Lebron, Inma; **Robinson, David A.**; Oatham, Mike; Wuddivira, Mark N.. 2012 Soil water repellency and pH soil change under tropical pine plantations compared with native tropical forest. *Journal of Hydrology*, 414-415. 194-200. 10.1016/j.jhydrol.2011.10.031

Soil Water Repellency and pH soil change under Tropical Pine Plantations Compared with Native Tropical Forest

Inma Lebron[1*] David A. Robinson[1] Mike Oatham[2] Mark N. Wuddivira[3]

1: Centre for Ecology and Hydrology, Environment Centre Wales, Deiniol Rd, Bangor, North Wales, UK.

2: Dept of Life Sciences, University of the West Indies, St Augustine, Trinidad and Tobago.

3: Dept of Food Production, University of the West Indies, St Augustine, Trinidad and Tobago.

* corresponding author

inmbin@ceh.ac.uk

Tel: 44 (0) 1248374531

Fax: 44 (0) 1248362133

Abstract

In temperate climates, soil water repellency (SWR) has been documented to develop with land-use change from native forest to pine plantations. In the tropics a sparse evidence base has been documented for the observation of SWR, but no investigation has been conducted to determine the consequences of changing land-use from native forest to pine plantations with regard to SWR. In our research we broaden the evidence base for tropical SWR by comparing the SWR behavior of seven tropical pine plantations in Trinidad with co-located native forest. We found that SWR occurred under both pine and native forest, but was more persistent and less heterogeneous under pine. The SWR was water content dependent with a threshold ~0.2 m^3m^{-3}, it showed a linear dependence with litter depth, and it was also found to be higher in more acidic soils. The forest floor pH, contrary to convention for temperate climates, was observed to increase under some pine plantations, as compared with native tropical forest. This only occurred in the very acidic tropical soils (pH<4), but may have important biogeochemical consequences with regard to soil and water quality.

Introduction

Soil water repellency (SWR) has been observed and studied for many years (Wander, 1949; Krammes and DeBano, 1965; Watson and Letey, 1970). However it has attracted more attention in the last 20 years because of increased awareness of the impact of SWR on hydrological and ecological systems (Ritsema and Dekker, 2003; Dekker et al., 2005), leading to a broad evidence base for temperate ecosystems (Doerr et al., 2000). Conversely the evidence base for tropical ecosystems is sparse with observations reported from, S. Africa (Scott and Van Wyk, 1990), Australia (Roberts and Carbon, 1971), Japan (Nakaya, 1982), Mali (Rietveld, 1978), and India (Das and Das, 1972). However, no evidence of causal links to tropical soil properties is provided. SWR has been well documented in forest ecosystems in temperate regions (Doerr et al., 1998; Doerr et al., 2000; Doerr and Thomas, 2000; Doerr et al., 2009); however, few studies have been conducted for tropical forest ecosystems. Jaramillo et al. (2000) presented one study for a humid tropical watershed in Colombia, with the focus of measurements being on pine (*pinus patula*) stands. They also observed some SWR under native tropical vegetation. Again, no data was presented to indicate soil factors that might be linked to the SWR.

In temperate environments studies of SWR indicate that a number of important soil properties correlate, or contribute to the development of SWR, including organic carbon (litter depth), water content (θ), pH and temperature. θ has been shown to have a strong impact on SWR (Doerr and Thomas, 2000). Both Doerr and Thomas (2000) and Buczko et al., (2007), studied SWR under pine vegetation and found the development of a θ threshold of ~0.2 m^3m^{-3}, perhaps consistent with field capacity. In addition, Lebron et al. (2007) demonstrated an almost linear dependence of SWR on litter depth under juniper in Utah. SWR has also been observed to decrease as a function of temperature (Graber et al., 2009). Given that temperatures generally experience smaller fluctuations and range in the tropics, temperature is considered less of an issue for tropical SWR. The actual mechanisms leading to the development of SWR are poorly understood but considered to be due to the accumulation of hydrophobic organic acids released as root exudates (Dekker and Ritsema, 1996; Doerr et al., 1998), fungal and/or microbial by-products (Savage et al., 1969; Jex et al., 1985), or from the decomposition of organic matter (McGhie and Posner, 1981). More recently several studies have identified polar organic compounds as responsible for SWR in sandy soils (Mainwaring et al. 2004; Morley et al., 2005) and in loam and sandy loam textured soils (de Blas et al., 2010). Graber et al (2009) endeavored to provide a more mechanistic understanding of SWR and identified fatty acids as the main components responsible for SWR. Moreover, given that the structure of fatty acids, and polar organic compounds in general, is pH dependent provides a possible causal link between soil pH and the development of SWR.

The role of soil pH in the development of SWR has not been widely studied. The effect of pH on SWR is likely to be complex, but is critical for our improved understanding of feedback processes in tropical ecosystems which can experience a broad range of soil pH. In temperate systems researchers have found that SWR is more persistent in acid soils than alkaline (Mataix-Solera and Doerr, 2004; Mataix-Solera et al., 2007), and that repellency increases as pH reduces. Mataix-Solera et al. (2007) studying a number of vegetation types on alkaline soils found that SWR was pH dependent under some vegetation, including pine, but not under others. They found that SWR tended to increase with a reduction in pH, and SWR levels were lower in soils with pH values higher than 7, as compared with the SWR observed on acidic soils. In a more comprehensive study, Dielhl et al. (2010) found that the relationship between pH changes and SWR was dependent on the availability and relative abundance of proton active sites at the mineral surface and at the organic matter functional groups for 14 soil samples from Europe and Australia. Given that globally, pine plantations have been linked to reducing soil pH (Jackson et al., 2005), an unintended consequence of changing native forest to pine in the Tropics could be to enhance SWR and alter hydrological and biogeochemical processes.

SWR, measured using the water drop penetration time (WDPT) test (Letey et al., 2000), provides a useful and important hydrological process indicator, signifying whether piston flow, or bypass / finger flow will be the dominant infiltration process over a landscape. SWR can reduce infiltration, especially when associated with fire, which often leads to surface runoff and erosion of hillslopes (Doerr et al., 2000); therefore, tropical environments with steep hillslopes are expected to be particularly vulnerable to SWR. Measurements of SWR can also provide a qualitative indicator of the likely behavior of a watershed during storm flow. Given that SWR enhances runoff from dry soils more than from wet soils (Zehe et al., 2007), the effects are expected to be most noticeable during the transition from dry season to wet season in the tropics. Therefore, developing an evidence base for SWR in tropical environments prior to further large scale modification of land-use would be advantageous.

