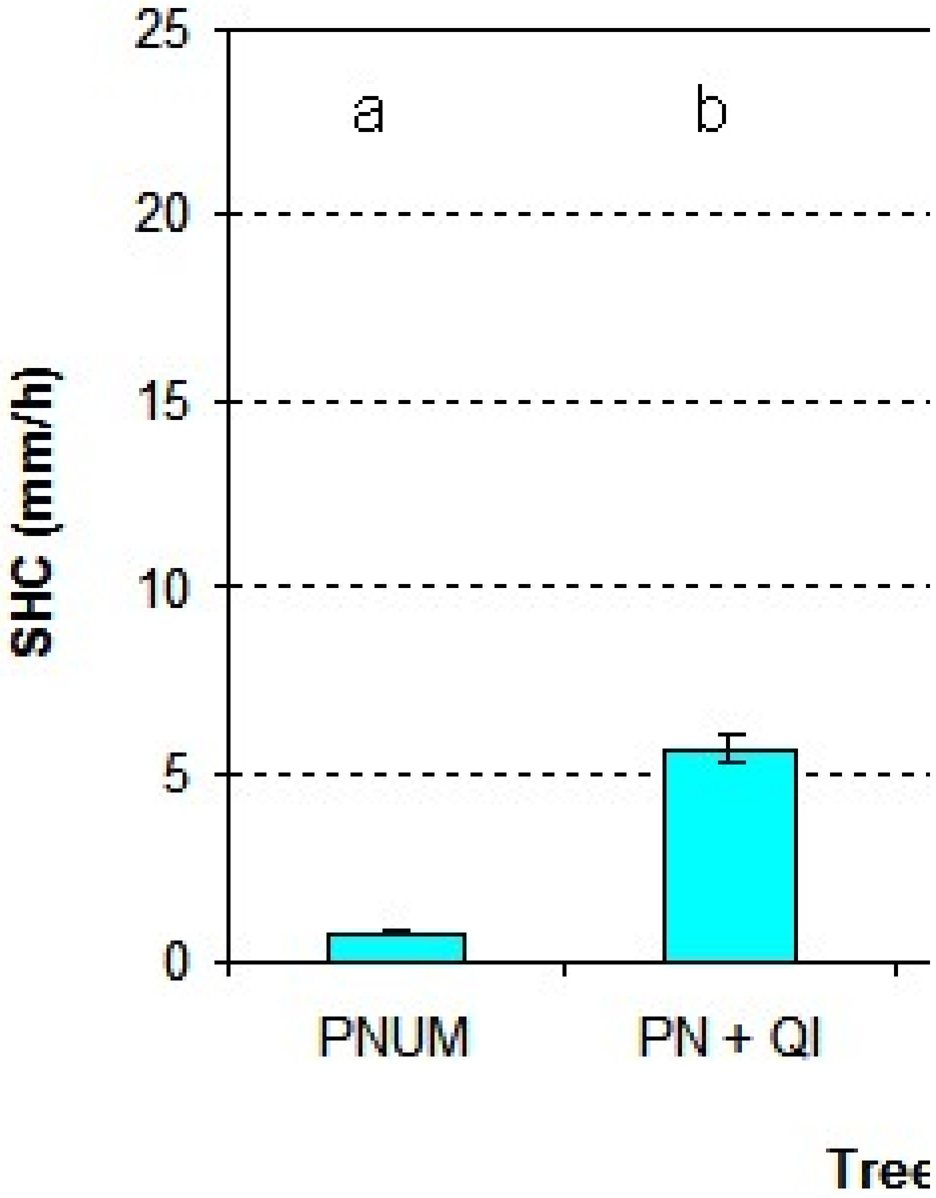


Figure 3 - SHC (a) and SWR (b) (mean ± standard deviation) in plots under four tree diversity levels (Los Palancares y Agregados, Castilla-La Mancha, Spain). Different letters indicate significant differences at $p < 0.001$. See the related list for the abbreviations.

