LAND DEGRADATION & DEVELOPMENT
Land Degrad. Develop. **28**: 317–327 (2017)

SPATIAL GRADIENTS OF INTENSITY AND PERSISTENCE OF SOIL WATER REPELLENCY UNDER DIFFERENT FOREST TYPES IN CENTRAL MEXICO

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Received: 22 June 2015; Revised: 26 March 2016; Accepted: 16 May 2016

ABSTRACT

Organic residues release hydrophobic compounds to the soil that may induce soil water repellency (WR), which may inhibit infiltration and increase runoff and soil loss rates. Although there are many studies on soil WR through the world, very few investigations have been conducted in Mexican areas. This paper studies the natural background of soil WR in soils from central Mexico under representative forest types, analyzing the spatial distribution of soil WR in relation with tree canopy, vegetation cover and main soil chemical (pH, $CaCO_3$, organic C content and exchangeable cations) and physical properties (texture). The water drop penetration time and the ethanol tests were used to assess persistence and intensity of soil WR, respectively. Although soil WR was not related with soil properties, it decreased strongly from soil below the canopy of conifers to soil below oaks. When different types of vegetation cover were considered, the proportion of water-repellent soil increased following the sequence: bare soil < shrubs and herbaceous plants < shrubs < trees from fir, fir-pine-oak and pine-oak forest. We found an inverse relation with distance to the tree trunks, contributing to create a patchy pattern of soil WR, with soils under the canopy of conifers showing the most severe WR levels. The spatial distribution of soil WR is also conditioned by microclimatic gradients, as persistence and intensity of soil WR were usually lower in shaded areas (upslope transects from the tree trunks), where soil moisture content is expected to be higher on average through the year.

KEY WORDS: coniferous forest; hydrophobicity; Mexican soils; pine forest; soil hydrology

INTRODUCTION

Soil water repellency (WR) is a result of the low affinity between soil particles and water. Infiltration into water-repellent soils may be delayed or inhibited during periods of time ranging from seconds to hours, days or weeks (Doerr *et al*., 2000). Some impacts of soil WR are increased aggregate stability (Granged *et al*., 2011a; Mataix-Solera *et al*., 2011; Jordán *et al*., 2014), enhanced runoff rates and erosion risk in forest (Doerr *et al*., 2000; Shakesby *et al*., 2000; Jordán *et al*., 2008; Jordán *et al*., 2015) or agricultural soils (González-Peñaloza *et al*., 2012; García-Moreno *et al*., 2013), the development of preferential flow paths (de Rooij, 2000; Jordán *et al*., 2009; Zavala *et al*., 2009a; Granged *et al*., 2011b) and accelerated leaching of soil nutrients and pollutants through preferential flow paths (Blackwell, 2000; Li *et al*., 2007; Müller *et al*., 2014).

Soil WR is generally induced by plant residues and substances excreted by roots, microorganisms and fungi. Many researchers have observed that soil WR is mostly associated with certain plant species with tissues rich in resins and waxes, as pines or eucalypts (Arcenegui *et al*., 2008; Hubbert *et al*., 2006; Martínez-Zavala & Jordán-López, 2009; Mataix-Solera & Doerr, 2004; Mataix-Solera *et al*., 2007; Rodriguez-Alleres et al., 2007). It has also been reported that soil properties may influence the development of soil WR (Doerr *et al*., 2000), as soil microbiology, texture, moisture content, acidity and mineralogy (Dekker *et al*., 2000; Mataix-Solera *et al*., 2013; Mataix-Solera *et al*., 2014; Jiménez-Pinilla *et al*., 2016). Other factors, like fire, may have no impact, destroy or enhance soil WR (Doerr *et al*., 2000; Jordán *et al*., 2013; Pereira *et al*., 2015). Consequently, different authors have investigated the natural soil WR background in different areas as USA (Pierson *et al*., 2008; Doerr *et al*., 2009), Iran (Mirbabaei *et al*., 2013), Mexico (Jordán *et al*., 2009), Spain (Rodríguez-Alleres *et al*., 2012; Zavala *et al*., 2014), South Africa (Scott, 2000) or Australia (Blackwell, 2000).

Although highland forests in central Mexico have played a key role in local economy over centuries, economical and management changes have led to serious deforestation processes (Álvarez-Icaza *et al*., 1993; Works & Hadley, 2004). In the Angangueo area, some of the most important disturbances include road-building, logging timber for stabilization of mine shafts, clear-cuts because of commercial logging or selective cutting (López-García & Alcántara-

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Ayala, 2012). Studies carried out by Jordán *et al*. (2009) and Jordán *et al*. (2011) reported relatively high values of soil WR in forest soils from Mexican volcanic highlands, particularly beneath the canopies of fir and pines. In all these cases, soil WR can increase soil erosion risk, especially at the beginning of the rainy season (Jordán *et al*., 2009; Gabarrón-Galeote *et al*., 2013).