Change of land-use in the tropics, especially to tree plantations, is of increasing interest to corporations and multinational companies, as not only is carbon sequestered, in compliance with the carbon credit trading system in Europe (Boemare and Quirion, 2002; Schultz and Williamson, 2005), but it also develops a future natural resource (Cacho *et al.*, 2003). The locations in demand for new plantations are often in the tropics, where fast growing rates can be easily achieved (Laurance, 2007). The planting of fast growing pine is becoming common practice in many tropical countries, Lamb (1973) described the use of Caribbean pine as an exotic plantation species in about 50 countries or regions of the world. Plantations of >40,000 ha have been reported in China (Wang et al., 1999), 90,000 ha in Belize (Anon 2002) and 200,000+ ha in Brazil (Lilienfeina et al., 2000) for example. Jackson et al., (2005) pointed out that reforestation policy has greater implications for the functioning of the earth system, due to impacts on both hydrology and biogeochemistry. In their research for the mainland USA they indicated that one consequence of developing plantations is a reduction in base flow in rivers, as well as increased possibility of soil salinization and acidification. Whilst this may be a problem in temperate / Mediterranean climates, reduced base flow may be considered a benefit in many flood prone tropical countries.

This increasing interest in reforestation and aforestation in the tropics with non-native plantation species creates three main concerns: first, the development of SWR, which in temperate systems has been linked to the modification of hydrological processes (Doerr et al., 2000); second, the possible increase in forest fires, which exacerbate SWR further (Certini, 2005); and third the likely change of soil pH which may impact biogeochemical cycling and plant fitness. It is known that reducing the acidity of the soil has a range of beneficial factors for plants such as improved physiological response, especially roots, and improved nutrition (Berthong et al. 2009); conversely, acidification will inhibit plant development and often leads to toxic levels of aluminium in soils (Rowell, 1988).

The aim of our study was to strengthen the evidence base for SWR in tropical forest ecosystems, with the objectives of I) determining the influence of soil water content on SWR, II) investigating the relationship between litter depth and SWR under tropical pine plantations and native forest, and III) comparing the impact of land-use change on soil pH levels under native forest and introduced pine.

Methods

Study Sites

The island of Trinidad in the Republic of Trinidad and Tobago has an area of 4,768 km^2 and is located between, 10^{o}3′N 60^{o}55′W and 10^{o}50′N 61^{o}55′W, ~11km from the NE coast of Venezuela near the out flow of the Orinoco River. Its proximity to Venezuela, and the presence of a land bridge thousands of years ago, give Trinidad a tremendous biodiversity. This makes the island a unique observatory for monitoring land management impacts on tropical ecosystems. The island has a wet and dry season and a noticeable rainfall gradient from ~2.5 m/yr in the east to ~1.5 m/yr in the west (Beard, 1946). The landscape is dominated by acidic alluvial soils, often high in solution Al^{3+} (Dalal, 1975).

Caribbean pine (*pinus caribaea var*, *hondurensis*) was first planted in Trinidad on an experimental scale in 1948 (Lackhan, 1976) in the Arena forest. The first large scale planting of ~40 ha was made in 1956 and by 1976 ~3640 acres had been planted. By 2001 Pine accounted for about 4200 ha of plantation land, from a total of ~15,400 ha (Anon, 2003). The rate of establishment of pine is relatively slow at 71ha per yr, but this is still 10 times greater than that for teak. The plantations were normally undertaken on nutrient poor soils, largely either on sands, or sand and clay mixtures. The plantations chosen for this study and some of the soil characteristics are shown in Table 1, Mt. St. Benedict and Lopinot plantations were established on the southern slopes of the Northern Range to restore lands degraded by frequent dry season fires. The original ecosystems in these areas were dry deciduous forests (Beard 1946) with a high proportion of deciduous trees in the canopy. The Cumuto and Arena Forest sites where established on the eastern part of the Caroni Plain where extensive rainfall supported evergreen seasonal rainforests (Beard 1946) with a dry season of three months (< 50 mm rainfall per month). The majority of trees in these ecosystems were evergreen with a few facultative deciduous trees. The Aripo Savannas and the Erin Savannas are edaphic savannas and the pine plantations largely replaced forests surrounding the savannas. These forests were seasonally inundated Marsh forest in the case of the Aripo savanna plantations and seasonal evergreen forests in the case of the Erin Savannas (Beard 1946). The Melajo plantations were established where seasonal evergreen forests once grew (Beard 1946).

Our interest was to capture changes in soil pH and SWR over a short distance. We selected areas where natural forest and pine plantations were next to each other. We adopted a systematic survey, by delineating a ~120 m transect perpendicular to the boundary. Half of the transect (50 m) was located on the pine plantation and the other half on the native forest (NF), sampling was established every 10 m with a total of 5 locations in the pine plantation and 5 in the NF. We kept a 10 m distance from the boundary before the first sampling location on each side of the transect to minimize mixed effects. 10 m is considered to be an appropriate distance, beyond which, the tree would not exert a major influence on the soil properties (Kuuluvaainen and Linkosalo, 1998).

Soil Measurements

SWR measurements were carried out during the dry season in the months of February to April in 2009 using the water drop penetration time test (WDPT) with ~5mm diameter drops, Krammes and Debano (1965). After carefully clearing the litter from the soil surface, and measuring the litter depth, twelve individual drops of water of approximately 0.05 mL were applied to the soil using a dropper in each location, the average of the penetration times noted. 12 repetitions were made at each location and the average penetration time used to represent the penetration time for the location. The WDPT test groups soils into classes according to the time taken for the water to penetrate into the soil (Dekker et al., 2001). A soil is considered to be wettable, if the penetration time is under five seconds, and increasingly water repellent above this, with anything above 1 hr considered severely water repellent. We limited our measurements to a maximum of 3 hr. At the same time we measured the soil water content using a Delta-T theta probe, type ML2x (Delta-T Devices, Cambridge, England). Sensor voltage output was converted to apparent permittivity, and consecutively to volumetric soil water content (θ_v) using the relationship given in Blonquist et al. (2005). This procedure is suitable for sandy and loamy soils.

Measurements in forest soils indicate that pH is generally consistent with depth; however differences arise between litter and mineral layers (Frankland et al., 1963; Sollins, 1998). SWR occurs in the mineral soil but in the tropics the boundary between the litter and mineral layer is not always distinct, to ensure consistency among our pH measurements we collected samples from 7.5 – 10 cm deep in accordance with previous work in the literature (Frankland et al., 1963; Bayer and Schaumann, 2007). Soil pH was measured in the field using a portable pH meter (IQ 150, Spectrum technologies Inc., Illinois, USA). We used the standard 1:1 measurement method in de-ionized water (USDA-NRCS, 2004). The soil sample

(≈ 3g of soil) was shaken with 3 mL of deionized water (DIW) and the pH measured after 30 minutes. Separate samples collected from the top 10 cm were taken back to the laboratory and tested for solution electrical conductivity using a 1:2 water solution extract (USDA-NRCS, 2004).

Statistical analysis

The pH values for each location along the transect were grouped together for each plantation site, the average and standard deviation were determined. The significance of the difference between the forest and pine plantation means was determined using a two-sample *t*-test, assuming unequal variance (Moore and McCabe, 2003). The significance at the 95% level was determined from P values which are reported (Table 2).

Results

Results for the SWR at the seven sites are presented as boxplots in Figure 1. The results represent the bulking of the 60 measurements for each site at each location and show a large degree of variability. The results for the Erin Savanna showed the highest degree of water repellency. The mean values of repellency are consistently higher in the pine forest, other than at the Erin Savanna site where the native forest was more repellent.

