Hydrophobicity of Sparta Sand under Different Vegetation Types in the Lower Wisconsin River Valley

Soil hydrophobicity is a characteristic that some soils exhibit where they repel water, and the plant community may play a role in its development. In the Lower Wisconsin River Valley (LWRV), some land with prairie has been planted with pines. There is an undetermined soil water repellency consequence of this land use change, as it was discovered that under pine plantation the soil was so desiccated at certain periods that it became extremely hydrophobic. The objective of this study was to determine the extent of soil hydrophobicity of Sparta sand (sandy, mixed, mesic Entic Hapludoll) in the LWRV under three vegetation types: prairie, pine plantation, and mixed prairie/forest (mixed vegetation). Soil samples were collected in 5-cm increments to a depth of 50 cm. Samples were analyzed using water drop penetration time (WDPT), soil wetted area (SWA), and molarity of ethanol (MED). Soil particle-size distribution (PSD), soil organic carbon (SOC), and soil water content were also determined. Additional surface samples were analyzed for chemical and particulate organic matter (POM) fractionation. Hydrophobicity was greater and extended to deeper depths in the pine plantation (35-cm depth) than in the prairie and mixed vegetations (10-cm depth). The greater water repellency in the pine resulted in drier soil conditions. This suggests there are strong plant–soil–hydrophobicity interactions for this soil. The PSD was not significantly different across vegetation, although it was across soil depth; this is expected since the soil parent materials were not different across sites. The SOC significantly decreased with depth but was not significantly different among vegetations. There were no relationships between water repellency, humic substances, and POM. A possible factor for the difference in soil water repellency among vegetations could be the quality of soil organic matter (SOM) produced by the different vegetation, with pine being the greater producer of hydrophobic material.

Abbreviations: cPOM, coarse particulate organic matter; DOC, dissolved organic carbon; fPOM, fine particulate organic matter; LOI, loss on ignition carbon; ISOM, litter soil organic matter; LWRV, Lower Wisconsin River Valley; MED, molarity of ethanol; POM, particulate organic matter; PSD, particle size distribution; scSOM, silt and clay soil organic matter; SOC, soil organic carbon; SOM, soil organic matter; SWA, soil wetted area; TC, total carbon; TDR, time domain reflectometry; TOC, total organic carbon; WDPT, water drop penetration time.

Soil water repellency has been recognized as an undesirable soil property for crop, grass, and forest management, yet the exact causes of soil hydrophobicity are not completely understood (Roy et al., 1999; Doerr and Thomas, 2000; Doerr, 2006). It has been suggested that the most important causes or factors in soil water repellency formation are type and amount of SOM, particle size, water content, lower pH values, frequency of fires, and vegetation type (Savage et al., 1969; DeBano, 2000; Mataix-Solera et al., 2007). Induced hydrophobicity associated with
Soil Physics

Soil water repellency is more commonly found in sandy soils that has a positive correlation between coarse POM (cPOM), fine POM (fPOM), and soil hydrophobicity, particularly for cPOM (Franco et al., 1995). In contrast, the clay and silt associated organic matter did not correlate with hydrophobicity (Franco et al., 1995). They argue that the presence of clay could reduce the effects of water repellent compounds, and other authors have demonstrated that the quantity of organic compounds and the type of clay are important in the development of hydrophobicity (e.g., Lichner et al., 2006, Mataix-Solera et al., 2008).

Humic substances have been in some cases associated with soil water repellency. Because of the aliphatic nature of some of humic substances, they could form stable aggregates by orienting the hydrophobic components to the outside of the aggregates, thereby impeding water entry (Piccolo and Mbagwu, 1999). A similar mechanism could occur in the case of hydrophobicity of single particles coated by organic material. Lichner et al. (2002) found that applications of humic acid (0.19–0.76%) extracted from peat silica sands significantly increased soil water repellency. In contrast, Savage et al. (1969) tested humic acid-type substance and polysaccharides applications from different bacterial and plant sources in an acid-washed soil. They found that only one extract from several bacterial culture solutions produced soil water repellency, suggesting that humic acid-type and polysaccharides probably did not play a role in water repellency formation. Fulvic acid has also been associated with soil water repellency (Chen and Schnitzer, 1978).