Because of these impacts, information on the natural severity of soil WR is necessary for adequate soil planning and management. Despite the general influence of climate gradients in soil hydrological and geomorphological processes, local factors may be extremely important (Cerdà, 1998; Imeson *et al*., 1998). Research of soil WR background presents some gaps in areas where it would help to understand hydrological and erosive soil processes. Only a few studies focusing soil WR have been carried out in Mexico. Some of these studies deal with hydrocarbon contaminated soils in the southern Gulf of Mexico region (Adams et al., 2008; Guzmán-Osorio and Adams, 2015). Jordán *et al*. (2009) studied the hydrological response of different vegetation types (fir, pine and oak forest and shrublands) in hydrophobic and wettable volcanic soils of central Mexico. They observed that soil WR contributed to fast ponding and runoff generation during simulated rainfall experiments. In the same area, Jordán *et al*. (2011) investigated the effects of fire severity on WR and aggregate stability. In a laboratory experiment, Zavala *et al*. (2010) studied the effect of burning temperature on WR and aggregate stability in Spanish, Mexican and Australian soils. However, more studies are necessary to increase the number of available data on soil WR and understand its implications on the hydrological and geomorphological soil processes in a region characterized by high ecosystem diversity. For this study, we selected the San Pedro area, near the village of Angangueo (Michoacan, Mexico), in the Mexican Neo-Volcanic Axis Range. Forest types in this area include tree species such as firs, cedars, pines and oaks, which induce different levels of soil WR (Jordán *et al*., 2009; Jordán *et al*., 2011). The objectives of this study are (i) to study the intensity and persistence of WR in soils under specific tree species (firs, cedars, pines and oaks); (ii) the relation between soil WR distance upslope (shadowed area) and downslope (sunny area) of the source of organic residues (tree trunk); (iii) the relation between soil WR and plant cover (tree, shrub and herbaceous cover) in different forest types and (iv) the relation between soil WR and physical and chemical soil properties.

MATERIAL AND METHODS

STUDY AREA

The study area is located in the south-facing slope of the San Pedro River catchment (19°37′31″ N, 100°16′26″ W), near Angangueo (Mich., Mexico). Elevation of the study area ranges from 2600 and 3400 masl. The lithological substrate is dominated by Miocene alkaline lavas (andesites). According to the Chincua weather station (19° 45′ 28·62″ N, 100° 17′ 5·42″ W, 2415 masl, approximately 14 km north of the study area), climate is characterized by a dry cool winter and a temperate rainy summer. Mean monthly temperature varies between 11·9 (January) and 17·0 °C (May), with average annual temperature 14·8 °C. Mean monthly rainfall varies between 6 (March) and 211 mm (July), with mean annual rainfall 913 mm.

Main species in the area are sacred fir (*Abies religiosa*), smooth-bark Mexican pine (*Pinus pseudostrobus*), oaks (*Quercus laurina*), shrubs and herbaceous plants. Fir forests also include willows (*Salix paradoxa*) and white cedar (*Cupressus lusitanica*). These forests distribute on Andosols in the upper part of slopes, between 3·100 and 3·500 masl, forming dense and diverse communities with tree height often reaching 30 m (Ramírez, 2001; Rzedowski & Rzedowski, 2001). Cedars in the area come from plantations carried out in the early XXth century (Madrigal, 1994; Ramírez, 2001; Rzedowski & Rzedowski, 2001). Pine-oak forests distribute mostly in the western slopes of the study area, below 3000 masl. These forests are formed by *A. religiosa*, *Alnus acuminata*, *Alnus jorullensis*, *Arbutus xalapensis*, *Clethra mexicana*, *Pinus leiophylla*, *Pinus michoacana*, *Pinus montezumae*, *P. pseudostrobus*, *Quercus crassipes*, *Q. laurina* and *Quercus rugosa* (Madrigal, 1994; Rzedowski & Rzedowski, 2001). Shrubs dominated by sunflowers (*Baccharis conferta*) and conifers (*Juniperus monticola*) occupy medium (2800–3300) and upper (3100–3500 masl) part of slopes, respectively. These shrubs also include *Acaena elongata*, *Senecio cinerarioides*, *Senecio salignus*, *Senecio angulifolius* and *Symphoricarpus microphyllus* (Rzedowski & Rzedowski, 2001).

EXPERIMENTAL DESIGN

The experimental work was carried out during December (2014) and January (2015), part of the dry season. In order to study the influence of tree canopy on soil WR, a set of 80 points was selected in the study area using UTM randomly generated coordinates (20 points for each tree type considered: firs, pines, cedars and oaks). Slope in the selected points ranged between 43·8 and 63·3%, 55·5% on average. At each one of these points, we selected the closest individual of each of the four species considered (firs, pines, cedars and oaks). In order to study differences in the intensity and persistence of soil WR between points at different distance from the source of residues, these parameters were determined at 10 points upslope (U) and 10 points downslope (D) from the trunk (100 cm from each other) for each tree. When canopies from different trees overlapped, the point was discarded and the next closest individual was selected.

In order to study the relation between soil WR and plant cover, 10 east-to-west oriented transects (15 m long) were established at randomly selected points under fir, fir-pine-oak and pine-oak forest types. At each transect, presence (1) or absence (0) of plant cover (T, tree; S, shrub; H, herbaceous cover) was recorded every 100 cm. The final number of observations was 480 (10 transects × 3 forest types × 16 points). Tree (T), shrub (S) and herbaceous cover (H) were expressed as the percentage of observations (points) for each combination of possible covers. We calculated the proportion of bare soil as the percentage of points where no plant cover was observed. Rock fragments (mineral particles larger than 2 mm), rocky outcrops and other elements (biological crusts, for example) were included in the "bare soil" class because of their negligible occurrence as compared to bare soil. They were also present in a very small proportion below the canopy of plants.

PHYSIC-CHEMICAL CHARACTERIZATION OF SOILS

Previously to the assessment of soil WR, soil samples (0–5 cm depth) were collected 200 cm upslope and downslope from each individual tree considered. Soil samples were transported in plastic bags to the laboratory for soil analysis, dried on paper tries at laboratory room temperature (25 °C) to constant weight and sieved (2 mm) to eliminate coarse soil particles. Soil acidity (pH) was determined in 1:2·5 soil: water extracts. Carbonate content was determined in soil samples with $\mathrm{pH} > 6 \cdot 0$ using the Bernard's calcimeter. Organic carbon (OC) content was determined by oxidation with acid-dichromate potassium and titration of dichromate excess with ferrous sulfate (Walkley & Black, 1934). Exchangeable cations were determined by the ammonium acetate method (Thomas, 1982) and cation exchange capacity (CEC) was determined by the $BaCl_2$ test (Rhoades, 1982).