Results for the SWR dependency on soil water content for the 7 pine plantations and corresponding native forest (NF) are presented in Figure 2. The results show SWR under both pine and NF at low soil water contents and a threshold type behavior with SWR disappearing above 0.2 m^3m^{-3}. This behavior has been previously observed, and the water content threshold is consistent with previous findings for pine in temperate ecosystems (Doerr and Thomas, 2000; Buczko et al., 2007).

Concurrently, data was collected for litter depth at each of the sites. Extreme values were removed then regression lines were fitted through the data, which indicated significant linear trends between WDPT and litter depth (NF r^2=0.25 p (>F)=0.002 slope =586; pine r^2=0.25 p (>F)=0.004 slope=265). The NF showed higher SWR than the pine for the same litter depth though the litter depth under the NF was generally thinner than under pine. The results are compared with results from measurements in temperate evergreen ecosystems (Lebron et al., 2007) in Figure 3. Presented on a log plot, the data show a strong dependence on litter depth. Comparison between the results for the tropical and temperate evergreen species, which represent data from humid and arid climates, show similar trends. The juniper and pinyon pine from the arid climate showed significant linear trends for WDPT as a function of litter depth (juniper r^2=0.68 p (>F)=4.8E-15 slope=236; pinyon pine r^2=0.22 p (>F)=1.2E-05 slope=86). However, one difference we observed was that the SWR at our tropical sites was more confined to the soil surface and did not generally go deeper than ~1 cm below the mineral soil surface, whereas in the temperate data SWR was observed to occur to depths of 20 cm+ down the profile. This has also been observed by others comparing dry and humid climates (Jaramillo et al., 2000). Electrical conductivity (EC) of the soils in NF was higher than in the pine plantations (Table 2), this observation agrees with meta-data analyses (Jackson et al, 2005), no relationship was found between EC and SWR.

Figure 4 presents' SWR (WDPT) data, as a function of soil pH. In addition to the data from the tropical systems, we collected metadata from the literature, where possible, that was consistent with pine vegetation for acidic soils (Doerr et al., 2000); data for alkaline calcareous soils comes from Graber et al. (2009) and Miralles et al. (2007). The synthesis of this data shows the paucity of data in the literature with regard to SWR and soil pH and that data sets are required that span the pH spectrum to draw firm conclusions about any potential relationship between pH and SWR. However, our results indicate the intriguing possibility of a bimodal distribution of SWR as a function of pH which is likely to be species dependent. SWR for the tropical data showed a maximum repellency around pH 4. SWR was negligible at soil pH values between pH 5.5 and 7, but very few data were observed to be in this pH range. This finding is consistent with the findings of others who also show higher levels of water repellency under more acidic conditions and lower repellency near neutrality (Mataix-Solera et al., 2007). Comparison with the literature data for alkaline soils indicates that the persistence of SWR in these tropical soils is greater than has generally been observed in the more alkaline soils (Figure 4).

Comparison of soil pH change was made between the pine plantation and the adjacent NF (change= pH pine - pH NF).The difference is presented in Figure 5 with negative numbers indicating a reduction in soil pH for the pine forest floor as compared with the soil pH in the NF, and positive numbers indicating an increase in pH under pine compared with NF. It also includes meta-data collected from the literature for pine on tropical soils. The meta-data indicates larger decreases in pH between NF and pine when the initial pH, assumed to be that of the NF, was higher than 4; the higher the initial pH the higher the decrease. For the plantations in this study we found a similar trend and when the pH in the NF was ≥ 4 the pH in the pine plantation decreased; however when the native vegetation had a soil pH ≤ 4 the soils in pine plantations showed an increase. Anecdotal reports from Los Gavitos in Colombia

(Feller, 2007) also suggest that soil pH increased when pine was planted on native tropical acid grasslands. Table 2 shows the results of significance tests for our sites and indicates that the pH increase is significant on at least two of the sites, Arena and Lopinot.

Discussion

Soil water repellency response in tropical forests

SWR is the reduction of the affinity of a soil to water in a way that rewetting is interrupted (Doerr et al. 2000). Disruption in the rewetting of soils is important hydrologically because it leads to changes in water redistribution at the landscape level, by altering infiltration and runoff (Wallis and Horne, 1992 and references within), and by promoting patchiness in the soil: water distribution (Robinson et al, 2010). The results presented here provide some baseline evidence for the consequences of land-use change, from NF to pine plantations in a tropical environment. Our observations indicated that SWR exists under both NF and under pine plantations, but the mean values are almost always higher under the pine (Fig 1). Therefore, regardless of forest vegetation type, NF or pine plantation, soils are subject to SWR in these environments.

SWR has been related with the quantity and quality of the soil organic matter (C:N ratio), the degradation process, and the microbial activity associated with it. The litter depth in the forests in this study showed variability (Figure 3) but has significant correlation with WDPT for both pine plantation and native forest, and they both followed a similar trend when compared with measurements from other climatic zones (Fig. 3). The WDPT increased linearly when litter depth as there was more organic matter on the forest floor. An interesting finding was that the SWR dependency with litter depth was strongest under the native tropical forest, and weakest under the pinyon pine from an arid environment according to the slopes of the relationships; the juniper, also from an arid environment, showed the most consistent behavior with the highest r^2 where as the NF, tropical pine and pinyon pine were all very similar explaining ~25% of the variance. This perhaps indicates species, soil type and climate dependence and may be linked to both the type of litter and the microbial and fungal communities that develop in association with these communities.

In our tropical soils pH is acidic and likely to limit bacterial growth with fungus being dominant, Hallett and Ritz. (2001) demonstrated that suppression of bacteria caused a significant increase in the SWR while when fungal activity was suppressed soils did not reach severe levels of SWR. Fungal:bacteria activity, in turn, has been also associated with the soil C:N ratio, with fungal:bacteria activity increasing when soil C:N ratio increases (Kuijper et al., 2005). In a separate study and using meta-analysis at the global scale Berthrong et al. (2009) showed that soils under pine plantations had the highest C:N ratios when compared with four other biomes. A synthesis of the information contained in these studies indicates that pine plantations increase fungal abundance in soils, and with time may lead to higher levels of SWR than found naturally under native forest; this increase in SWR is supported by our findings for these tropical sites.

SWR is a complex phenomenon, with multiple contributing factors at the molecular scale, so that in order to develop a more mechanistic understanding of the pH dependence of SWR we must relate it to surface and solution chemistry. A survey of the wider literature indicates broad interest in water repellency in a number of fields of research, including medical (Cistola et al., 1988), geochemical (Rezaei Gomari and Hamouda, 2006) and soils (Graber et al., 2009). This research identifies a range of organic compounds like aliphatic hydrocarbons, amphiphilic and long-chained fatty acids (Wander, 1949; Horne and McIntosh, 2000; Graber et al., 2009) as potential contributors to water repellent behavior. However, Graber et al. (2009), for soil environments, attributes the hydrophobic properties to fatty acids; which in the case of pine are known to occur in both litter (Li, 1978; Wolff et al., 1997; Fries et al., 1985) and root exudates (Fries et al., 1985).