Organic compounds initiate water repellency by coating the soil particles with layers of hydrophobic compounds, with the outermost layer being presumed to determine the wetting properties of the particle (Doerr, 2006). Thus, particles with a small surface area, like sands, tend to be more easily coated than particles with greater surface area, like clays. For this reason soil water repellency is more commonly found in sandy soils (DeBano, 2000; Doerr et al., 2000).

Water or the absence of it plays a role in the formation of soil water repellency. In general, soil drying conditions enable hydrophilic groups of the organic compounds to orient themselves closer to the soil particle leaving the hydrophobic groups to the outside of the particle (Sposito, 2008; Stevenson, 1994). This is another reason why water repellency tends to be associated with sandy soils.

There is evidence that vegetation also plays a role in soil hydrophobicity formation. For example, Keizer et al. (2005) found that soil water repellency increased with proximity to southern blue gum (Eucalyptus globulus Labill.) tree stems. Native grassland soils in South Africa were less hydrophobic than indigenous forest and pine plantations (Scott, 2000). This is in agreement with other researchers who found that soil water repellency is a common condition of unburned forest soils, especially in pine plantations (Krammes and DeBano, 1965; DeBano and Rice, 1973; Richardson and Hole, 1978, Doerr et al., 1998; Buczko et al., 2005; Buczko and Bens, 2006; Moral Garcia et al., 2005; Doerr et al., 2009). Soil water repellency is not limited to forests; it has also been reported in other vegetation types such as crops, grasslands, and turfgrass (Cisar et al., 2000; Cooley and Lowery, 2000; Morley et al., 2005; Cooley et al., 2007). However, water repellency is most often associated with periods of very dry soil conditions. In addition different vegetation types increase soil hydrophobicity by supplying hydrophobic organic compounds (Doerr et al., 1998; Harper et al., 2000). For example, in hydrophobic grassland soils there is a greater amount of large polar compounds than in hydrophilic soils (Morley et al., 2005). In turfgrasses, the formation of hydrophobic dry patches has been partially attributed to basidiomycete-type fungi (York and Canaway, 2000; Fidanza et al., 2007).

In a more direct approach to prove the role of vegetation as a source of soil-hydrophobicity-producing organic compounds, Krammes and DeBano (1965) applied chaparral vegetation litter leachate to previously hydrophilic soils, rendering them hydrophobic. Doerr et al. (1998) did a similar experiment with leachates of pine needles and found an increase of soil hydrophobicity in the treated soils. Hongve et al. (2000) found that percolates from deciduous and coniferous litter contained large fractions of hydrophobic compounds, with coniferous litter having the greatest concentrations. These experiments with pine leachates are in agreement with findings of soil water repellency in unburned pine forests (Richardson and Hole, 1978; Scott, 2000; Doerr et al., 2009). An early water repellency study in Wisconsin documented greater soil water repellency in areas with pine than in prairies subjected to prescribed burning (Richardson and Hole, 1978).

In the LWRV, some land with prairie has been planted with pines. This vegetation shift has initiated soil changes towards podzolization of the soil (Quideau and Bockheim, 1996). However, there is an undetermined soil water repellency consequence of this land use change. In addition, relic prairies are being rapidly encroached on by woody vegetation (Scharenbroch et al., 2010).

In this study by Scharenbroch et al. (2010), it was also discovered that under pine plantation the soil was so desiccated at certain periods that the soil became hydrophobic, but this was noted under other vegetation like prairie. The objective of this research was to measure the severity of soil water repellency
under three vegetation types (prairie, mixed prairie including oak and jack pine [*Pinus banksiana* Lamb.], and pine plantation) in an area that was originally prairie grasses to determine if these vegetation changes are transforming the soil wettability. A second objective was to determine if there is a relationship between the amount of organic C and the observed soil water repellency.