Previously to textural analysis, soil subsamples (about 100 g) were pre-treated with H_2O_2 (6%) to remove organic matter and soluble salts and, later, with HCl (35%) to remove $CaCO_3$ if present. These pre-treated samples were dried in the oven to obtain the initial weight, dispersed with a $(NaPO_3)_6$ solution (5%), and mechanically shaken. Soil material was then sieved to separate the sand (0·05–2 mm) fraction. The clay (<0·002 mm) fraction was determined by the Bouyoucos method (Bouyoucos, 1962).

SOIL WATER REPELLENCY

Persistence and intensity of soil WR were assessed under field conditions on the soil surface, after gently removing the litter manually. Intensity of soil WR was determined using the ethanol percentage test (EPT). Drops (50 µL) of decreasing ethanol concentrations (increasing surface tensions) were applied onto the soil surface using a micropipet until one of the drops infiltrated within 5 s after application. This allows the classification of the soil surface into a surface tension category between two consecutive ethanol concentrations. EPT classes were classified as in Doerr (1998): very wettable (1, 0·0% ethanol), wettable (2, 3·0%), slightly water repellent (3, 5·0%), moderately water repellent (4, 8·5%), strongly water repellent (5, 13·0%), very strongly water repellent (6, 24·0%) and extremely water repellent (7, 36·0%).

Persistence of soil WR was determined using the water drop penetration time (WDPT) test (Wessel, 1988). At each point, 10 drops (0·5 µL) of distilled water were applied in a circular area (10 cm in diameter) of the soil surface using a micro-pipet from a height of approximately 5 mm to avoid excess kinetic energy affecting soil-droplet interactions, and time for complete infiltration was recorded. The median WDPT was considered representative for each case and soil was classified as wettable (1, $\mathrm{WDPT} \leq 5\,\mathrm{s}$), slightly water repellent (2, $5\,\mathrm{s} < \mathrm{WDPT} \leq 60\,\mathrm{s}$), strongly water repellent (3, $60\,\mathrm{s} < \mathrm{WDPT} \leq 600\,\mathrm{s}$), severely water repellent (4, $600\,\mathrm{s} < \mathrm{WDPT} \leq 1\,\mathrm{h}$) and extremely water repellent (5, $\mathrm{WDPT} > 1\,\mathrm{h}$).

DATA ANALYSIS

The normal distribution of data and homogeneity of variances was tested using the Shapiro–Wilk's and Levene's test, respectively. When both null-hypotheses were accepted, parametric statistics (mean, standard deviation) and tests (ANOVA) were used. Otherwise, non-parametric statistics (median, range and Spearman rank correlation coefficient) and tests (Kruskal–Wallis and Mann–Whitney *U* tests) were used. The Spearman rank correlation coefficient (r_s) was used to study the relation between EPT and WDPT data and among them and the rest of soil variables. A principal component analysis (PCA) was performed using intensity of WR data (transformed as ln(EPT)) and soil chemical and physical parameters (pH, OC content, exchangeable Ca^{2+}, Mg^{2+}, K^+ and Na^+, CEC, and sand and clay contents). All computations were performed using SPSS v.23 (IBM Corp., 2015).

RESULTS

Soil characterization

The ANOVA test did not found significant differences between soil chemical and physical properties in U- and D-points. A summary of soil characteristics is shown in Table I. Studied soils were slightly to strongly acidic, with mean pH values ranging from 5·4 ± 0·4 (soils below oaks) to 6·2 ± 0·4 (below cedars). Mean soil $CaCO_3$ content per tree species and orientation varied between 0·0 ± 0·0 (oaks and pines) and 0·07 ± 0·30% (cedars); it was 0·00% in all cases except in three soil plots under the canopy of cedars and three below firs with pH 6·8–7·0 (0·01–1·44% $CaCO_3$). Organic C content varied between 7·76 ± 0·89 (cedars) and 11·31 ± 0·43% (oaks), 9·39 ± 1·52% on average.

The content of exchangeable cations was relatively high for Ca^{2+} (6·17 ± 3·07 cmol (+) kg^{-1}, on average) and Mg^{2+} (2·21 ± 1·24 cmol (+) kg^{-1}). Mean values for K^+ and Na^+ were 0·45 ± 0·26 and 0·09 ± 0·06 cmol (+) kg^{-1}. Generally, soil CEC decreased following the sequence oaks > pines > firs > cedars, with mean values ranging

Table I. Soil characterization (mean ± standard deviation) under different tree species: pH; $CaCO_3$ content (%); organic C content; exchangeable cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+); cation exchange capacity (CEC) and sand and clay contents. $N = 40$ in all cases

