

Water repellency of volcanic ash soils from Ecuadorian páramo: effect of water content and characteristics of hydrophobic organic matter

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Summary

Water repellency of volcanic ash soils from the Ecuadorian páramo was studied by a combination of extraction and analysis of water-repellent products, Molarity Ethanol Droplet values, water contact-angle measurements by capillary rise, and N₂ adsorption isotherms. The undried samples studied are hydrophilic, but exhibit water repellency after moderate drying (48 hours at 30°C). The advancing water contact-angle measured by capillary rise varies from 78° to 89°. These water contact-angles decrease strongly after extraction of organic materials by an isopropanol–water mixture. Elemental analysis, infrared spectra and gas chromatography–mass spectrometry analyses were used to characterize the extracts. The results show that long-chain fatty acids and more complex non-polar alkyl components (waxes) are the main water-repellent materials. The deposition of such extracted materials onto hydrophilic sand leads to the rapid increase of water contact-angle until values close to those measured on the soil samples are achieved. Assuming a coating of the mineral surface by organic hydrophobic products and using Cassie's law, the water contact-angle of extracted materials was computed. The values ranged from 100° to 157°. Nitrogen specific surface areas of the soils studied were very small, indicating a low adsorbent–adsorbate interaction on hydrophobic surfaces. These results partially validate the hypothesis of water-repellent materials that occur as coatings at least after a drying process.

Introduction

Occurrence of water repellency has been extensively reported in many countries and soil types (e.g. the reviews of DeBano, 1981, 2000 and Doerr *et al.*, 2000) and in a wide range of soil textures and amounts of organic matter, as follows: peat soils (Valat *et al.*, 1991; Michel *et al.*, 2001), sandy soils (Miller & Wilkinson, 1977; Dekker & Ritsema, 1994; Franco *et al.*, 1995) or clayey soils (Dekker, 1998; de Jonge *et al.*, 1999; Doerr *et al.*, 2000). Although some studies have shown the occurrence of water repellency in soils of high water content (King, 1981; Jex *et al.*, 1985; de Jonge *et al.*, 1999) most studies indicate that soils are most repellent when dry and least repellent or non-repellent (hydrophilic) when moist (e.g. DeBano, 1981, 2000; Dekker & Ritsema, 1994; Dekker, 1998; Doerr & Thomas, 2000; Michel *et al.*, 2001). However, the reported critical soil

moisture thresholds demarcating water-repellent and non-repellent conditions vary widely (e.g. Tschapek, 1984; Dekker & Ritsema, 1994; Doerr & Thomas, 2000) and the exact relationship between hydrophobicity and soil moisture remains far from understood.

On the other hand, the development of water repellency in soils is largely related to the content and the composition of soil organic matter (see Doerr *et al.*, 2000, and references therein). Various authors have emphasized the role of humic substances, such as humic acids (Savage *et al.*, 1969; Tschapek *et al.*, 1973; Jouany, 1991) and fulvic acids (Miller & Wilkinson, 1977), on the development of hydrophobic behaviour. Other studies have provided evidence of the role played by more specific organic materials in water repellency in soils, such as lipids (Ma'shum *et al.*, 1988; Capriel, 1997; Horne & McIntosh, 2000), waxes (Franco *et al.*, 1995) or the global aliphatics soil fraction (Savage *et al.*, 1972; Capriel *et al.*, 1995). Further research on the relationships between water content, water repellency and

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organic matter has led to suggestions that at least two types of soil hydrophobicity development are linked with organic matter during drying.

The first type of soil hydrophobicity has been attributed to conformational changes of the organic macromolecules which coat soil particles and microaggregates. During the drying process, the polar groups of the organic coatings should interact through hydrogen bonds. This forces the organic macromolecules into a micellar microstructure with their polar groups attached to the mineral surfaces (inner surface micelle microstructure) and their non-polar groups orientated outwards (outer surface micelle microstructure), rendering these organic coatings water repellent (Tschapek, 1984; Ma'shum & Farmer, 1985; Valat *et al.*, 1991). The second type, clearly shown by Franco *et al.* (1995) after heating, involves a redistribution of waxes already present in the soil matrix as interstitial globules. In both cases, the drying process involves both change of soil structure and organic matter.