**MATERIALS AND METHODS**

**Site Description**

Soil samples were collected from a site in the LWRV, (43°11′ N, 89°55′ W). The soil is Sparta sand (Soil Survey Staff, 2013). This soil is composed of very uniformly rounded silica sand grains that were deposited as outwash by the Wisconsin River during the last glaciation (Syverson and Colgan, 2004).

Soils at this site were developed under native dry prairie vegetation, but part of the area was planted in 1960 to red pine (*P. resinosa* Aiton) and white pine (*P. strobus* L.) plantations (Scharenbroch et al., 2010). The understory in the pine plantation is scarce, with predominately blackberry (*Rubus* spp.). In other areas, the prairie is being encroached on by woody plants. The prairie consists of triple awn grass (*Aristida oligantha* Michx.), little bluestem (*Andropogon scoparius* Michx.), moss (*Polytrichum piliferum* Hedw.), lichens [*Cladonia rangiferina* (L.) Weber], and some trees, mainly black oak (*Quercus velutina* Lam.) and jack pine. The forest encroachment areas (mixed vegetation) contain grasses similar to the prairie but are dominated by black oak, jack pine, and red and white pine. The plant community in the encroachments is composed of 90% red pine, white pine, and jack pine, and the remainder 10% black oak, red cedar (*Juniperus virginiana* L.), and black cherry (*Prunus serotina* Ehrh.) (Scharenbroch et al., 2010). This land has not been burned by the owners for at least 50 yr, and there was no evidence of wild fire either in the trees of the prairie or pine plantation or ground.

**Soil Sampling, Soil Analysis, and Experimental Design**

Three vegetation types (prairie, mixed prairie including oak and jack pine, and red pine plantation) were studied; the white pine areas were not included. In each of the three vegetation types, six 14 by 14 m plots were randomly established. One representative soil pit was dug in 2005 in four of the six plots of each vegetation type, and samples were collected from the side of the pit starting at ground level every 5 cm to a depth of 50 cm for a total of 10 depth intervals (Fig. 1). Another soil pit was dug and samples collected in all six plots of each vegetation type in August 2006. Samples were placed in sealed plastic bags and stored at room temperature (22°C) until they were analyzed for water repellency, total organic C, and soil particle size distribution. For the organic C analysis, a subset of three depths (0–5, 5–10, and 35–40 cm) was selected from the 2006 samples for analysis because each of these depth zones represented different degrees of water repellency.

To prepare samples for the water repellency tests, each soil sample bag was thoroughly mixed to assure homogeneity. The soil samples were air-dried, loosened manually, and passed through a 2-mm sieve. The sieved soils were transferred to 8.2-cm diam. Petri dishes to a height in the dish of approximately 1 cm. The three water repellency methods performed were the WDPT method and MED test as described by Doerr (1998) and the SWA test as described in Flores-Mangual et al. (2011). The MED was performed in the samples from 2005 only as further confirmation of the water repellency, and the WDPT and SWA in the 2006 soil samples for a more detailed look at the degree of wettability. The SWA test consists of monitoring with a caliper the wetted area of the soil after the water drop from the WDPT has penetrated the soil. The SWA assumes that the differences in the size of the wetted area in air dried and sieved sandy soils of similar particle size distribution is caused by differences in water repellency (Flores-Mangual et al., 2011). For this method, the smaller the value of soil wetted area, the more hydrophobic is the soil sample.

For the WDPT and SWA, three drops of water were monitored per Petri dish. The WDPT was discontinued after 1 h if the water drop did not penetrate the soil because after this time the drops started to evaporate. The SWA was monitored for 1 h after the water penetrated the soil. In the SWA test, the largest wetted area of each water drop was used as the datum to be analyzed statistically (Flores-Mangual et al., 2011). In samples where the water drop did not penetrate the soil, the diameter of the water drop was used to calculate the wetted area. The MED test

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**Fig. 1. Soil profile.**
was done using the guidelines of Doerr (1998). The procedure consists of applying drops of diluted ethanol at increasing concentrations (0, 3, 5, 8.5, 13, 24, and 36% by volume) until drop penetration is achieved before 3 s. Each concentration was later assigned a category from one to seven for statistical analysis. Three drops were monitored in each sample.