SHC and SWR were both significantly different (Pseudo-F = 47.9; P(perm) < 0.001 and Pseudo-F = 95.5; P(perm) < 0.001, respectively) among the tree diversity levels according to the PERMANOVA routine. In relation to the pairwise comparisons among tree diversity levels, for SHC, only the differences between PN + QI and PN + JT as well as PN + JT and PN + QI + JT were not significant; for SWR, all couples of tree diversity levels were significantly different, except the difference between PN + QI and PN + QI + JT (non-significant at $p < 0.001$) (Figure 3). Furthermore, no significant correlations were found between these hydrological variables for the studied forest stands ($R^2 < 0.20$), except for PN + QI forest soil ($R^2 = 0.87$) (Figure 4).

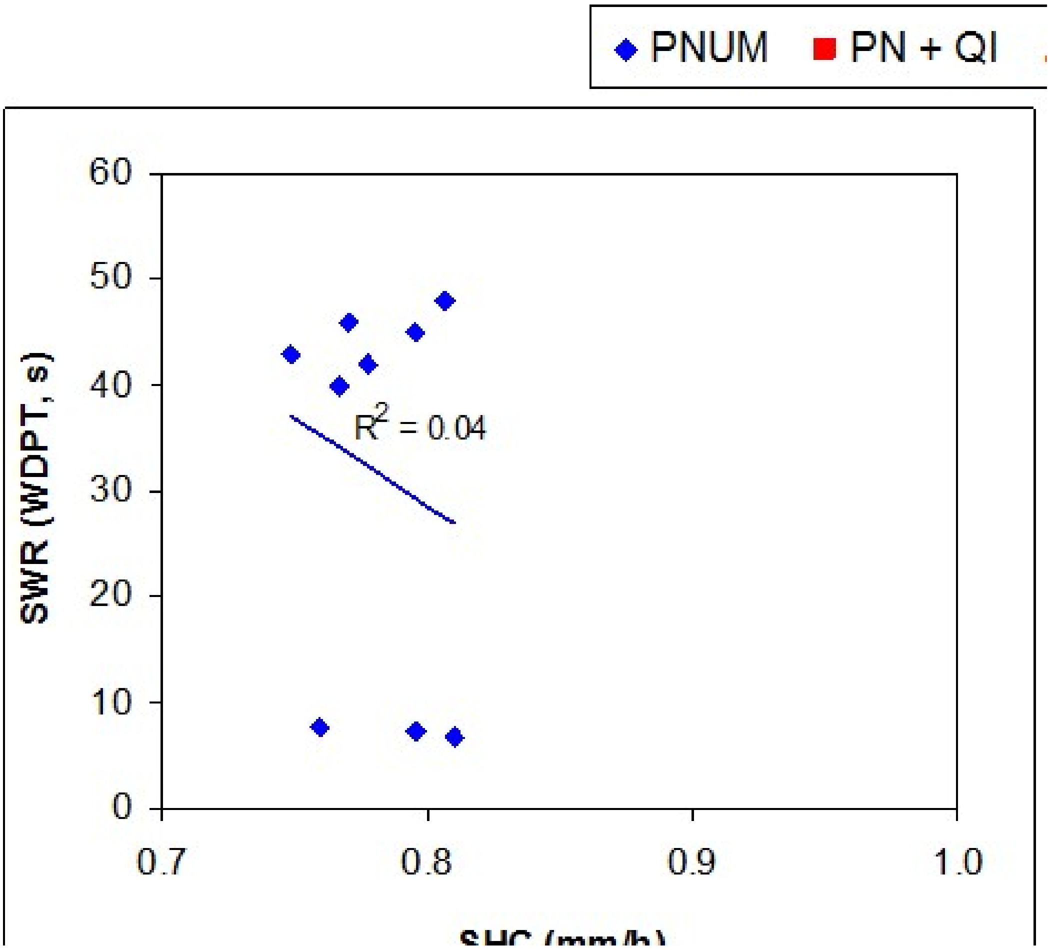


Figure 4 - Linear regressions between SHC and SWR in forest plots under four tree diversity levels (Los Palancares y Agregados, Castilla-La Mancha, Spain). See the related list for the abbreviations.