The soils belonging to the Andisol order of soil taxonomy (Soil Survey Staff, 1999), and particularly the non-allophanic ones, are known to be among the richest in soil organic matter (Batjes, 1996). On the other hand, the complete and irreversible change of physical structure and hydric properties with drying is one of the classical characteristics of these soils. However, water repellency occurrence with drying in Andisols, and particularly in volcanic ash Andisols, is not currently described (see, e.g., Nanzyo *et al.*, 1993). Clothier *et al.* (2000) have recently reported water repellency in an unsaturated New Zealand Andisol, using a combination of solute transport and continuous TDR measurements, but these results demonstrate the occurrence of initial hydrophobicity.

In the high-altitude grasslands of Ecuador, Poulénard *et al.* (2001) have observed, under simulated rainfall, strong erosion of the topsoils by floating of aggregates on very dry, recently bare fallow Andisols. This behaviour was explained by the

potential water repellency of the dry Andisol aggregates. Thus, in this environment, currently submitted to intense change of land use, the development of water repellency of dry topsoils can have a major impact on the erosive and hydrodynamic behaviour of the soil. The aim of this paper is therefore to study the interactions between potentially hydrophobic organic matter and soil moisture on the hydrophobic behaviour of a range of Andisol topsoils derived from volcanic ash in the Ecuadorian páramo.

This study involved the estimation of the degree of water repellency by the Molarity Ethanol Droplet method and measurements of water contact-angle by capillary rise, the extraction and characterization of water-repellent organic materials, and the measurement of N₂ adsorption isotherms where N₂ acts as a polar microprobe of the soil surface.

Materials and methods

Soil samples

The paper deals with the A1 horizons of five profiles characteristic of the range of Andisols occurring in the high-altitude grassland ecosystem of Ecuador known as 'páramo' (Poulénard, 2000). Table 1 lists on the one hand the classification of these profiles according to Soil Survey Staff (1999), and, on the other, some physical and chemical properties of the topsoil horizons selected for this study. As shown in Table 1, our samples differ mainly by their carbon and volumetric water contents, and consequently by their bulk density values. More details concerning the GEL, CUE and AZO samples can also be found elsewhere (Poulénard *et al.*, 2003).

Disturbed and undisturbed samples of these topsoils were collected in January 1998. Disturbed samples taken at moisture contents very close to their field capacity were stored in plastic bags at 4°C. Undisturbed samples were collected as large

Table 1 Main properties of the soil samples studied

Profile name	Soil classification ^a	Topsoil horizon depth /cm	Bulk density /g cm ⁻³	Organic carbon	Allophane content ^b /g kg ⁻¹	Al-humus content ^c	Volumetric water content ^d	
							Moist samples ^e	48 hours at 30°C dried samples
							/cm ³ cm ⁻³	/cm ³ cm ⁻³
CHI	Typic Melanudand	0–30	0.65	86	17.0	52	0.76	0.04
PIC	Thaptic Hapludand	0–20	0.82	125	1.4	20	0.47	0.02
GEL	Hydric Pachic Melanudand	0–30	0.39	212	2.8	90	0.68	0.05
CUE	Hydric Melanudand	0–30	0.35	233	5.0	256	0.81	0.05
AZO	Hydric Pachic Melanudand	0–15	0.33	180	2.1	110	0.75	0.05

^aSoil classification according to Soil Survey Staff (1999).

^bAllophane content was assessed according to the formula: allophane = 7.1 Si_o, where Si_o is the ammonium oxalate-extractable Si (Parfitt & Wilson, 1985).

^cAl-humus was assessed according to the formula: Al-humus = 7.5 Al_p, where Al_p is the pyrophosphate-extractable Al (Poulénard & Herbillon, 2000).

^dWater content with reference to the oven-dried samples (48 hours at 105°C).

^eKept at field moisture content.

(3000 cm³) clods, wrapped in several plastic bags and also stored at 4°C. A part of each undisturbed soil sample was dried at 30°C for 48 hours in 28 cm³ cylinders for (i) analyses of moisture content, specific surface area, water contact-angle by capillary rise, and (ii) extraction and characterization of water-repellent materials. This moderate drying was chosen to simulate the air-drying which may occur in the field after removing the vegetal cover of the páramos for agriculture.