The conceptual model for SWR proposed by Graber et al. (2009) suggests that repellency develops as fatty acids become ionized and the hydrophilic acid head groups attach to the surface, either through physi-sorption or chemi-sorption, leaving the hydrophobic tails pointing out from the surface. Graber also found that SWR increased with increasing cation concentration. They noted from the literature that the pKa can drop in the presence of Al^{3+} (pKa ~3.8 (Aveyard et al., 1990)) causing an increase in the SWR. Given the strong impact of Al^{3+} on the pKa, tropical soils, with Al^{3+} saturated exchange complexes (Dalal, 1975) are likely to exhibit strong SWR at low pH values, which is consistent with our findings (Fig 4). It is clear from the literature that pH contributes to water repellency in thin films (Langmuir, 1938; Peng et al., 2001), but how this translates to soils is not well understood. Further study should be focused on improving our understanding of the role of pH on SWR development and persistence.

Soil pH change from native to pine plantation

Soil pH has been proposed as the most useful single indicator for soil function and processes (Borggaard, 2000), in recent years several meta-analyses have been published synthesizing the effects of forestation and aforestation on fundamental soil properties at the continental and global scales (Jackson et al. 2005; Fierer and Jackson, 2006; Berthrong et al., 2009). However, there is still little evidence to suggest any consistent effect of tree plantation on soil pH in the tropics (Evans, 2002). Most of these studies report a decrease in soil pH when using pinus or other conifers for plantation schemes, this pH decrease has been linked to an uptake of cations by the trees, leaving behind Na^+ and H^+ in the soil solution (Jobbagy and Jackson 2003 and 2004; Berthrong et al., 2009), production of organic acids, and to an enrichment of CO_2 in the soil solution from higher rates of autotrophic respiration (Richter and Markewitz, 1995). Liao et al. (2010) showed also with meta-analysis data that plantations had lower aboveground litter mass than native forest indicating that plantations might have less amount of litter K, Ca, Mg, and nutrients returning to soils than native forests, causing an accumulation of H^+ concentration and the consequent increase in soil acidity below plantations (Jobbagy and Jackson, 2003). The majority of studies reviewed by Jackson et al. (2005) support the generally accepted understanding that soils from the same climatic region tend to be more acidic below forest than non-forested lands. However, Feller (2007) reported that for many years anecdotal reports have come from Los Gavitos in Colombia that suggest that soil pH increased when pine was planted on native tropical acid grasslands. Our data, combined with metadata (Fig. 5) indicate that the initial pH of the native forest may be important in determining the future pH change for landuse change to a pine plantation. Given an initial soil pH that is very acidic (pH$\leq$ 4) it seems likely, from our data, that a pine plantation may increase the soil pH, however, the lack of data in the literature for the tropics prevents us from making this a broader, more definite conclusion for tropical soil in general. However, it does disprove the generic hypothesis that a switch from native vegetation to a pine plantation will always result in a soil pH decrease. In the tropics soil acidity values of 3.5-4.0 are not uncommon due to mineral weathering and the prevalence of aluminium in the soil solution (Rowell, 1988), so this improvement of soil pH with pine plantations potentially could be a broadly applicable result. However, when the initial soil pH > 4.5 a change to pine generally resulted in the soil pH decreasing, consistent with the findings of Jackson et al. (2005) in their meta analysis; if the soils have highly buffered parent materials like limestone, pH values will most likely be maintained (Jackson et al, 2005). An additional problem with changes in soil pH is that the dependence of SWR on pH is poorly understood and not well documented in the literature. Most available results from the literature indicate that SWR increases with acidification (Mataix-Solera et al., 2007, Doerr et al., 2009; Martínez-Zavala and Jordán-López, 2009), with which our results are consistent. Furthermore, SWR magnitude in acid, compared with alkaline soils, indicates much greater SWR development in acidic soils (e.g. Dekker and Jungerius 1990; Doerr et al., 1998; Benito et al., 2003; Mataix-Solera and Doerr, 2004). Undoubtely, SWR is an emerging soil property as a result of complex phenomena and more studies are needed to elucidate the effect of plantation schemes on the biogeochemistry of the soils of the tropics, in particular with reference to controls such as pH.

Conclusions

We find strong soil water repellency under both tropical pine and native forest in the tropical soils of Trinidad. SWR dependence on soil water content is similar to other observations with a threshold of ~0.2 m^3m^{-3}. The dependence of SWR on litter depth is also found to be consistent with similar observations in semi-arid evergreen woodland. In the acid environment of the soil tropical forest in this study we found maximum SWR in the interval 4<pH> 4.5 and we did not find any SWR above pH 5.2. In addition, we found that changes in pH between native forest and pine plantations is larger when the initial pH was closer to neutral and reduced as the soil became more acidic. At very low pH <4, we also observed statistically significant increases in soil pH under pine compared with native vegetation. This supports anecdotal findings from foresters in Colombia who have claimed that pine plantations can ameliorate acidic tropical soils.

REFERENCES

Anon, 2002. Mountain pine ridge carbon sequestration project, Belize. Progress Report, Silviculture Belize.

Anon, 2003. Achieving the ITTO objective 2000 and sustainable forest management in Trinidad and Tobago. Thirty fourth session, International Tropical Timber Council, Panama City, Panama, 12-17 May.

Aveyard, R., Binks, B.P., Carr, N., Cross, A.W., 1990. Stability of insoluble monolayers and ionization of Langmuir–Blodgett multilayers of octadecanoic acid. Thin Solid Films 188, 361–373.

Bayer, J.V., Schaumann, G.E., 2007. Development of soil water repellency in the course of isothermal drying and upon pH changes in two urban soils. Hydrological Processes 21, 2266-2275.

Beard, J.S., 1946. The mora forests of Trinidad, British West Indies. Journal of Ecology 33, 173-192

Benito, E., Santiago, J.L., de Blas, E., Varela, M.E., 2003. Deforestation of water-repellent soils in Galicia (NW Spain): effects on surface runoff and erosion under simulated rainfall. Earth Surface Processes and Landforms 28, 145–155. DOI:10.1002/esp.431.

Berthrong, S.T., Jobbagy, E.G., Jackson, R.B., 2009. A global meta-analysis of soil exchangeable cations, pH, carbon and nitrogen with afforestation. Ecological Applications 19, 2228-2241.

Blonquist, J. M. Jr., Jones, S.B., Robinson, D.A., 2005. Standardizing characterization of electromagnetic water content sensors: 2. Evaluation of seven sensing systems. Vadose Zone Journal 4, 1059–1069.

Boemare, C., Quirion, P., 2002. Implementing greenhouse gas trading in Europe: lessons from economic literature and international experiences. Ecological Economics 43, 213-230.

Borggaard, O.K., 2000. Soil chemistry in a pedological context. DSR Forlag, Copenhagen.

Buczko, U., Bens, O., Huttl R.F., 2007. Changes in soil water repellency in a pine–beech forest transformation chronosequence: Influence of antecedent rainfall and air temperatures Ecological Engineering 31, 154–164.