Species	pH	$CaCO_3$ %	Organic C %	Ca^{2+} cmol(+) kg^{-1}	Mg^{2+} cmol(+) kg^{-1}	K^+ cmol(+) kg^{-1}	Na^+ cmol(+) kg^{-1}	CEC cmol(+) kg^{-1}	Sand %	Clay %
Cedar	6·2 ± 0·4	0·07 ± 0·30	7·76 ± 0·89	5·82 ± 3·08	2·08 ± 1·28	0·42 ± 0·26	0·09 ± 0·06	14·43 ± 7·98	29·3 ± 6·4	12·4 ± 2·1
Fir	6·1 ± 0·4	0·05 ± 0·17	8·47 ± 0·69	7·08 ± 3·20	2·58 ± 1·30	0·51 ± 0·27	0·11 ± 0·061	24·15 ± 11·70	29·3 ± 7·1	12·7 ± 2·0
Oak	5·4 ± 0·4	0·00 ± 0·00	11·31 ± 0·43	5·88 ± 2·91	2·13 ± 1·23	0·43 ± 0·26	0·09 ± 0·05	38·23 ± 19·82	32·2 ± 5·2	12·4 ± 1·9
Pine	5·7 ± 0·3	0·00 ± 0·00	10·02 ± 0·36	5·92 ± 3·02	2·055 ± 1·10	0·42 ± 0·24	0·09 ± 0·05	30·33 ± 15·58	33·7 ± 5·4	12·9 ± 1·6
All	5·9 ± 0·5	0·03 ± 0·17	9·39 ± 1·52	6·17 ± 3·07	2·21 ± 1·24	0·45 ± 0·26	0·09 ± 0·06	26·79 ± 16·78	31·1 ± 6·3	12·6 ± 1·9

between 14·43 ± 7·98 (cedars) and 38·23 ± 19·82 cmol (+) kg^{-1} (oaks). Soil texture was silt loam, with average sand and clay contents 31·1 ± 6·3 and 12·6 ± 1·9%, respectively.

Soil Water Repellency Under Different Tree Species

Intensity of soil water repellency

EPT classes varied between 1–2 and 7 in U- and D-points below firs and cedars. We observed extreme intensity (EPT = 7) below pines only in D-points. In the case of oaks, EPT classes only varied between 1 and 3 (U-points) or 1 and 5 (D-points). Generally, EPT decreased with distance from the trunk (Table II). In U-points below firs, for example, EPT decreased from 7 (1 m from the trunk) to 3(10 m from the trunk). Although soil below the canopy of firs, pines and cedars was usually very strongly or extremely water-repellent in a 2-m radius he trunk, EPT classes below the canopy of oaks varied between 3 and 4 near the trunk, quickly decreasing to 1 or 2 with distance.

Median intensities of soil WR in U- and D-points below the canopy of studied trees were not significantly different, yet we found some differences between them at different distances from the tree trunks. EPT decreased one class at 1-m position from U- to D-points ($p < 0·001$), and increased one class at 6 and 7 m ($p < 0·001$ in both cases) below firs. Median EPTs below pines, cedars and oaks increased in one class at least for each distance from the trunk in D-points ($p < 0·001$) except in one case. In some soil plots below oaks, this only meant changing from wettable to very wettable.

Persistence of soil water repellency

WDPT classes varied between 1 and 7. The proportion of points with extreme persistence of soil WR (WDPT = 7) varied between 35 (pines, U-points) and 72% (firs, D-points) for soil below the canopy of firs, cedars and pines. Below oaks, the proportion of extremely persistent WR was only 3 (U) and 6% (D), and very wettable or wettable soil points dominated (71%, U, and 54%, D). As seen for EPT values, WDPT significantly decreased with distance from the trunk of trees, varying between 4 and 7 (firs), 3 and 7 (pines and cedars), and 1 and 3 (oaks) (Table III). Generally, the influence of the relative position (U- and D-points) was not important when all cases were considered together. However, we found 1-class increments between U and D equivalent positions in 3 points below the canopy of firs, 3 points below pines and 5 points below cedars and oaks ($p < 0·001$ in all cases). In the latter case, this only meant jumping from wettable to slightly water repellent. Wettable soil points were not observed below the canopy of firs, and only in some cases below pines and cedars (between 7 and 10 m from the trunk). On the other hand, most of soil points below oaks were classified as wettable (WDPT = 1; 41·5 and 16·5%, U- and D-points, respectively) or slightly water repellent (WDPT = 2; 28·5 and 36·0%, U- and D-points, respectively).

Table II. Intensity of soil water repellency (EPT classes: median and range between parentheses) per tree species, orientation (U: upslope; D: downslope) and distance from trunk. EPT classes: 1: very wettable; 2: wettable; 3: slightly water repellent; 4: moderately water repellent; 5: strongly water repellent; 6: very strongly water repellent; 7: extremely water repellent. S–W, *p*: *p*-value of the Shapiro–Wilk test for normality of EPT data distribution below each species and at different orientations; K–W, *p*: *p*-value for the Kruskal–Wallis test of differences between EPT values at different distances from the trunk below each species and at different orientations; M–W, *p*: *p*-value for the Mann–Whitney *U* test for comparison of median EPTs below upslope and downslope points below tree species. For each species and distance from the trunk, significant differences ($p > 0 \cdot 05$) between the intensity of soil water repellency of upslope and downslope areas are marked with an asterisk (*). The number of samples for each tree species, orientation and distance is 20