Assessment of water repellency by MED value

The effect of water content on water repellency was studied by taking samples after different drying times at 30°C. The water repellency was then assessed by the Molarity Ethanol Droplet (MED) method (King, 1981; Doerr, 1998; Roy & McGill, 2002). Solutions with different ethanol concentrations (0, 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12.5, 15, 17.5, 20, 25% by volume) were prepared. Drops (1 ml) of increasing ethanol concentrations were applied onto the surface of soil aggregates using a hypodermic syringe, until drop penetration occurred within 10 s. For the samples at different moisture content with different time of drying, 10 replicates of each MED measurement were made and the mean value and the standard deviation were calculated.

Water contact-angle measurements by capillary rise

The determinations of advancing water contact-angle, θ (°), were made on moist samples and on those dried for 48 hours at 30°C, by capillary rise using the Krüss Processor Tensiometer K12[®] (Michel *et al.*, 2001), and using the Washburn equation, which defines the liquid flux through the capillarity, as follows:

$$(m^2/t) = (C \rho_L^2 \gamma_L \cos\theta)/(2\eta_L), \quad (1)$$

where m is the weight of adsorbed liquid (g), t is time (s), ρ_L is the density of the liquid (g cm⁻³), η_L and γ_L are the viscosity (mPa) and the surface tension (mJ m⁻²) of the liquid, respectively, and C (cm⁵) an empirical constant related to soil porosity and its tortuosity. Thus, the advancing contact-angle (θ) can be measured using the speed of capillary rise if the other parameters are known (Michel *et al.*, 2001).

Homogeneously compacted samples were placed in a glass tube kept at 20°C, which was permanently weighed by a microbalance connected to a computer. A receptacle which contained the liquid was applied automatically to the bottom of the column which consisted of a porous glass sieve. The speed of capillary rise, translated into the increase in sample weight, was recorded by the computer. For each soil sample, the structural parameter, C , of Washburn's equation was calculated using a liquid with a very low surface tension (e.g. hexane) on the assumption that this liquid completely wets the sample ($\cos\theta = 1$). Then, C was introduced in Equation (1). This allowed computation of the water contact-angle after

recording the speed of water capillary rise in the soil. By definition, when $\theta > 90^\circ$, capillary rise cannot occur, so this method does not permit the measurement of contact-angles larger than 90°.

Extraction and characterization of water-repellent materials

Extractions of water-repellent materials were performed according to Ma'shum *et al.* (1988). Ten grams of soils were extracted by 200 ml of isopropanol:water (7:3 by volume) mixture during 16 hours using a Soxhlet apparatus. The extracts were dried, weighed, and kept for further analysis. After extraction, excess of isopropanol was removed under vacuum, and the water repellency measured by the advancing contact-angle using the capillary rise technique after the soil had air-dried.

Elemental analysis (C, H, N) of the dried extracts was made by dry combustion using a CHN autoanalyser (Carlo Erba 1108). The analysis of the chromatogram of the analyser shows the absence of sulphur. Oxygen was calculated assuming C + H + N + O = 100%. The fact that P was not included in the equation has a low impact on the O/C atomic ratio as P is < 1% of the average composition of soil organic matter (Baldock & Nelson, 2000). Infrared (IR) spectra were obtained with a Bruker Vector 22 IRTF spectrophotometer (1 mg samples dried over P₂O₅ and compressed with 200 mg KBr at 10 t pressure). Gas chromatography-mass spectrometry analyses (GC-MS) were carried out on a Varian 3400 CX GC coupled with a Varian ION TRAP Saturn III MS. Compounds were separated by He-flow on a 30-m DB5 MS column (0.25 mm internal diameter and 0.25 μm film thickness) programmed from 70°C to 280°C at 5°C m⁻¹. Samples (1 μl of material dissolved in dichloromethane) were injected using a programmable sample injector mode. Operating conditions of the MS were: electron energy 70 eV, source temperature 200°C, scanning from 40 to 650 m/z. Part of the materials was analysed directly and part was first methylated before analysis. Before the GC-MS determination, the methyl esters of fatty acids were prepared using a rapid esterification method with BF₃-methanol mixture (Knapp, 1979).