The comparative (Mantel-type) tests indicated that several physico-chemical properties and covers of soil samples in plots under different tree diversity levels were correlated both with SWR (Sample statistic (Rho): 0.21, significance level: 0.1%) and SHC (Rho: 0.34; significance level: 0.1%). By applying the distance linear models (DISTLM), the marginal tests revealed that all soil covers as well as ClC, pH and OM significantly influenced SHC, while almost all the evaluated physico-chemical soil properties and covers (except BSC and pH) affected SWR, when those variables were considered as isolated (Figure 5). The sequential tests indicated that the best distance linear model (R^2 = 0.81; AICs = 180.96) for predicting SHC consisted of C:N, ClC, BD, OM and SaC (Table 3), while a much larger set of variables should be used in the best distance linear model (R^2 = 0.92, AICs = 216.7) for predicting SWR (Table 4).

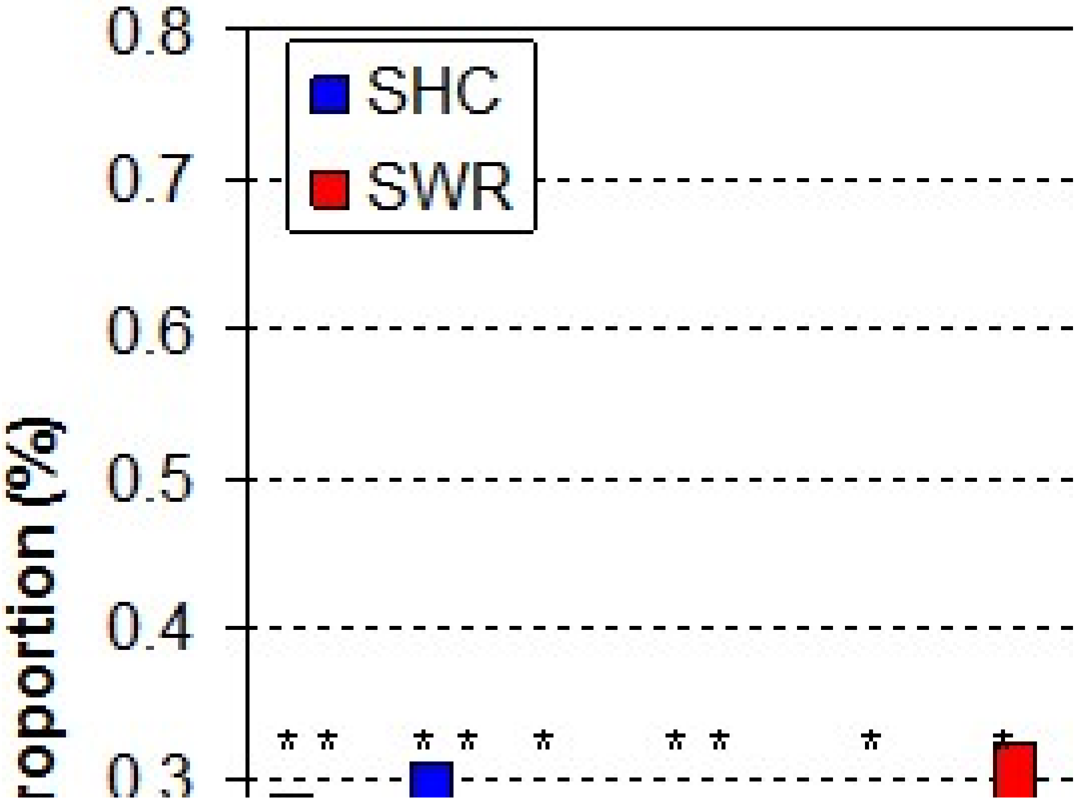


Figure 5 - Proportion of the variability of SWR or SHC explained by the selected soil property/cover under four tree diversity levels after the marginal tests using matched resemblance matrices (DISTLM) (Los Palancares y Agregados, Castilla-La Mancha, Spain). Notes: asterisks show the soil properties and covers that significantly influence SHC and SWR. See the related list for the abbreviations.

Table 3 – 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 diversity levels using matched resemblance matrices (DISTLM) (Los Palancares y Agregados, Castilla-La Mancha, Spain).