Distance (m)	Fir-U	Fir-D	Pine-U	Pine-D	Cedar-U	Cedar-D	Oak-U	Oak-D
1	7 (6, 7)	6 (5, 7) *	5·5 (5, 6)	7 (5, 7) *	6 (5, 7)	7 (5, 7)	3 (2, 3)	4 (2, 5) *
2	6 (5, 7)	6 (5, 7)	5 (4, 6)	6 (4, 7) *	6 (4, 7)	7 (5, 7) *	2 (1, 3)	3 (1, 4) *
3	6 (5, 6)	6 (5, 6)	4·5 (4, 5)	6 (4, 7) *	5 (4, 6)	6 (4, 7) *	2 (1, 3)	3 (1, 5) *
4	5 (4, 6)	5 (4, 6)	4·5 (3, 5)	5 (3, 7) *	4 (3, 5)	5 (4, 7) *	1 (1, 2)	2 (1, 5) *
5	5 (4, 5)	5 (4, 6)	5 (4, 5)	6 (5, 7) *	4 (3, 4)	5 (3, 6) *	1 (1, 2)	2 (1, 4) *
6	4 (3, 5)	5 (4, 6) *	4 (3, 5)	5 (3, 7) *	3 (2, 4)	4 (3, 6) *	1 (1, 2)	3 (1, 4) *
7	3 (3, 4)	4 (4, 4) *	3 (3, 4)	5 (3, 6) *	2 (2, 3)	3 (2, 4) *	1 (1, 1)	2 (1, 3) *
8	4 (3, 4)	4 (3, 4)	3 (3, 4)	4 (3, 6) *	2 (2, 3)	3·5 (2, 4) *	1 (1, 1)	2 (1, 3) *
9	3 (3, 3)	3 (3, 4) *	3 (3, 3)	4 (3, 5) *	2 (2, 3)	3 (2, 5) *	1 (1, 1)	2 (1, 3) *
10	3 (2, 3)	2 (1, 3)	2 (2, 3)	4 (2, 5) *	2·5 (2, 3)	3·5 (2, 5) *	1 (1, 1)	2 (1, 3) *
All cases	4 (2, 7)	5 (1, 7)	4 (2, 6)	5 (2, 7)	3 (2, 7)	4 (2, 7)	1 (1, 3)	2 (1, 5)
S–W, *p*	<0·001	<0·001	<0·001	<0·001	<0·001	<0·001	<0·001	<0·001
K–W, *p*	<0·001	<0·001	<0·001	<0·001	<0·001	<0·001	<0·001	<0·001
M–W, *p*	>0·05		>0·05		>0·05		>0·05	

Table III. Persistence of soil water repellency (WDPT classes: median and range between parentheses) per tree species, orientation (U: upslope; D: downslope) and distance from trunk. WDTP classes: 1: wettable (0–5 s); 2: slightly water repellent (5–60 s); 3: strongly water repellent (60–600 s); 4: severely water repellent (600 s–1 h); 5: extremely water repellent (1–3 h); 6: extremely water repellent (3–6 h); 7: extremely water repellent (>6 h). S–W, *p*: *p*-value of the Shapiro–Wilk test for normality of WDPT data distribution below each species and at different orientations; K–W, *p*: *p*-value for the Kruskal–Wallis test of differences between WDPT values at different distances from the trunk below each species and at different orientations; M–W, *p*: *p*-value for the Mann–Whitney *U* test for comparison of median WDPTs below upslope and downslope points below tree species. For each species and distance from the trunk, significant differences ($p > 0 \cdot 05$) between the intensity of soil water repellency of upslope and downslope areas are marked with an asterisk (*). The number of samples for each tree species, orientation and distance is 20

Distance (m)	Fir-U	Fir-D	Pine-U	Pine-D	Cedar-U	Cedar-D	Oak-U	Oak-D
1	7 (5, 7)	7 (5, 7)	6 (4, 7)	6 (4, 7)	7 (4, 7)	7 (4, 7)	2 (1, 5)	3 (2, 5) *
2	7 (5, 7)	7 (5, 7)	5 (3, 7)	5·5 (3, 7)	6 (4, 7)	6·5 (5, 7)	3 (1, 5)	3 (2, 5)
3	6 (4, 7)	6·5 (4, 7)	5 (3, 6)	5 (3, 6)	6 (4, 7)	7 (4, 7)	2·5 (1, 5)	3 (1, 6)
4	6 (4, 7)	6·5 (5, 7)	4 (3, 6)	5 (3, 7)	5 (3, 7)	5 (3, 7)	2 (1, 4)	3 (1, 5)
5	5·5 (3, 7)	6 (4, 7)	4 (3, 6)	5 (3, 7)	4 (2, 6)	5 (2, 7)	2 (1, 4)	3 (1, 4)
6	5 (2, 7)	5·5 (2, 7)	4 (2, 6)	4 (3, 6)	3·5 (2, 5)	4 (3, 6)	2 (1, 4)	2 (1, 5)
7	4 (2, 5)	5 (2, 6)	4 (2, 5)	4·5 (2, 6)	3·5 (1, 5)	4 (1, 5)	2 (1, 3)	2 (1, 4)
8	4 (2, 6)	5 (3, 6)	4 (2, 5)	4 (2, 6) *	3 (1, 5)	4 (2, 5)	1 (1, 2)	2 (1, 3)
9	3 (2, 5)	3 (2, 6)	3 (2, 4)	3 (2, 5)	3 (1, 5)	4 (1, 6)	1 (1, 2)	2 (1, 3) *
10	4 (2, 5)	4 (2, 6)	2 (1, 4)	3 (1, 5)	3 (1, 5)	4 (2, 6)	1 (1, 2)	2 (1, 3) *
All cases	5 (2, 7)	6 (2, 7)	4 (1, 7)	5 (1, 7)	4 (1, 7)	5 (1, 7)	2 (1, 5)	2 (1, 6)
S–W, *p*	<0·001	<0·001	<0·001	<0·001	<0·001	<0·001	<0·001	<0·001
K–W, *p*	<0·001	<0·001	<0·001	<0·001	<0·001	<0·001	<0·001	<0·001
M–W, *p*	>0·05		>0·05		>0·05		>0·05	

Relation Between Intensity and Persistence of Soil Water Repellency

Spearman's rank correlation coefficients between EPT and WDPT were significant ($p < 0 \cdot 0001$) and positive for soil points below firs ($r_s = 0 \cdot 7240$), pines ($r_s = 0 \cdot 6832$) and cedars ($r_s = 0 \cdot 7246$). In contrast, correlation for soil points below oaks was weak ($r_s = 0 \cdot 4607$; $p < 0 \cdot 0001$). EPT from soils below pines and firs was not significantly different ($p = 0 \cdot 9719$). In contrast, EPT classes below cedars were significantly lower than below firs ($p = 0 \cdot 0002$) and pines ($p = 0 \cdot 0001$). Soils below oaks showed lower EPT values than soils below the rest of species ($p = 0 \cdot 0000$). Concerning WDPT, we found significant differences between median WDPT values in all cases except for soils below cedars and pines ($p = 0 \cdot 1780$). Soils below firs showed higher WDPT values than soils below pines and cedars. As in the previous case, soils below oaks showed lower WDPT values than soils below the rest of species.