Effect of extracted material on the water contact-angle of quartz

Isopropanol-water-extracted materials from the GEL topsoil were dissolved in dichloromethane (100 ml of dichloromethane per 100 μg of extracted materials). Various volumes (5, 10, 15, 25, 50 and 75 ml) of this solution were added separately to 35 g of hydrophilic quartz (Fontainebleau sand). The Fontainebleau sand is characterized by a narrow particle-size distribution between 0.1 and 0.4 mm (median located at 0.22 mm) and a large degree of purity (97–99% quartz). After mixing, the solvent was evaporated under vacuum and the sand air-dried. The advancing water contact-angle was determined on the quartz

with and without adsorbed GEL water-repellent materials, following the procedure described previously.

N₂ specific surface area measurements

Nitrogen gas adsorption isotherms at liquid nitrogen temperature (77 K) were obtained with a custom-made, volumetric apparatus equipped with a Datametrics 0–1000 Torr pressure gauge. The 30°C-dried soil samples were degassed overnight at 20°C at 0.03 Torr. Total and micropore specific surface areas were calculated from the BET equation and the *t*-plot procedure, respectively (Rouquerol *et al.*, 1999).

Results and discussion

Effect of drying on water repellency

Molarity Ethanol Droplet (MED) values for moist samples (data not shown) were zero for all the samples showing hydrophilic behaviour of the topsoils before drying. During the drying process, the MED value of the sample CHI remained at zero. Figure 1 presents the relation between the water repellency estimated by MED value and the moisture content for the four other samples during the drying process. There is a clear increase in water repellency as moisture content decreases. The relationship appears to be linear for three samples (GEL, CUE, AZO) and the slope of the relation is seen as a relevant index to the susceptibility to repellency after drying. The PIC sample shows two-stage behaviour. During the first

part of drying there is high development of water repellency while at low water content, the slope is greatly reduced.

Water contact-angles, θ , of the moist and 30°C-dried topsoils, computed from capillary rise experiments, are listed in Table 2. Water contact-angle of moist samples ranges between samples from 0° to 71° and it is noticeable that with $\theta > 70^\circ$, the MED value was zero. This large discrepancy between the methods comes mainly from the high porosity of the moist samples (see the low bulk density values in Table 1) leading to rapid infiltration of pure water even if the water contact-angle is > 0 . The water contact-angle of 30°C-dried samples was large, with a narrow range from 85° to 89° for most soils studied. This characterizes strong hydrophobic behaviour, very near the point where water repellency prevents capillary rise ($\theta \geq 90^\circ$). The CHI dried sample had a water contact-angle of 78°, but the MED value is zero. Thus, we oppose water contact-angle $< 78^\circ$ with hydrophilic behaviour (moist samples and CHI dried samples) and $> 78^\circ$ with hydrophobic behaviour (all the other dried samples) (Table 2). This simple criterion appears here more relevant than the material classification of Van Oss (1996) in which all the moist and dried samples were considered as ‘partially hydrophobic’ with $54^\circ > \theta > 90^\circ$.

These results confirmed previous studies that reported that soils are most repellent when dry and least repellent or non-repellent (hydrophilic) when moist (DeBano, 1981, 2000; Dekker & Ritsema, 1994; Dekker, 1998; Doerr & Thomas, 2000; Michel *et al.*, 2001). Furthermore, these results confirm the field observation of strong water repellency on highly dried