Cacho, O., Hean, R.L., Wise, R.M., 2003. Carbon-accounting methods and reforestation incentives. Australian Journal of Agricultural and Resource Economics 47, 153-179.

Certini, G., 2005. Effects of fire on properties of forest soils: a review. Oecologia 143, 1-10.

Cistola, D.P., Hamilton, J.A., Jackson, D., Small, D.M., 1988. Ionization and phase behavior of fatty acids in water: application of the Gibbs phase rule. Biochemistry 27, 1881-1888.

Dalal, R.C., 1975. Hydrolysis products of solution and exchangeable aluminum in acidic soils. Soil Science 119, 127-131.

Das, D.K., Das, B., 1972. Characterization of water repellency in Indian soils. Indian J. Agric. Sci. 42, 1099–1102.

de Blas, E., Rodriguez-Alleres, M., Almendros, G., 2010. Speciation of lipid and humic fractions in soils under pine and eucalyptus forest in northwest Spain and its effect on water repellency. Geoderma 155, 242-248.

Dekker, L.W., Jungerius, P.D., 1990. Water repellency in the dunes with special reference to the Netherlands. Catena Supplement 18, 173–183.

Dekker, L.W., Ritsema, C.J., 1996. Variation in water content and wetting patterns in Dutch water repellent peaty clay and clayey peat soils. Catena 28, 89–105. DOI:10.1016/S0341-8162(96)00047-1.

Dekker, L.W., Doerr, S.H., Oostindie, K., Ziogas, A.K., Ritsema, C.J., 2001. Water repellency and critical soil water content in a dune sand. Soil Sci. Soc. Am. J. 65, 1667–1674.

Dekker, L.W., Oostindie, K., and Ritsema C.J. 2005. Exponential increase of publications related to soil water repellency. Australian Journal of Soil Research. 43, 403–441.

Diehl, D., Bayer, J.V., Woche, S.K., Bryant, R., Doerr, S.H., Schaumann, G.E., 2010. Reaction of soil water repellency to artificially induced changes in soil pH. Geoderma. 158, 375-384.

Doerr, S.H., Thomas, A.D., 2000. The role of soil moisture in controlling water repellency: new evidence from forest soils in Portugal. Journal of Hydrology 231-232, 134-147.

Doerr, S.H., Shakesby, R.A., Walsh, R.P.D., 1998. Spatial variability of soil hydrophobicity in fire prone eucalyptus and pine forests, Portugal. Soil Science 163, 313-324.

Doerr, S.H., Shakesby, R.A., Walsh, R.P.D., 2000. Soil water repellency: its causes, characteristics and hydro-geomorphological significance. Earth-Science Reviews 51, 33-65.

Doerr, S.H., Woods, S.W., Martin, D.A., Casimiro, M., 2009. 'Natural background' soil water repellency in conifer forests of the north-western USA: Its prediction and relationship to wildfire occurrence. Journal of Hydrology 371, 12-21.

Evans, J.,2002. Plantation forestry in the tropics. Oxford University Press, Oxford, N.Y. USA.

Feller, G., 2007. What would Bateson's work look like today? Inside one of the world's most violent nations, now a model for peacemaking and sustainability. Kybernetes 36, 1134-1140.

Fierer, N., Jackson, R.B., 2006. the diversity and biogeography of soil bacterial communities. PNAS, 103, 626-631.

Fimbel, R.A., Fimbel, C.C., 1996. The role of exotic conifer plantations in rehabilitating degraded tropical forest lands: a case study from the Kibale Forest in Uganda. Forest Ecology and Management 81, 215-226.

Frankland, J.C., Ovington, J.D., Macrae, C., 1963. Spatial and seasonal variations in soil, litter and ground vegetation in some Lake District woodlands. Journal of Ecology 51, 97-112.

Fries, N., Bardet, M., Serck-Hanssen, K., 1985. Growth of ectomycorrhizal fungi stimulated by lipids from a pine root exudates. Plant and Soil 86, 287-290.

Graber, E.R., Tagger, S., Wallach, R., 2009. Role of divalent fatty acid salts in soil water repellency. Soil Sci. Soc. Am. J. 73, 541-549.

Hallett, P.D., Ritz, K., 2001. Microbial derived water repellency in golf course soil. International Turfgrass Society Research Journal 9, 518-524.

Horne, D.J., McIntosh, J.C., 2000. Hydrophobic compounds in sands in New Zealand: Extraction, characterization and proposed mechanisms for repellency expression. J. Hydrol. 231–232, 35–46.

Jackson, R.B., Jobbágy, E.G., Avissar, R., Roy, S.B., Barrett, D.J., Cook, C.W., Farley, K.A., le Maitre, D.C., McCarl, B.A., Murray, B.C., 2005. Trading Water for Carbon with Biological Carbon Sequestration. Science 310, 1944 – 1947.

Jaramillo, D.F., Dekker, L.W., Ritsema, C.J., Hendrickx, J.M.H., 2000. Occurrence of soil water repellency in arid and humid climates. Journal of Hydrology 231-232, 105-111.

Jex, G.W., Bleakley, B.H., Hubbell, D.H., Munro, L.L. 1985. High humidity-induced increase in water repellency in some sandy soils. Soil Science Society of America Journal 49, 1177–1182.

Jobbagy, E.G., Jackson, R.B., 2003. Patterns and mechanisms of soil acidification in the conversion of grasslands to forests. Biogeochemistry, 64, 205-229.

Jobbagy, E.G., Jackson, R.B., 2004. The uplift of soil nutrients by plants: biogeochemical consequences across scales. Ecology, 85, 2380-2389.

Kadeba, O.,Aduayi, E.A., 1985. Impact on soils of plantations of Pinus Caribaea stands in natural tropical savannas. Forest Ecology and Management, 13, 27-39.

Krammes, J.S., DeBano, L.F., 1965. Soil wettability: a neglected factor in watershed management. Water Resources Research 1, 283-286.

Kuijper, L.D.J., Berg, M.P., Morrien, E., Kooi, B.W., Verhoef, H.A., 2005. Global change effects on a mechanistic decomposer food web model. Glob. Chang. Biol., **11**, 249-265.

Kuuluvainen, T., Linkosalo, T., 1998. Estimation of a spatial tree-influence model using iterative optimization. Ecological Modelling 106, 63-75.

Lackhan, N.P., 1976. Pinus caribaea (var. hondurensis) in Trinidad and Tobago. Port of Spain, Trinidad and Tobago: Ministry of Agriculture, Lands, and Fisheries; Forestry Division. 35 pp.

Lamb, A.F.A., 1973. Pinus caribaea, vol. 1, Tropical Forestry Papers, No. 6, Oxford Forestry Institute, 254 pp.

Langmuir, I., 1938. Overturning and anchoring of monolayers. Science 87, 493–500.

Laurance, W. F., 2007. A new initiative to use carbon trading for tropical forest conservation. Biotropica 39:20-24.