After the water repellency methods were performed, small amounts of soil were collected from each Petri dish sample and analyzed for particle size (only for the 2006 samples) using laser techniques (Arriaga et al., 2006). In addition, samples from the depths 0 to 5, 5 to 10, and 35 to 40 cm were analyzed for total organic C (TOC) using an automated Vario EL III Elemental Analyzer (Elementar Analysen systime GmbH, Germany) (Nelson and Sommers, 1996). It was assumed that total carbon (C) was equal to TOC. The reasoning was that in Sparta sand series, carbonates are at 200 cm or more, and the pH is moderately acid; therefore, it was assumed that there was minimal contribution of inorganic C to TC (Soil Survey Staff, 2013).

Additional soil sampling was performed in 2011 to determine the humic compounds and POM fractions. We collected one composite sample from the 0- to 10-cm depth on each plot. To avoid any effect due to surfactant application (which was another study), we collected samples from outside the plot, about 1 m from each of the four corners of the surfactant-applied plots. The analyses performed on these samples were total C, fulvic acid C, humic acid C and humin separation by the soil humus fractionation method described by Anderson and Schoenau (2008), and particulate forms of organic matter included silt and clay organic matter and fine and coarse particulate organic matter.

Particulate organic matter fractions were isolated by a particle size fractionation method as described by Gregorich and Beare (2008). Soil samples were shaken for 15 h with a solution of NaPO₃. After, the soil samples were passed through a series of nested sieves of different meshes. The organic matter collected on the 2000-mm sieves was considered litter soil organic matter (lSOM), while that collected on 250-mm sieves was considered cPOM and that on 53-mm sieves was fPOM, respectively. Silt and clay soil organic matter (scSOM) passed through the 53-mm sieve and was calculated by the equation: scSOM = total SOM – lSOM – fPOM – cPOM. Loss on ignition C (LOI) and automated dry combustion methods were used to determine organic matter and C in each size fraction.

Soil water content (θᵥ) and wetting front movement (time domain reflectometry, TDR, response time after a rain event) were measured with probes and data loggers (consist of CR10 and CR10X loggers, storage modules, and CS615-L and CS616-L TDR probes, Campbell Scientific Inc., Logan, UT, 84321). In 2005 and 2006, one soil pit was dug for the installation of TDR probes in each plot (3 vegetation types × 6 replications = 18 plots) (Fig. 1). Three TDR probes were installed horizontally at three different depths (5, 25, and 70 cm) in each soil pit. Data from the probes were logged at 30 min intervals during 2006 and every 10 min during 2007 and 2008 (Datiri and Lowery, 1991; Hart et al., 1994). The TDR output period was converted to soil water content (m³ m⁻³) using the calibration equations provided in Campbell Scientific CS615 and CS616 manuals (Campbell Scientific Inc., 1996; Campbell Scientific Inc., 2004). These calibrations proved to be accurate for this soil as they were crosschecked with calibrations from samples from the study site (data not shown).

Statistical Analyses

Data were analyzed by analysis of variance individually (JMP 7.0 software, SAS Institute, Cary, NC). The statistical model for all the different data sets included main effects for vegetation types, soil depth, and their interactions. The WDPT data were found to not be normally distributed. Therefore, the data were log transformed (logarithmic base 10) before statistical analysis to achieve normality.