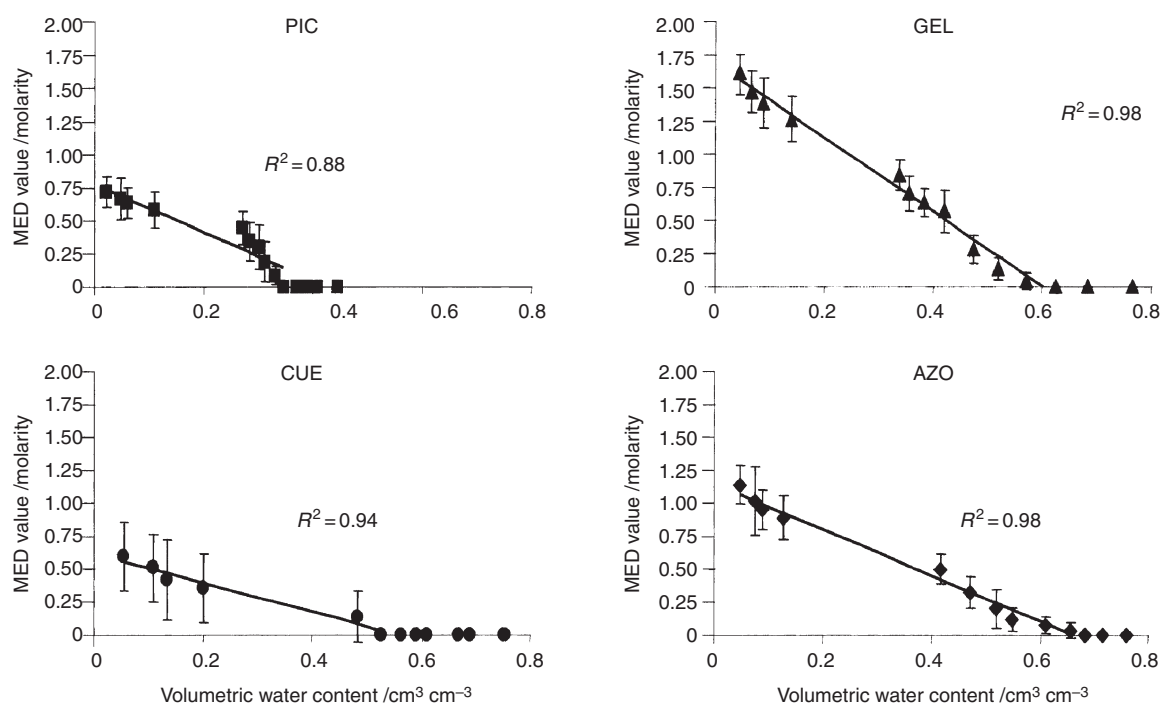


Figure 1 Relationships between MED values recorded during drying at 30°C and the volumetric water content for the four water-repellent samples.

Table 2 Mean and standard deviation (SD) of advancing contact-angle (θ) in degrees ($^{\circ}$) (three replicates) for moist and 30°C-dried samples, before and after isopropanol–water extraction

	Before isopropanol–water extraction				After isopropanol–water extraction	
	Wet samples		30°C-dried samples		30°C-dried samples	
	Mean	SD	Mean	SD	Mean	SD
CHI	0	0	78	2.8	57	2.1
PIC	52.5	13.3	87	0.7	60	6.4
GEL	69	1.8	84.5	1.0	74	3.1
CUE	60.5	2.2	86.5	0.3	37	5.1
AZO	71	2.7	89	0.2	20	14.9

páramos soils (Podwojewski *et al.*, 2002). The drastic erosion by the unexpected process of flotation of aggregates shown by Poulenard *et al.* (2001) on highly dried, bare fallow plots in the high grassland of Ecuador is probably due to the water repellency of such topsoil aggregates. The degree of drying, controlling the intensity of water repellency, can therefore be a key point for the erosion intensity by flotation on former-cultivated páramos Andisols.

Extraction and characterization of water-repellent materials

The amounts and characteristics of materials extracted by isopropanol–water are given in Table 3. First, they are similar in moist and dried samples of each topsoil. These amounts of extracted materials were also nearly 10 times larger than those found in an Australian water-repellent soil studied by Ma'shum *et al.* (1988), with the same extraction procedure. Extracted carbon represented 3.5–5.5% of the total soil organic carbon.

Second, the more organic is the soil, the greater is the mass extracted. The GEL, CUE and AZO mature Andisols, rich in organic matter (Table 1), contained much more water-repellent organic material than the CHI and PIC young Andisols (Table 3). Conversely, the O/C and the C/N atomic ratios of the materials extracted by isopropanol–water either decreased or

increased, respectively, as a function of the amount of extracted materials (Table 1). Again, there was a distinction between the GEL, CUE and AZO mature Andisols (O/C and C/N atomic ratio ranges of 0.29–0.32 and 84.7–118.2, respectively) and the two CHI and PIC young Andisols (O/C and C/N atomic ratio ranges of 0.37–0.43 and 57.7–69.4, respectively).