Lebron, I., Madsen, M.D., Chandler, D.G., Robinson, D.A., Wendroth, O., Belnap, J., 2007. Ecohydrological controls on soil moisture and hydraulic conductivity within a pinyon-juniper woodland. Water Resour. Res. 43, W08422, DOI 10.1029/2006WR005398.

Letey, J., Carrillo, M.L.K., Pang, X.P., 2000. Approaches to characterize the degree of water repellency, J. Hydrol. 231–232, 61– 65.

Li, C.Y., 1978. Soil fatty acids under alder, conifer, and mixed alder-conifer stands of coastal Oregon. Soil Sci. 125, 92-94.

Liao, C.Z., Luo, Y.Q., Fang, C.M., Li, B., 2010. Forest plantations reduced ecosystem carbon stock globally. PloS ONE 5(5):e10867.doi:10.1371/journal.pone.0010867.

Lilienfeina, J., Wilckea, W., Angelo Ayarzab, M., Vilelac, L., do Carmo Limad, S., Zech, W., 2000. Soil acidication in Pinus caribaea forests on Brazilian savanna Oxisols. Forest Ecology and Management 128, 145-157.

Mainwaring, K.A., Morley, C.P., Doerr, S.H., Douglas, P., Llewellyn, C.T., Llewellyn, G., Matthews, I., Sten, B.K., 2004. Role of heavy polar organic compounds for water repellency of sandy soils. Environmental Chemistry Letters 2, 35-39.

Martínez-Zavala, L., Jordán-López, A., 2009. Influence of different plant species on water repellency in Mediterranean heathland soils. Catena 76, 215-223.

Mataix-Solera, J., Doerr, S.H., 2004. Hydrophobicity and aggregate stability in calcareous topsoils from fire-affected pine forest in the south-east of Spain. Geoderma 118, 77–88, DOI:10.1016/S0016-7061(03)00185-X.

Mataix-Solera, J., Arcenegui, V., Guerrero, C., Mayoral, A.M., Morales, J., Gonz´alez, J., Garc´ıa-Orenes, F., G´omez, I., 2007. Water repellency under different plant species in a calcareous forest soil in a semiarid Mediterranean environment. Hydrol. Process. 21, 2300–2309.

McGhie, D.A., Posner, A.M., 1981. The effect of plant top material on the water repellence of fired sands and water repellent soils. Australian Journal of Agricultural Research 32, 609–620, DOI: 10.1071/AR9810609.

Miralles, I., Ortega, R., Sanchez-Maranon, M., Soriano, M., Almendros, G., 2007. Assessment of biogeochemical trends in soil organic matter sequestration in Mediterranean calcimorphic mountain soils (Almerı´a, Southern Spain). Soil Biology & Biochemistry 39, 2459–2470.

Moore, D.S., McCabe, G.P., 2003. Introduction to the practice of statistics, 4th Ed. W.H. Freeman and Company, New-York.

Morley, C.P., Mainwaring, K.A., Doerr, S.H., Douglas, P., Llewellyn, C.T., Dekker, L.W., 2005. Organic compounds at different depths in a sandy soil and their role in water repellency. Australian Journal of Soil Research 43, 239-249.

Nakaya, N., 1982. Water repellency of soils. Jpn Agr. Res. Quart. 16, 24–28.

Nsabimana, D., Klemedtson, L., Kaplin, B.A., Wallin, G., 2008. Soil Carbon and nutrient accumulation under forest plantations in southern Rwanda. African Journal of Environmental Science and Technology, 2, 142-149.

Peng, J.B., Barnes, G.T., Gentle, I.R., 2001. The structures of LangmuirBlodgett films of fatty acids and their salts. Advances in Colloid and Interface Science 91, 163-219.

Rezaei-Gomari, K.A., Hamouda, A.A., 2006. Effect of fatty acids, water composition and pH on the wettability alteration of calcite surface, J. Petrol. Sci. Eng. 50, 140–150.

Richter, D.D., Markewitz, D., 1995. How deep is soil? Bioscience, 45, 600-609.

Rietveld, J., 1978. Soil non-wettability and its relevance as a contributing factor to surface runoff on sandy soils in Mali. Wageningen Agricultural University, The Netherlands, 179 pp.

Ritsema, C.J., Dekker, L.W., 2003. Soil water repellency: occurrence, consequences, and amelioration. Elsevier, Amsterdam, The Netherlands.

Roberts, F.J., Carbon, B.A., 1971. Water repellence in sandy soils of southwestern Australia. I. Some studies related to field occurrence. Fld. Stn. Rec. Div. Pl. Ind. CSIRO (Aust.) 10, 13–20.

Robinson, D.A., Lebron, I., Ryel, R.J., Jones, S.B., 2010. Soil Water Repellency, a Method of Soil Moisture Sequestration in Pinyon – Juniper Woodland. Soil Sci. Soc. Am J. 74: 624-634.

Rowell, D.L., 1988. Soil acidity and alkalinity, p. 844-898. In A. Wild (ed.), Russell's soil conditions and plant growth. John Wiley & Sons, New York.

Rusell, A.E., Raich, J.W., Valverde-Barrantes, O.J., Fisher, R.F., 2007. Tree species effects on soil properties in experimental plantations in tropical moist forest. Soil Sci. Soc. Am. J. 71, 1389-1397.

Sanchez, P.A., Palm, C.A., Davey, C.B., Szott, L.T., Rusell, C.E., 1985. Tree crops as soil improvers in the humid tropics? In Attributes of trees as crop plants (eds. M.G.R. Cannell and E.J. Jackson) pp 327-358. National Environmental Research Council, Institute of Terrestrial Ecology, Huntingdon.

Savage, S.M., Martin, J.P., Letey, J., 1969. Contribution of some soil fungi to natural and heat-induced water repellency in sand. Soil Science Society of America Proceedings 33, 405–409.

Schultz, K., Williamson, P., 2005. Gaining competative advantage in a carbon-constrained world: strategies for European business. European Management Journal 23, 383-391.

Scott, D.F., Van Wyk, D.B., 1990. The effects of wildfire on soil wettability and hydrological behaviour of an afforested catchment. J. Hydrol. 121, 239–256.

Smith, G.D., 1983. Correlation of the soils of the Commonwealth Caribbean , Puerto Rico, The Virgin Islands and Guyana. Soil and Land Use Surveys, No. 27, Farnham , UK : August Publications.

Sollins, P. 1998. Factors influencing species composition in tropical lowland rain forest: does soil matter? Ecology 79, 23-30.

USDA-NRCS, 2004. Soil survey laboratory methods manual. Soil survey investigations report no 42, Natural Resources Conservation Service, Lincoln, Nebraska.

Wallis, M.G., Horne, D.J., 1992. Soil water repellency. *In* Advances in Soil Science (B.A. Stewart (ed). Vol 20, 91-146. Springer Verlag, New York.

Wang, H., Malcolm, D.C., Fletcher, A.M., 1999. Pinus caribaea in China: introduction, genetic resources and future prospects. Forest Ecology and Management 117, 1-15.

Wander, I.W., 1949. An interpretation of the cause of water-repellent sandy soils found in citrus groves of central Florida. Science 110, 299–300.