RESULTS

The WDPT, MED, and SWA methods showed significant differences for the effects of vegetation types, soil depth, and their interactions. The WDPT data were found to not be normally distributed. Therefore, the data were log transformed (logarithmic base 10) before statistical analysis to achieve normality.
the WDPT analysis, samples from the soil top layer of all three vegetation types had the greatest water drop penetration times (Fig. 2A). However, water repellency was greater for the pine plantation averaging almost the maximum allowable time of 3600 s. The WDPT decreased with each subsequent depth, but this decrease was not uniform among vegetation types. Specifically, soils from the pine plantation were water repellent (>5 s for water drop penetration; Doerr, 1998) from the surface to a depth of 35 cm, while in the prairie water repellency extended only 10 cm below the surface, and in the mixed vegetation water repellency extended to 15 cm. This is in keeping with in situ soil water content data from the three sites where the soil water content was consistently lower in the pine plantation before and after rain events (Fig. 3 and 4). Also, during both rain events $\theta_v$ increased rapidly and declined rapidly following peak intensities until it stabilized into a small or negligible decrease in soil water content. Hart et al. (1994) found that for Sparta sands, 85% of soil water was redistributed during 24 h of drainage after saturation.

As previously mentioned, the SWA method is useful for comparing degrees of soil water repellency among samples with similar particle-size distributions (Flores-Mangual et al., 2011). Near the soil surface, all three vegetation types were equally hydrophobic according to the SWA method (Fig. 2B). There was an increase of soil wetted area with soil depth for all three vegetation types (Fig. 2B). The increase in soil wetted area (less water repellency) with soil depth was observed at shallower depths in mixed and prairie vegetation than in the pine plantation. This confirms the results found with the WDPT test, in that for both vegetation types the soil hydrophobicity is observed nearer to the soil surface. Furthermore, the soil wetted area in the pine was significantly smaller (more hydrophobic) than in mixed vegetation and prairie from a 10- to 50-cm depth (Fig. 2B).

The MED test exhibited a similar pattern as the other two methods. Similar to the SWA test, all vegetation types had water repellency at the soil surface, and the water repellency decreased with increasing soil depth (Fig. 2C). Likewise, the soil in the pine plantation maintained greater water repellency at increasing soil depths than the other vegetation types. For example, at the depth of 45 to 50 cm the soil under pine was slightly hydrophobic (although not significantly different from the other vegetation types), while the prairie and mixed vegetation were hydrophilic from depths of 10 to 15 cm to 45 to 50 cm (Fig. 2C).

The SOC and particle size analyses were performed to get a better understanding of why the water repellency is greater in the pine and mixed vegetation. The SOC was significantly different only for the effect of soil depth (whole model $F_{5, 48} = 2.66, P = 0.0338$; soil depth $F_{1, 45} = 10.70, P = 0.0020$; vegetation type $F_{2, 45} = 0.87, P = 0.4257$; vegetation type by soil depth $F_{2, 45} = 0.42, P = 0.6615$). The amount of SOC was very small for all three depths and vegetation types (Table 1). The percentage of

![Fig. 2C](image-url)
SOC as a function of soil depths was significantly greater at 0 to 5 cm, followed by 5 to 10 cm, and 35 to 40 cm being the smallest (Table 1). The prairie and the mixed vegetation had similar SOC at all three depths; however, SOC at 0 to 5 cm was significantly greater than at 35- to 40-cm depth, and SOC at 5 to 10 cm was not significantly different than for the other depths (Table 1). In contrast, in the pine plantation there were no significant differences within depths for SOC. Although, not significantly different, the amount of SOC in the pine was smaller than the other vegetation types at all soil depths.

There were significant correlations, although weakly predictive, between SOC and WDPT (prairie: \( r^2 = 0.29 \), mixed: \( r^2 = 0.32 \)) for the prairie and mixed vegetation, and between SOC and SWA (prairie: \( r^2 = 0.28 \)) for prairie (Fig. 5A and 5B). No significant correlations existed between SOC and with either WDPT or SWA for pine (Fig. 5A and 5B). Also there were no significant correlations between SOC and SWA for mixed vegetation and pine (Fig. 5B).

The particle size fractions were significantly different among soil depths but not significantly different across vegetation types and depth by vegetation type (Fig. 6). This was expected because Sparta sands are composed of very homogeneous silica sands that extend deep into the soil profile (94–97% sand among all samples) (Hart et al., 1994). The sand fraction was significantly smaller than the other soil depths from 25- to 40-cm deep, although the sand fractions was still the predominant particle at this depth range (sand fraction >94% of the particles). Similarly, at the same soil depths the lime and clay fraction increase significantly, although only slightly.