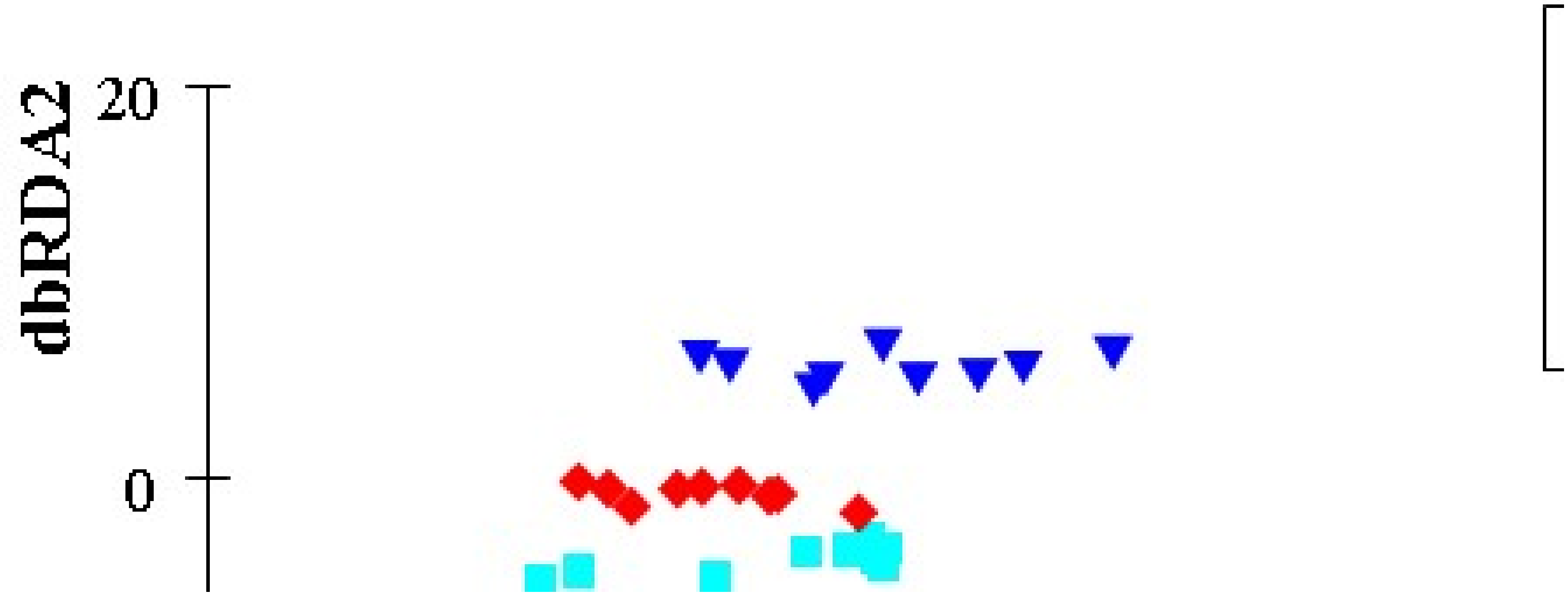
Soil property/cover	P	Prop.	Cumul.
SHC			
+ C:N	0.001	0.709	0.709
+ ClC	0.061	0.027	0.736
+ BD	0.013	0.041	0.777
+ OM	0.057	0.233	0.800
+ SaC	0.029	0.027	0.827
- C:N	0.396	0.005	0.822
SWR			
+ RC	0.028	0.120	0.120
+ VC	0.075	0.076	0.196
+ BSC	0.221	0.035	0.231
+ DWD	0.013	0.118	0.349
+ SaC	0.035	0.085	0.434
+ SiC	0.185	0.032	0.466
+ ClC	0.002	0.168	0.634
+ pH	0.594	0.004	0.639
+ EC	0.240	0.019	0.658
+ OM	0.002	0.111	0.768
+ TN	0.646	0.003	0.771
+ C:N	0.888	0.001	0.771
+ $CaCO_3$	0.090	0.027	0.799
+ BD	0.001	0.122	0.921

Notes: 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; + indicates that the variable is added to the model, while - indicates a variable removed from the model. See the related list for the abbreviations.