Watson, C.L., Letey, J., 1970. Indices for characterizing soil-water repellency based upon contact angle-surface tension relationships. Soil Science Society of America Journal 34, 841-844.

Wiesmeier, M., Dick, D.P., Rumpel, C., Dalmolin, R.S.D., Hilscher, A., Knicker, H., 2009. Depletion of soil organic carbon and nitrogen under pinus taeda plantations in Southern Brazilian grasslands (campos). European Journal of Soil Science, 60, 347-359.

Wolff. R.L., Comps, B., Marpeau, A.M., Deluc, L.G., 1997. Taxonomy of Pinus species based on the seed oil fatty acid composition. Trees 12, 113-118.

Zehe, E., Elsenbeer, H., Lindenmaier, F., Schulz, K., Bloschl, G., 2007. Patterns of predictability in hydrological threshold systems. Water Resour Res. 43, W07434, doi:10.1029/2006WR005589

Figure captions

Figure 1. Water drop penetration time (WDPT) for the seven sites, with data for pine plantation denoted with (P) and native forest (N). Values of WDPT that are more than 1.5 times the interquartile range, from the nearest quartile are displayed as diamonds; if more than 3 times, they are displayed as asterisks.

Figure 2. Water drop penetration time (WDPT) as a function of soil volumetric water content under Caribbean pine (Pine) and native forest (NF).

Figure 3. Water drop penetration time (WDPT) as a function of litter depth for tropical pine and native forests (NF). Measurements are also presented for juniper and pinyon pine from a semi-arid region of Utah.

Figure 4. SWR, for tropical forest measurements compared with literature data for alkaline soils (scaled according to the maximum measured value). Literature data is included from Graber et al. (2009) and from Miralles et al. (2007) for alkaline soils. The transparent rectangles indicate pH zones that the data appear to fall into.

Figure 5. Trinidad results and meta-data analysis of the change of pH from native forest to pine plantation as a function of initial pH. Negative values indicate an increase in acidity, positive values amelioration. Literature data from Fimbel and Fimbel, 1996; Kadeba and Aduayi, 1985; Russell et al., 2007; Sanchez et al.,1985; Lilienfeina et al., 2000; Wieismeir et al., 2009; Nsabimana et al.,2008

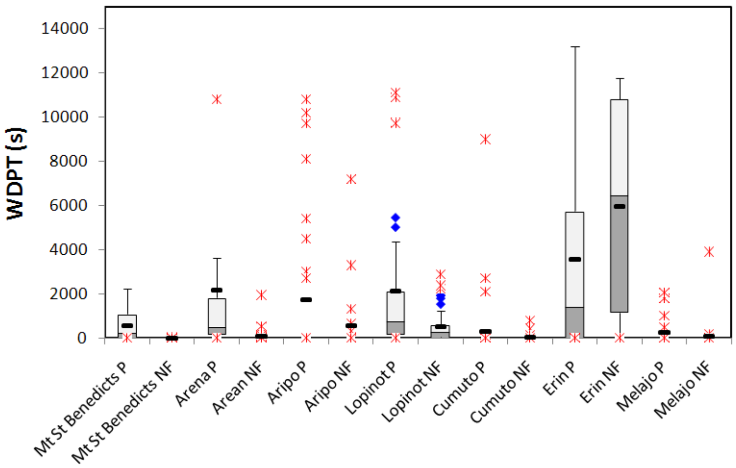
Table captions

Table 1. Soil characteristics according to the soil survey of Trinidad and Tobago (Smith, 1983).

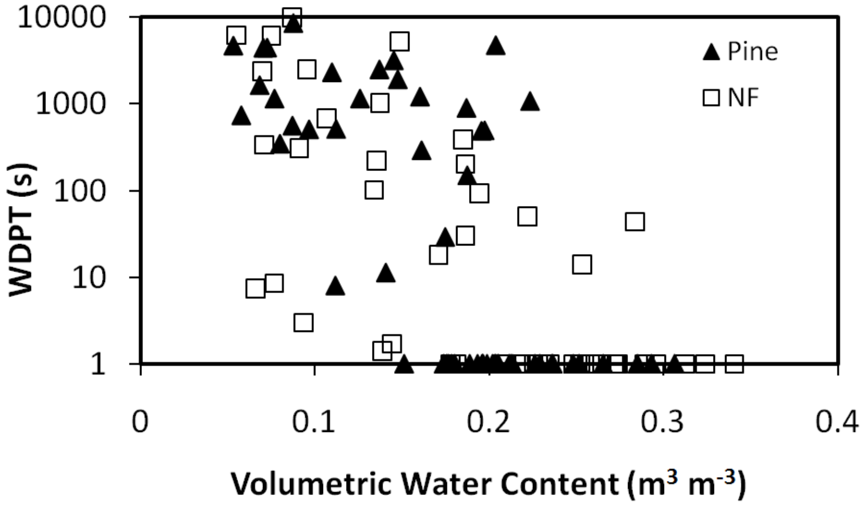
Table 2. 1:2 solution extract electrical conductivity (dS/m), standard deviation shown in brackets. pH measured in 1:1 soil:water ratio in native forest (NF) and pine forest (P) with standard deviation in brackets.

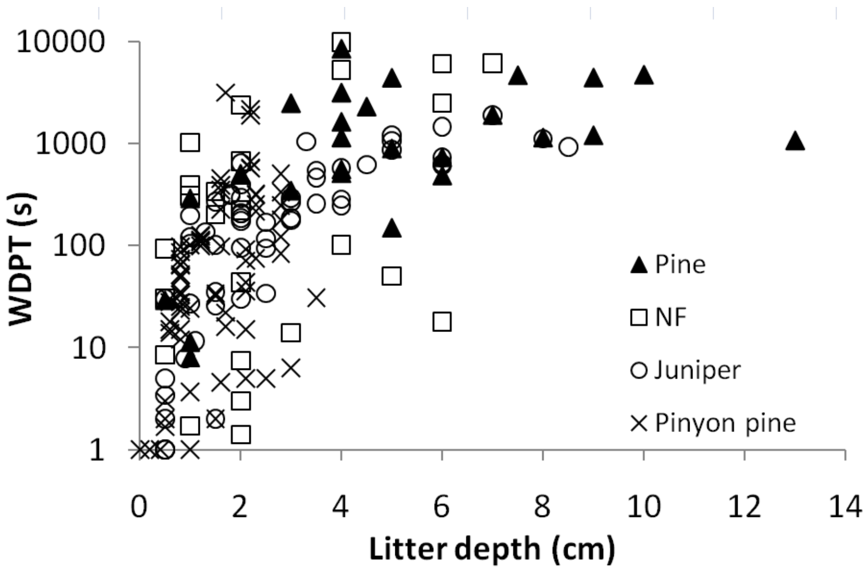
Site	**Soil Series**	**Texture**	**Subgroup**	**Family**	**Drainage**
Mount St. Benedict	Matelot	Sandy clay loam	Orthoxic Tropudults	fine- loamy, micaceous	Free
Lopinot	Santa Cruz	Fine sandy loam	Typic Eutropepts	loamy-skeletal, mixed	Free
Aripo	Long Stretch	Sandy clay loam	Plinthic Tropaquults	clayey, kaolinitic	Impeded
Arena	Valencia	Sandy clay loam	Typic Troporthods	coarse-loamy,silaceous	Imperfect
Cumuto	Las Lomas	Fine sandy loam	Orthoxic Tropudults	clayey, kaolinitic	Free
Erin	Moruga	Fine sandy clay	Typic Haplustults	fine-loamy, mixed	Imperfect
Melajo	Piarco	Fine sandy loam	Aquoxic Tropudults	clayey, kaolinitic	Imperfect