In contrast, the large H/C atomic ratio of 1.7–1.8 was nearly constant, whatever the soil (Table 3). This shows the large degree of aliphaticity of all the materials extracted. The atomic ratios of the extracted material plotted according to Van Krevelen (H/C versus O/C; results not shown) was very close to the position of soil lipids extracted with benzene or diethyl ether and analysed by Jambu *et al.* (1978). However, soil lipids are more a convenient analytical group than a specific type of compound, being a mixture of fatty acids and compounds with a complex molecular structure such as waxes, terpenes, sterols and resins (Dinel *et al.*, 1990). All these compounds have large aliphatic units as well as hydrophilic groups.

The IR spectra of the organic materials extracted by isopropanol–water (Figure 2) confirmed that the materials extracted were lipids with a high degree of aliphaticity and small amounts of nitrogen groups. The two strong IR peaks at 2920 and 2860 cm^{-1} correspond to the aliphatic CH_3 and CH_3CH_2 radicals, respectively. We also found the asymmetric deformations of the same aliphatic groups at 1460–1450 cm^{-1} and at 1380 cm^{-1} , respectively. The wide IR band which

Table 3 Amounts and elemental analysis of extracted materials with isopropanol–water from moist and dried samples

	Extracted materials						EC/TC ^a /%	Atomic ratio		
	Wet	Dried	C	N	H	O		O/C	C/N	H/C
	/g kg ⁻¹ of soil									
CHI	5.5	5.5	57.6	0.97	8.58	32.8	3.7	0.43	69.4	1.81
PIC	8.8	9.2	60.3	1.22	8.69	29.8	4.4	0.37	57.7	1.71
GEL	13.5	14.5	64.0	0.88	9.60	25.5	4.4	0.29	84.7	1.80
CUE	13.3	13.0	62.8	0.64	9.63	26.9	3.5	0.32	114.4	1.84
AZO	11.9	15.5	63.5	0.62	9.56	26.3	5.5	0.31	118.2	1.81

^aEC, extracted carbon; TC, total carbon.

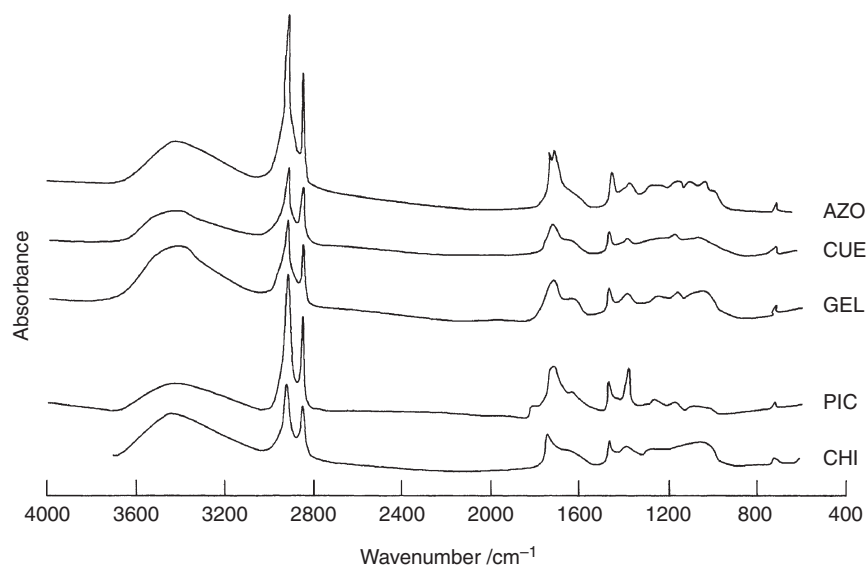


Figure 2 Infrared spectra of the materials extracted by isopropanol-water on the 30°C-dried soil samples.

centred at 3400 cm^{-1} was attributed to the O–H of carboxylic acids, alcohols and/or phenols. The ratio between the $2800\text{--}3000\text{ cm}^{-1}$ aliphatic area of the IR spectra and the amount of organic carbon was very large. In agreement with Capriel (1997), this indicates that the materials extracted were very hydrophobic in permanent grass ecosystems. The IR peak at $1710\text{--}1700\text{ cm}^{-1}$ was attributed to the vibration of C=O of carboxylic acids and ketones. Two neighbouring small IR peaks at 1630 cm^{-1} (vibration of C=O in quinones and amides) and at 1040 cm^{-1} (the vibration of C–O of alcohols) were also identified. The materials were therefore characterized by both hydrophobic groups ($\text{CH}_3\text{-CH}_2$) and hydrophilic ones (OH, C=O, C–O). The features of the IR spectra in Figure 2 are also quite similar to those of previously published IR spectra of water-repellent organic materials (Giovannini *et al.*, 1983; Ma'shum *et al.*, 1988).