Relation Between Intensity of Soil Water Repellency and Plant Cover

On average, tree cover varied between 75·6% in fir-pine-oak forest and 92·5% in fir forest (Table IV). On the other hand, shrub cover was higher in fir-pine-oak forest (83·8%) and slightly lower under fir and pine-oak forests (78·8 and 78·1%, respectively). Herbaceous plant cover varied in a narrow range between 46·9 (fir and fir-pine-oak forests) and 50·6% (pine-oak forest). The proportion of bare soil was below 2·5% in most cases (only 11 bare soil points were observed for 480 observations).

Median EPT value from soil points below the canopy of trees (median ETP = 5, strongly water repellent) was significantly higher (Mann–Whitney *U* test $p = 0 \cdot 0000$) than below shrubs or shrubs and herbaceous plants (median EPT = 2, wettable). Generally, soil WR was more intense in tree-covered points from fir and fir-pine-oak forests than from pine-oak forest (Figure 1). For both forest types, shrub-covered points (S and S + H) were very wettable to slightly water repellent. No extreme soil water-repellent points were observed in pine-oak forest, with very wettable to very strongly water repellent conditions below trees (T, T + S and T + S + H points) and very wettable to slightly water repellent below shrubs (S and S + H). In all cases, bare soil showed wettable conditions (EPT values 1 and 2).

Relation Between Intensity of Soil Water Repellency and Soil Properties

The intensity of soil WR (EPT) did not show significant correlations with most soil variables, except for OC content ($r_s = -0 \cdot 578$, $p \leq 0 \cdot 01$), pH ($r_s = 0 \cdot 186$, $p \leq 0 \cdot 05$) and CEC ($r_s = -0 \cdot 294$, $p \leq 0 \cdot 01$). These coefficients were significant and negative, but, generally, indicated moderate (EPT/OC) or weak correlations (EPT/pH and EPT/CEC). For soil points below different tree species, the maximum Spearman correlation coefficient observed was 0·623 ($p \leq 0 \cdot 01$) below firs, while in other cases r_s was always close to zero. The PCA divided the soil samples in three groups (Figure 2). Group A includes soil points below the canopy of firs and cedars, without any clear separation between them. Group B includes soil points below pines and group C soil points below the canopy of oaks, with group B in an intermediate position between groups A and C. Regarding the ordination of soil variables, factor 1 shows a high correlation with CEC and exchangeable cations, while factor 2 corresponds to soil acidity (pH), intensity of soil WR and organic C content.

DISCUSSION

Different severities of intensity and persistence of soil WR have been observed in soils under different types of forests and tree species in the study area. Although strong relations between soil WR and soil properties have been reported in many areas (Mataix-Solera *et al*., 2008; Zavala *et al*., 2009b; Mataix-Solera *et al*., 2013; Mataix-Solera *et al*., 2014; Zavala *et al*., 2014), no relevant correlations have been observed in this research at the working scale. On the other hand, the spatial distribution of soil WR in the study area is strongly conditioned by vegetation, in agreement with results reported by other authors, who observed that, in areas with homogeneous soil properties, vegetation is the main factor controlling soil WR (Doerr *et al*., 1996; Cerdà *et al*., 1998; Buczko *et al*., 2005; Cerdà & Doerr, 2007; Jordán *et al*., 2008; Jordán *et al*., 2009; Bodí *et al*., 2011; Granged *et al*., 2011b; Bodí *et al*., 2012; Zavala *et al*., 2014; Jiménez-Pinilla *et al*., 2015).

Soils below fir and fir-pine-oak forest were extremely water-repellent under the canopy of trees (T, T + S and T + S + H plots). Although extreme values were not observed in tree-covered soils under pine-oak forest, T, T + S and T + S + H also showed the highest intensity of soil WR (very strong WR). Generally, the proportion of water-repellent soil points increased following the sequence bare soil < shrubs and herbaceous plants (S + H) < shrubs (S) < trees (T, T + S and T + S + H). This observation is in agreement with most of previous research, which has reported a limited contribution of herbaceous plants to soil WR (Zavala *et al*., 2009a; Schnabel *et al*., 2013; Zavala *et al*., 2014).

Although differences between OC content were found (Kruskal–Wallis $p = 0 \cdot 000$), these are relatively small. The Spearman correlation coefficient between OC content and WR suggests that there is no direct relation between both properties in the study area. Therefore, each type of tree species, vegetation and associated microbiota may contribute to the development of different hydrophobicity severities. The highest severity of soil WR has been observed below conifers (firs, cedars and pines), whereas soils below oaks have been found to be much more wettable. These results are in agreement with findings from other authors, who have reported that conifers are much more prone than oaks to induce soil WR, because of the chemical composition of their tissues, which include resins, waxes and other substances able to cause hydrophobicity in soils (Conde *et al*., 1998; Ito *et al*., 2002; Mataix-Solera & Doerr, 2004; Lozano *et al*., 2013; Mao *et al*., 2015). Different authors have

Table IV. Fir, pine, cedar, oak, total tree, shrub and herbaceous cover (%) for fir: fir-pine-oak and pine-oak forests in the study area. *Tree cover is calculated as the sum of all points below the canopy of one or more trees (firs, pines, cedars and/or oaks)