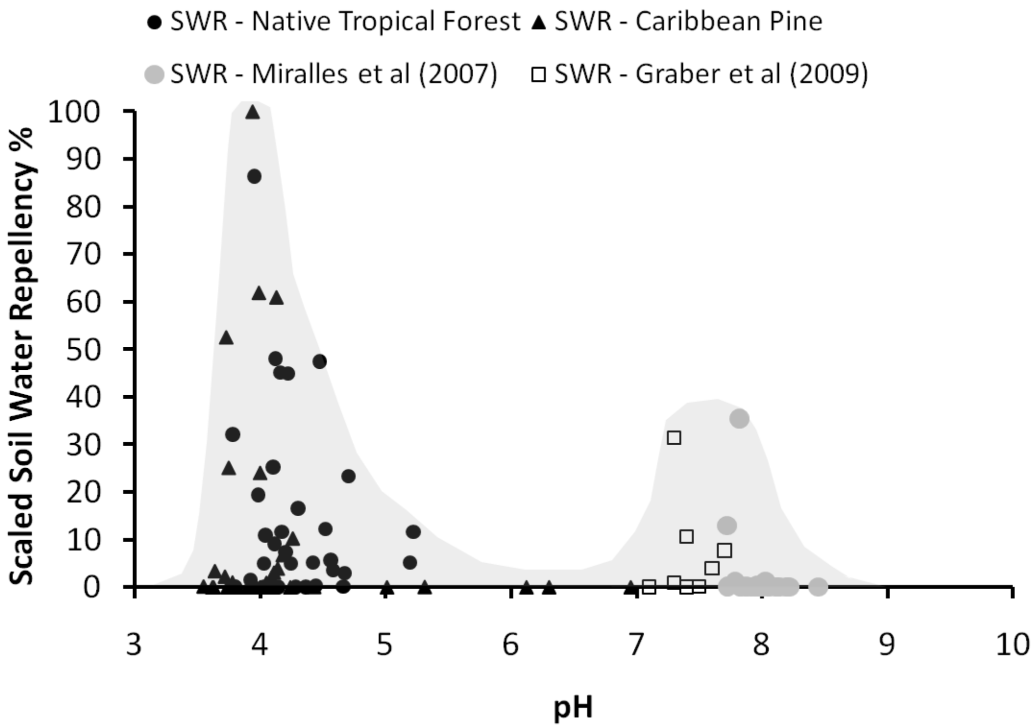
Site	Pine ECw 1:2	Native forest ECw 1:2	Pine pH_P (1:1, H_2O)	Native forest pH_{NF} (1:1, H_2O)	pH_{NF}-pH_P	significance
Mount St Benedicts	**0.1048**	**0.1853**	**4.87**	**5.94**	-1.07	0.032
	(0.0056)	(0.0498)	(0.38)	(0.78)		
Aripo Savannas	**0.0566**	**0.1115**	**3.93**	**4.07**	-0.13	0.112 (NS)
	(0.0070)	(0.0434)	(0.15)	(0.07)		
Arena	**0.0407**	**0.0419**	**4.26**	**3.75**	0.52	0.029
	(0.0110)	(0.0151)	(0.35)	(0.07)		
Lopinot	**0.0584**	**0.0825**	**4.47**	**4.02**	0.45	0.016
	(0.0307)	(0.0252)	(0.10)	(0.26)		
Cumuto	**0.0642**	**0.0731**	**4.13**	**4.13**	-0.01	0.951 (NS)
	(0.0064)	(0.0395)	(0.13)	(0.17)		
Erin Savannas	**0.0557**	**0.0595**	**4.27**	**3.96**	0.32	0.062 (NS)
	(0.0312)	(0.0107)	(0.27)	(0.15)		
Melajo	**0.0544**	**0.0649**	**4.04**	**3.84**	0.20	0.20 (NS)
	(0.0198)	(0.0050)	(0.19)	(0.25)		



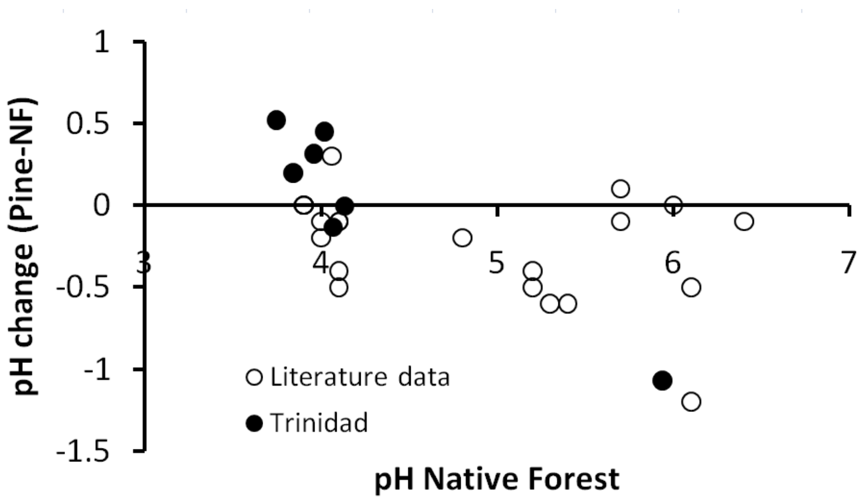
WDPT (s)
14000
12000
10000
8000
6000
4000
2000
0
Mt St Benedicts P
Mt St Benedicts NF
Arena P
Arean NF
Aripo P
Aripo NF
Lopinot P
Lopinot NF
Cumuto P
Cumuto NF
Erin P
Erin NF
Melajo P
Melajo NF


10000
1000
100
10
1
WDPT (s)
0
0.1
0.2
0.3
0.4
Volumetric Water Content (m³ m⁻³)
Pine
NF


WDPT (s)
10000
1000
100
10
1
0
2
4
6
8
10
12
14
Litter depth (cm)
Pine
NF
Juniper
Pinyon pine



SWR - Native Tropical Forest
SWR - Caribbean Pine
SWR - Miralles et al (2007)
SWR - Graber et al (2009)
Scaled Soil Water Repellency %
100
90
80
70
60
50
40
30
20
10
0
3
4
5
6
7
8
9
10
pH


pH change (Pine-NF)
1
0.5
0
-0.5
-1
-1.5
3
4
5
6
7
Literature data
Trinidad
pH Native Forest