The particulate organic matter analysis showed significant differences for the cPOM, fPOM, POM, and the ratio of POM/scSOM (Table 2). The mean separation analyses show that for cPOM, fPOM, POM, and POM/scSOM, prairie was significantly greater than for the other vegetation types (Table 3). However, pine and mixed vegetation were not significantly different from each other for cPOM, fPOM, POM, and POM/scSOM. There were no significant differences for the TC, SOM, litter OM, total SOM, scSOM, and LOI.

Humic acid was the only organic compound that showed significant differences among vegetation types (Table 2). The
mean separation analysis of humic acid showed that prairie was significantly greater than mixed vegetation, while pine was not significantly different than prairie or mixed vegetation (Table 3). The fulvic acid, the humin, and the ratio of fulvic acid/humic acid were not significantly different among vegetation types.

**DISCUSSION**

The WDPT for the top layer under the pine plantation was significantly greater than the prairie and mixed vegetation. This result is consistent with the findings of Richardson and Hole (1978) who reported greater soil water repellency in pine than in periodically burned prairies in Wisconsin. However, it should be noted that the prairie in this study has not been burned in recent years. We looked for evidence of fire in the pine plantation but did not find any. We did not find charcoal in any of the soils. Despite the apparent lack of fires, there is evidence in the literature that soil water repellency is a common condition of even unburned forest especially pines (Moral García et al., 2005; Doerr et al., 2009). Doerr et al. (1998) found hydrophilic soil changed to hydrophobic after only 2 yr of planting eucalyptus trees (*Eucalyptus globulus* Labill.).

The water content follow a similar trend in which the soil water content in pine was consistently low at all soil depths before and after rain events compared to the prairie and the mixed vegetation (Fig. 3 and 4).

Our data suggest that the increase in water repellency is related to the quality of the SOC in the pine plantation. This could be a direct product of pine root and shoot growth and decay or the result of an association between the pine or soil fungus. In turfgrasses, it has been observed that an increase in soil water repellency because of fungus growth in what are called fairy rings (Fidanza et al., 2005; Fidanza et al., 2007). Soil water repellency associated with fairy rings can decrease with soil depths within a few centimeters (0–3-cm deep) in some cases from strongly water repellent to nonrepellent (Fidanza et al., 2007). In the case of the pine plantation, although the water repellency decreased with soil depths at 35 cm the soil is moderately hydrophobic for WDPT and slightly hydrophobic at 50 cm for SWA and MED analyses, suggesting that water repellency, at least at deeper depth might be associated to combination of properties in addition to SOC. It is shown here that this increase in soil water repellency resulted in lower water contents in the pine plantation at all soil depths (5, 25, and 70 cm). Kobayashi and Shimizu (2007) found in a Cyprus forest that soil water repellency decreased the change in water

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**Fig. 5.** Correlation by vegetation type of soil organic C and (A) water drop penetration time (WDPT) and (B) soil wetted area (SWA). The WDPT data were log transformed to reduce the range of the distribution. Whole model Linear Fit of C and WDPT in: Mixed Vegetation $F_{1, 17} = 7.82$, $P$ value = 0.01; Pine $F_{1, 17} = 1.61$, $P$ value = 0.22; Prairie $F_{1, 17} = 6.60$, $P$ value = 0.02. Whole model Linear Fit of C and SWA in: Mixed Vegetation $F_{1, 17} = 1.87$, $P$ value = 0.19; Pine $F_{1, 17} = 0.02$, $P$ value = 0.88; Prairie $F_{1, 17} = 6.33$, $P$ value = 0.02.
content during rain events, especially during antecedent dry soil conditions.