Vegetation type	Fir	Pine	Cedar	Oak	Total tree*	Shrubs	Herbaceous plants	Bare soil
Fir	87·5	0·0	31·9	0·0	92·5	78·8	46·9	1·9
Fir-pine-oak	51·9	34·4	0·0	21·3	75·6	83·8	46·9	2·5
Pine-oak	0·0	64·4	0·0	42·5	80·6	78·1	50·6	2·5

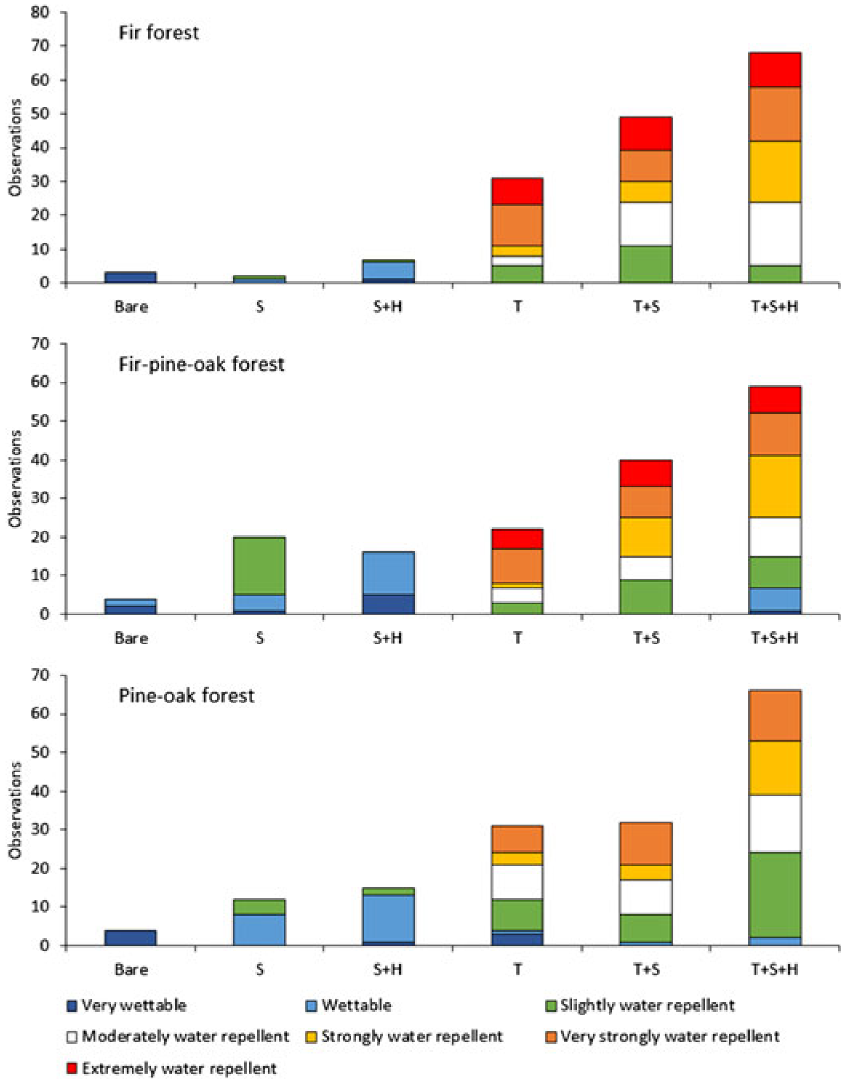

Figure 1. Number of observations of intensity of soil water repellency classes (EPT) from fir, fir-pine-oak and pine-oak forest plots for different cover types, bare soil (Bare), shrub cover (S), shrub and herbaceous cover (S + H), tree cover (T), tree and shrub cover (T + S) and tree, shrub and herbaceous cover (T + S + H). $N = 160$ for each forest type. No observations below tree and herbaceous cover (T + H) or below herbaceous cover (H) only were recorded.

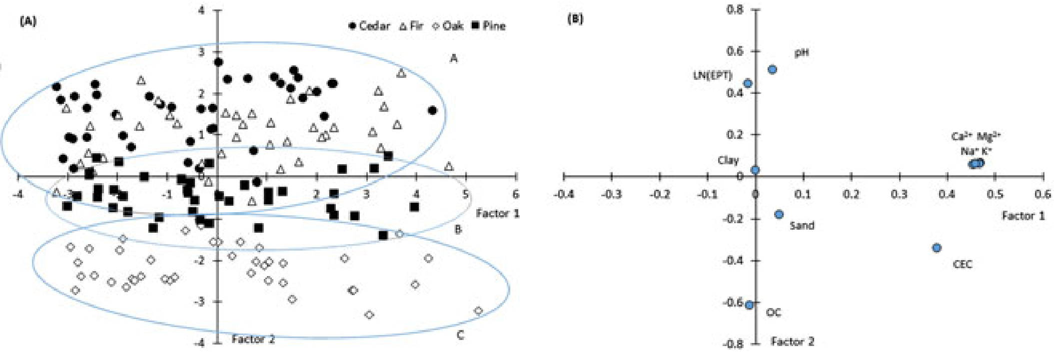

Figure 2. Principal component analysis of intensity of soil WR (LN(EPT)) and soil chemical and physical variables, pH, organic C content (OC), exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}), cation exchange capacity (CEC) and sand and clay contents for soil plots under cedars, firs, oaks and pines. (A) cases; (B) variables.

reported soil WR in oaklands from Mediterranean areas (Cerdà *et al*., 1998; Mataix-Solera *et al*., 2007; Jordán *et al*., 2008; Zavala *et al*., 2009b; Zavala *et al*., 2014). Although our results show that severity of soil WR below oaks is lower than in soils below conifers, as shown by Zavala *et al*. (2009b) and Zavala *et al*. (2014), preeminence of conifers versus oaks, however, is not always clear. Jiménez-Morillo *et al.* (2014) studied soil WR under different vegetation types in an area in southwestern Spain and found more severe WR in soils below oaks than below pines or other species. They attributed this to higher organic matter contents and a high degree of evolution of organic matter, mainly in organic films coating the finer particles. Recurrent wildfires in the region may contribute also to the development of hydrophobic soil conditions (Ramírez Ramírez *et al.*, 2005; Garduño Bernal, 2011; Jordán *et al.*, 2011).