According to the variations (out of the fitted model and out of the total variation) explained by the axes of dbRDA, axis one (dbRDA1) applied to SHC reflected 97.2%

of the fitted model and 78.7% of the total variation of the variables, whereas the axis two (dbRDA2) explained 2.8% of the fitted model and 2.2% of the total variation (Figure 6a). When dbRDA was applied to SWR, the axis one (dbRDA1) explained 94.8% of the fitted model and 87.3% of the total variation, whereas the axis two (dbRDA2) explained 5.0% of the fitted model and 4.6% of the total variation (Figure 6b). ClC, SaC and OM content were the soil properties that most influenced these two axes in the dbRDA model predicting SHC. Instead, all the evaluated soil properties and covers influence the two axes in the SWR prediction model, although with variable loadings (Figures 6a and 6b).

Finally, 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 SWC were 0.132 ± 0.04% (PNUM), 0.152 ± 0.004% (PN + QI), 0.117± 0.004% (PN + JT) and 0.121± 0.005% (PN + QI + JT).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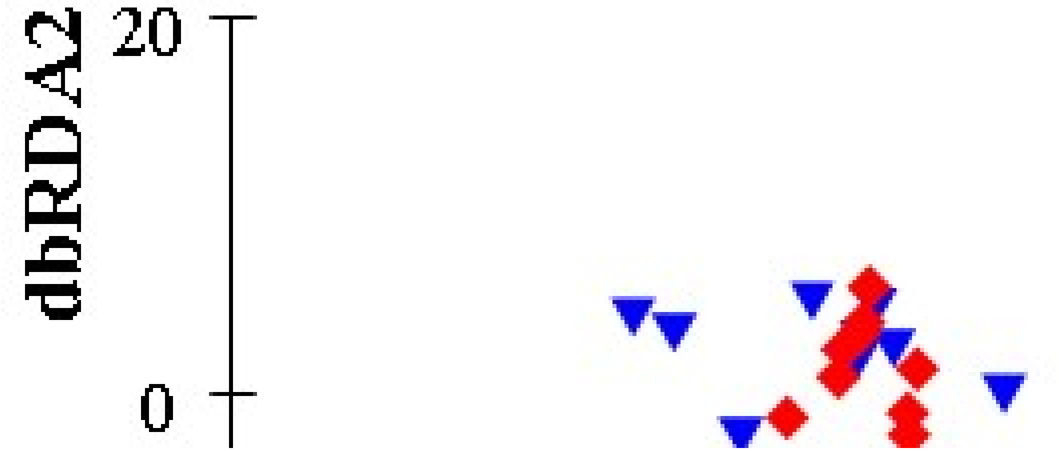
480 

Figure 6 - Biplots of dbRDA applied to SHC (a) and SWR (b) of soils under four tree diversity levels (Los Palancares y Agregados, Castilla-La Mancha, Spain). See the See the related list for the abbreviations.

4. Discussions

It is well known how and to what extent the hydrology of the Mediterranean forests strictly depends on infiltration capacity and surface conditions of soils (Di Prima et al., 2020). These features are clearly driven first by the soil characteristics (e.g., texture and organic matter) (Bens et al., 2007; DeBano & Rice, 1973; Martínez-Zavala & Jordán-López, 2009; Wahl et al., 2003), but also the interactions of soil characteristics with plant composition can play a significant role. Recent laboratory studies have shown that vegetation can influence soil water flow and thus SHC, by inducing very low levels of water repellency (Lichner et al., 2007). Moreover, water-repellent soils appear to be the rule rather than the exception in forest soil (Stoof et al., , 2011).