Water repellency was more persistent at deeper depths in the pine plantation than the other vegetation types. This is comparable to the results found by Doerr et al. (1996) in Portugal, where eucalyptus and pine plantation soils showed water repellency down the profile all the way to C horizon. The formation of the pine soil hydrophobicity at deeper depths could be linked to the soil podzolization process. Quideau and Bockheim (1996) found in this same pine plantation evidence that water repellency compounds. The mixed vegetation contained 90% pine of 11 yr average age, and it is likely that since pine has not dominated the landscape for a long period of time the organic matter from these are not controlling soil physical behavior (Scharenbroch et al., 2010). It is unclear if the upper profile water repellency in the prairie and the mixed vegetation is the result of past fire events or the occasional extreme drying. In Fig. 3 and 4, the dry natural conditions can be seen at the soil surface, where the prairie and mixed vegetation have an θ_v of 0.06 and 0.09 before the rain events of 2006 and 2007, respectively. While in the pine θ_v before these rain events were 0.04 and 0.08 for rain events 2006 and 2007, respectively. These soil water contents are associated with soil water tensions between 5 and 6 kPa (Hart et al., 1994). There was no physical evidence of fire in either vegetation type (Scharenbroch et al., 2010) or recollection of fire by the owner for at least the past 50 yr (L. Bjorklund, personal communication, 2006).

The lack of significant differences in SOC concentrations among vegetation types suggests that the differences in water repellency could be related to the type of organic C and not the amount. This is especially true for the pine plantation because the amount of organic C was less than the other vegetation types; however, it was the soil with the greatest water repellency. Clarke (1996) found that forested soils, especially pine tended to be hydrophobic regardless of the amount of organic C. Some researchers report a correlation between the amount of organic C and soil hydrophobicity, while others have found no relationship (Buczko et al., 2005; Morley et al., 2005). The amount of organic C could explain more precisely the differences in soil water repellency if it is compared within the same vegetation (Mataix-Solera and Doerr, 2004). However, there were no significant correlations between SOC, WDPT, and SWA for pine plantation, which had the greatest water repellency of all the vegetation types (Fig. 5).

Table 2. Summary of analysis of variance for the effects of vegetation type on several soil organic C fractions at a 0- to 10-cm depth.

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<th>Source†</th>
<th>DF</th>
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<th>FA</th>
<th>FA/HA</th>
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<td>† HA: Humic acid, FA: fulvic acid, SOM: soil organic matter, cPOM and iPOM are coarse and fine particulate organic matter, respectively, scSOM: silt and clay soil organic matter, and LOI: loss by ignition organic carbon.</td>
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</table>
In addition, the separation of humic compounds and the POM analysis did not show a pattern that could explain the differences in water repellency among vegetation type at the soil surface. Only the humic acid was different among vegetation types, while there was no significant difference between the prairie and pine. Only the prairie and the mixed vegetation were significantly different in humic acid, but there were no differences among these vegetation types in terms of soil water repellency. This is in accordance to what Savage et al. (1969) found, that only certain sources of humic acid produce soil water repellency. Savage et al. (1969) tested the water repellency of sands using different humic acid sources: a loam soil humic acid extract, peat humic acid extract, and microbial humic acid from cultures of *Epicoccum nigrum*, *Stachybotrys atra*, and *Streptomyces* sp. The humic acid from *S. atra* culture was the only humic acid that rendered the soil hydrophobic (Savage et al., 1969). They also tested the effect of metallic cations in combination with humic acid at different pH values from 1 to 10 on soil water repellency (Savage et al., 1969). They found a positive correlation between Fe and Al and humic acid, and soil water repellency, especially at lower pH values.