Tree cover conditioned the spatial variation of soil WR. Soil WR decreased with increasing distance from individual trees. Although results between firs, cedars and pines were different for intensity (EPT) and persistence (WDPT) of soil WR, both properties decreased with distance from the trunk and showed strong correlations. In the case of oaks, the severity of soil WR was limited but also decreased with distance (according to median values, intensity of WR decreased from very wettable/wettable to slightly/moderately water repellent and persistence decreased from wettable/slightly water repellent to slightly/strongly water repellent). The scattered disposition of trees contributes to a patchy pattern of soil WR, which may contribute to form a runoff generation/infiltration pattern. Very few authors have reported data about the spatial distribution of soil WR regarding the relative distance to tree trunks or canopy boundaries. In burned soils under junipers and pines, Madsen *et al.* (2010) found a correlation between the spatial distribution of soil WR and the canopy boundary. They observed that about 66% of the canopy region was water repellent, and persistence of soil WR decreased with distance from the canopy boundary, with wettable conditions in the inter-canopy areas (Madsen *et al.*, 2008; Madsen *et al.*, 2010). Our results show a similar decreasing trend with distance, but, in many cases, hydrophobic conditions were observed at relatively long distances from the tree canopy.

Keizer *et al.* (2005) studied the variation of soil WR with distance from eucalypt trees, and found that distance only is not enough to explain hydrophobicity patterns. They concluded that local variability in topsoil WR may be caused by differences in tree characteristics and soil properties related to potential sources of hydrophobic compounds. Our results show significant differences between the intensity of soil WR from upslope and downslope points at all distances from the trunk below the canopy of pines and oaks, most of points below cedars (2–10 m) and some points below firs (1, 6, 7 and 9 m). In most cases, these differences were only one EPT class. These differences may be explained by different soil microclimate conditions. Although soil WR is known to vary irregularly during drying (González-Peñaloza *et al.*, 2013), it is generally destroyed above certain critical soil moisture content (Doerr & Thomas, 2000; Dekker *et al.*, 2001; Zavala *et al.*, 2010). Plant cover and shading may affect soil microclimate both in the canopy and inter-canopy regions through interception of sunlight, and this effect is much more marked in the case of woody plants (Lebron *et al.*, 2007; Madsen *et al.*, 2008). Soils from upslope transects, preferentially shaded by trees in a south-facing slope in the study area, are expected to show relatively higher moisture contents through the year and, consequently, relatively lower severity of soil WR is expected.

As soil WR is induced by organic compounds released by plant residues and soil microbiota (Doerr *et al.*, 2000), it may be suggested that hydrophobicity is induced not only below the canopy of trees, but also in neighbor inter-canopy areas where litter and hydrophobic soil particles are redistributed by wind or surface water flow. It can be concluded that, in the area, soil WR distributes following a heterogeneous spatial pattern conditioned by canopy and inter-canopy areas. Especially in soils under oaks, inter-canopy areas are wettable or show subcritical WR.

CONCLUSIONS

The spatial distribution of soil WR in the San Pedro River catchment (Angangueo, Mich., Mexico) is strongly conditioned by vegetation. Generally, soils below conifers showed the strongest WR. The highest intensity and persistence of soil WR were observed below firs/pines and firs, respectively. In both cases, soils below oaks showed the weakest values.

Persistence and intensity of soil WR inside the 1-m radius area near the tree trunk of coniferous species were very strong to extreme and decreased progressively with distance, with wettable inter-canopy areas at 10-m distance. Although soils under oaks showed a wide range of values, soil WR was generally weaker, with subcritical WR or wettable conditions at shorter distances.

It can be suggested that the position of trees in the study area contributes to a patchy pattern of soil WR, which, in turn, may contribute to a patchy distribution of runoff and infiltration areas. The irregularity of WR at the soil surface may have significant influence on soil hydrological and geomorphologic processes.

For all studied forest types (fir, fir-pine-oak and pine-oak forest), the intensity of soil WR increased according to the sequence bare soil (very wettable to wettable conditions), shrubs (very wettable to slight water repellency) and trees (very wettable to extreme water repellency). Although tree-covered areas include also shrubs and herbaceous vegetation, our results show that residues from tree vegetation are the main source of soil hydrophobic substances.

This study alone cannot explain the effects of soil WR on runoff and sediment connectivity patterns in the study area. Further studies should aim at mapping the influence of soil WR in connectivity pathways, identifying runoff generation and infiltration areas and sediment sources and sinks through the slope.

ACKNOWLEDGEMENT(S)

The first author received funding for an international stay during her MSc studies by the Mexican Council for Science and Technology (CONACYT). This study was funded by the Spanish Ministry of Economy and Competitiveness through the research projects POSTFIRE (CGL2013-47862-C2-1-R) and GEOFIRE (CGL2012-38655-C04-01). Authors acknowledge Joan and the Cerdocarpa Team for their help during the fieldwork. Two anonymous reviewers have contributed to improve the quality of the original manuscript.

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