The Mediterranean forest sites selected for our study are representative of *Pinus nigra* Arn. ssp *salzmanni* monospecific and mixed forest stands of Cuenca Mountains. Moreover, these selected forest stands had similar ecological, physiographical and climatic conditions (same precipitation and temperature for all surveyed plots, Figure S1). Thus, the influence of the tree diversity levels on SHC and SWR may be mainly associated to other factors, such as soil and covers properties (e.g. mainly texture, but also OM quantity), some of these factors being influenced by tree species composition. In our study, SHC was the highest in PN + JT and PN + QI + JT forest stands and the lowest in PNUM soils. According to literature, Madsen et al. (2008) demonstrated the importance of *Juniperus* and *Pinus* vegetation in modifying soil unsaturated hydraulic conductivity, whilerelatively high SHC under juniper trees has been reported by Wilcox et al. (2003). Jarvis et al. (2013) and Olorunfemi & Fasinmirin (2017) reported that

SHC strongly depends on OM content of soil, which influences also bulk density and aggregate size.

In the studied forest stands, the SHC of all forest stands decreases with increasing clay contents ($R^2 = 0.78$, $p < 0.05$, data not shown) and decreasing sand fractions ($R^2 = 0.45$, $p < 0.05$, data not shown). Moreover, the higher SHC in PN + JT and PN + QI + JT stands compared to the PN + QI forest detected may be explained primarily by the different soil texture, but also by the higher OM content of these soils (which increases the stability of aggregates and therefore the soil macro-porosity, Chenu et al., 2000: Devine et al., 2014), which in turn influence SWR. The reasons of the lowest SHC detected in the PNUM soils (having the highest OM content among the studied stands) is instead less clear. Presumably, the higher clay content of PNUM soils compared to the other forest stands could have played a major influence on the low SHC, but also the not negligible SWR could have played a role in decreasing the soil infiltration (Wahl et al., 2003). The highest vegetation cover of PNUM soils among the stands also suggests that the fine roots have a limited effect on infiltration.

In general, none of the studied forest stands showed a high level of repellency, but only a slight (PNUM plots, dominated by pines) or a moderate hydrophobicity (PN + JT soils) was evident, while forest soils with holm oaks were wettable. The soils with higher OM (PNUM and PN + JT) are those showing significant SWR. This result is in accordance with those of Lozano et al. (2013), who found higher SWR under *Pinus* trees beside strongest persistence of SWR in *Quercus* forests, attributed these contrasts to the significant differences between soils under different plant species, in particularly for OM. Therefore, the differences in SWR can be related primarily to the soil OM content (Cesarano et al., 2016; Esposito et al., 2014), and the latter is the main driver in formation of SWR. In forest soils, the high SWR may be due to its high carbon content in all the sieve fractions (both the finest and the coarsest fractions can be repellent) as well as to the OM quality (Rodríguez-Alleres et al., 2007). Buczko et al. (2002) found that soil OM and WDPT had positive linear correlations (r = 0.73), explained by the higher proportion of mor-type humus and a greater thickness of the humose topsoil at mixed beech stands compared to the pure pine sites. More in general, significant positive relationships between SWR and soil OM were reported in literature (e.g., González-Romero et al., 2018; Martínez-Zavala & Jordán-López, 2009; Olorunfemi & Fasinmirin, 2017; Plaza-Álvarez et al., 2018), particularly when the other soil physico-chemical properties are similar (Chenu et al., 2000; Kajiura et al. 2012; Mataix-Solera & Doerr, 2004; McKissock et al., 2002).

Past studies has showed that (i) soil OM, alone, cannot fully account for SWR variability, and (ii) in some cases, the soil texture may be a factor with significant influence on SWR level. In our study, besides OM content, the differences in soil texture, detected among the studied forest stands, could have affected SWR, but these soil properties seem to be less important compared to OM. For instance, soils samples in PN + QI + JT stands showed a large content of sand but not SWR, while PN + JT soils with a similar sand content were more repellent. It can not be excluded that soils with significant sand and OM content are more susceptible to repellency.