Mataix-Solera et al. (2007) found a negative correlation between pH and soil water repellency under certain trees in calcareous soil. They found that under alpino pine (*P. halepensis* Mill.) soil water repellency was more prevalent than soils under kermes oak (*Q. cocifera* L.), prickly juniper (*Juniperus oxycedrus* L.), and Rosemary (*Rosmarinus officinalis* L.). Quideau and Bockheim (1996) found at the same site of our study that pH was lower in the pine plantation (from pH 5.2 at the surface to 5.7 at 50-cm deep) than in the prairie (from pH 5.6 at surface to 5.9 at 50-cm deep) after 40 yr of afforestation of part of the site with pine trees. This decrease in pH could partially be responsible for the dramatic increase in water repellency and thus lower soil water content before and after rain events (Fig. 3 and 4). Another possible proof of the relationship between pH in the pine plantation and water repellency is that at 36-cm deep the pH in the pine plantation increased from 5.2–5.3 to 5.5, coinciding with an absence of detection of WDPT analysis of water repellency after soil depths lower than 35 cm (Fig. 2; Quideau and Bockheim, 1996). The decrease in water repellency with soil depth in the pine plantation could be a combination of decreasing sand content and hydrophobic forming organic compounds and an increase in soil pH.

The POM analysis showed that the prairie had more coarse and fine POM fractions than the other vegetation. Particulate organic matter has been associated with water repellency, being a source of water repellent substances (Franco et al., 1995). However, this does not match what was observed in the prairie vegetation. Also, prairie had a similar water repellency to mixed vegetation and significantly lower repellency than pine.

### CONCLUSIONS

There was greater soil water repellency in areas converted from prairie to pine than in native prairie or mixed vegetation. Also, prairie had a similar water repellency to mixed vegetation. However, this does not match what was observed in the prairie vegetation. Also, prairie had a similar water repellency to mixed vegetation. Moreover, there were marginal or no correlations between SOC and WDPT or SWA for prairie and mixed vegetation and no correlations for the soil samples from pine plantation.

It seems that in the pine vegetation there are other processes involved in the formation of soil hydrophobicity beside the processes of coating and/or orientation of organic compounds around the soil particles, perhaps the production of different types of organic C. It is possible that the pine plantation is increasing the amount of soil hydrophobicity forming compounds. The sources of these compounds are most likely from the decomposition of above ground plant material, as the water repellency decreased with soil depth. It could also be related to fungus population in the soil of the pine plantation. In addition, the migration of water repellency downward through the soil profile in the pine could be related to podzolization processes. Increases in pH due to pine growth could be responsible for the increase in soil water repellency below pine trees. This increase in soil water repellency has resulted in a decrease in soil water content throughout the pine plantation soil profile.

Future studies should focus on determining the sources (e.g., pine needle litter) of the hydrophobic forming substances, their movements through the soil profile, and potential to increase soil water repellency in pine vegetation.

### ACKNOWLEDGMENTS

Special thanks to Mrs. Louise Bjorklund for letting us use her land for this study. We also thank Phillip Speth, Peter Wakeman, and Ben Bisbach for their help.

### REFERENCES


### Table 3. Mean separation of humic acid, coarse particulate organic matter (POM), Fine POM, POM, and POM/sc SOM (silt and clay soil organic matter).

<table>
<thead>
<tr>
<th>Vegetation</th>
<th>Huminic acid†</th>
<th>Coarse POM</th>
<th>Fine POM</th>
<th>POM</th>
<th>POM/scSOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed vegetation‡</td>
<td>19.66B</td>
<td>2.43B</td>
<td>1.53B</td>
<td>3.93B</td>
<td>0.26B</td>
</tr>
<tr>
<td>Pine</td>
<td>20.17AB</td>
<td>2.55B</td>
<td>1.68B</td>
<td>4.23B</td>
<td>0.26B</td>
</tr>
<tr>
<td>Prairie</td>
<td>20.81A</td>
<td>3.93A</td>
<td>4.60A</td>
<td>8.50A</td>
<td>0.67A</td>
</tr>
</tbody>
</table>

† Means followed by different letters within the column are significantly different at the P level of 0.05.
‡ Soil depth of 0 to 10 cm.


Scott, D.F. 2000. Soil wettability in forested catchments in South Africa; as measured by different methods and as affected by vegetation cover and soil characteristics. J. Hydrol. 231–232:87–104. doi:10.1016/S0022-1694(00)00186-4