If the hydraulic properties of soils are associated to the forest composition, we observe that the monospecific stand showed a significantly lower SHC (see PERMANOVA) together with a slight SWR. Water infiltration capacity of the soil was instead noticeable in the other mixed forest stands (particularly in PN + JT and PN + QI + JT). The mixed stands showed SHC over the mean value averaged among the tree diversity levels, and this helps to reduce the negative impacts of surface runoff and erosion. Moreover, SHC and SWR were not correlated, as confirmed by the low and non-significant linear regressions. Instead, in some studies, a negative correlation between SHC and SWR have been found (Olorunfemi & Fasinmirin, 2017). This lack of correlations between the two hydrological parameters could be due to the different but distinct influence of the studied soil properties and covers on SWR and SHC. For instance, while many soil cover parameters clearly affect SWR, the same influence on SHC was not as evident. Moreover, although the SHC and SWR were simultaneously measured in the same or, at least, very close points, the different spatial variability of these parameters can have played a role on their different dynamics. It is well known how SWR is highly variable in space and time, even over the same soil moisture, and this variability is difficult to explain (e.g., Pierson et al., 2008; Robichaud et al., 2008). The comparative (Mantel-type) tests highlighted that several physico-chemical properties and covers play individually a significant influence on SWR and SHC (in some cases, on both of the studied hydrological parameters, such as three of the four soil cover variables as well as ClC and OM contents of soil, according to the tree diversity level). This result is in close accordance with those of the previous discussion, showing that ClC and OM are key parameters in driving the hydrological characteristics of a forest soils. However, the synergistic effects among these properties or soil covers cannot be neglected, at least for SHC, since these effects reduced, or eliminated, the significance of some individual parameters (e.g., the ratio C:N for explaining SHC). This was shown by the multiregression model built using dbRDA, which was particularly able to explain the variability of SHC or SWR among the different forest stands. The dbRDA-assisted multiregression model explained high percentages (more than 80% for SHC and 90% for SWR) of the total variation of the soil properties and covers. By this model, silt and clay contents as well as OM of soils were the most meaningful variables in predicting SHC for the different forests stands, while a much larger set of variables must be used to differentiate the SWR among the studied forest soils. Also, in the biplots related to dbRDA, clear clusters were evident, discriminating forest soils with lower SHC (PNUM stands) from soils with the highest SHC (PN + QI, PN + JT and PN + QI + JT stands) as well as repellent or slightly repellent soils (PN + JT and PNUM stands) from non-repellent soils (PN + QI and PN + QI + JT stands). In the study of Šimkovic et al. (2009), the results of multiple regression analysis showed that SWR in topsoil material is significantly controlled by water and organic carbon contents, while this study has shown that the differences among the forest stands are determined by a more complex combination of physico-chemical properties and soil covers. Regarding SHC, this analysis further confirms that particle size but also OM content of soil (i.e., the variables with the large influence on axis 1) create a noticeable gradient (and thus a clear difference) between PNUM and the other three forest stands (having lower OM and clay contents compared to PNUM plots). Finally, the physico-chemical properties of soils were found to exert a greater influence on the studied hydrological properties of soils compared to the soil covers.

5. Conclusions

This study has shown that soil texture exerts a significant control on the hydraulic conductivity of forests with different stand composition, and this influence can be influenced by soil water repellency, where substantial organic matter is present. Soil hydraulic conductivity was higher in managed stands of *Pinus nigra* Arn. ssp *salzmanii* with *Juniperus thurifera* and *Quercus ilex* compared to unmanaged 100-120 years old *P. nigra* stands. These differences in water infiltrability were due primarily to the soil texture, but also to its organic matter content. None of the surface soils of the studied forests showed a high level of water repellency. Only slight hydrophobicity (in unmanaged plots, dominated by pines) or a moderate repellency (in *P. nigra* stands with *J. thurifera*) were evident; yet, forest surface soils in *P. nigra* stands with *Q. ilex* were wettable. Cross-stand differences in soil water repellency were primarily related to the soil OM content and, secondarily, to texture. Finally, a robust and meaningful multiregression model developed in this study and based on db-RDA, indicated that few soil variables, specialised for each different forest stand, may be good predictors of soil hydraulic conductivity; however, the water repellency level of study forest soils was influenced by several variables.

Overall, the results of this study advance efforts to identify differences among key parameters driving the hydrological response of Mediterranean forests according to their biodiversity and soil characteristics. More research is certainly needed, in particular about litter quality (only indirectly considered in this study within the physico-chemical and covers of forest soils) and its feedback with water repellency, since litter quality certainly may influence forest hydrology.

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