The GC-MS analysis of non-methylated extracts indicated the presence of large amounts of vanilline, a compound typically attributed to residues of lignin degradation abundant in high-altitude grasslands (Serve *et al.*, 1983). The GC-MS ana-

lysis of the methylated extracts (Figure 3) showed the presence of 121 products, with a predominance of *n*-fatty acids ranging from C_8 to C_{28} . When the 74 m/z ion was monitored as specific to methylated fatty acids we did not observe the dominance of any particular type of fatty acid as Ma'shum *et al.* (1988) reported for an Australian soil water-repellent material. In contrast, a large number of fatty acids, from C_{14} to C_{28} , and an abundance of long-chain fatty acids (with $\text{C} > 19$) were observed (Figure 3). Terpenes, sterols and waxes were also identified in the extracts, but not quantified. The involvement of long-chain fatty acids in water repellency has been reported previously by different authors (Savage *et al.*, 1972; Ma'shum *et al.*, 1988; Diné *et al.*, 1990). Moreover, Coulibaly (1984) has shown that for the same amount of products deposited on soil, long-chain fatty acids have more effect on water repellency than small-chain fatty acids.

The question now arises as to the origin of the lipid fraction in the topsoils of this study. In the páramos, as well as in other mountain regions where vegetation is adapted to cold alpine conditions, the amount of lipids in plants is high (Körner,

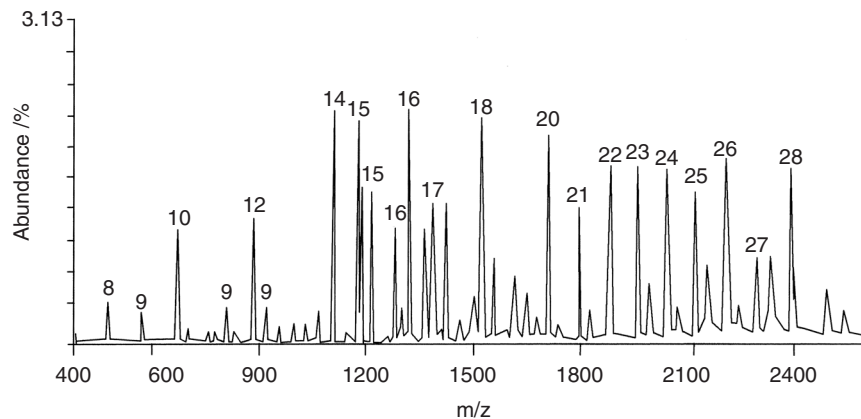


Figure 3 Relative abundance of long-chain fatty acids extracted by isopropanol-water from the 30°C-dried GEL Andisol.

1999). Amongst the eco-physiological adaptations of alpine plants, thick plant cuticles is one of the most frequently reported (Körner, 1999). Cuticles are known to be rich in long-chain ($C > 19$) fatty acids (Jambu *et al.*, 1978; Diné *et al.*, 1990) such as those quantified here in the isopropanol–water extracts (Figure 3). They are known to be more resistant to biodegradation than small-chain ($C < 19$) fatty acids, whose origin is mainly cellular. The thickness of the cuticle, linked with the alpine conditions prevalent in the páramos, is therefore one of the factors that explains the larger number of long-chain fatty acids ($C > 19$) occurring in the organic fraction of the topsoils studied. The other main factor is the low carbon mineralization due to the cold climatic conditions. Diné *et al.* (1990) have shown that lipids are generally more recalcitrant to microbial decomposition than other organic compounds such as cellulose, hemicellulose or proteins. This leads to a relative accumulation of lipids (Capriel, 1997) and explains the relatively large lipid/total organic matter ratios found in this study (Table 3).

Effect of extracted materials on water repellency

As shown in Table 2, the water contact-angle of the soils clearly decreased after extraction by isopropanol–water, ranging from 20° to 74° for the AZO and GEL dry topsoils, respectively. This result confirms that the amphiphilic solvent (H-bonding) reduced soil water repellency as shown by Ma'shum *et al.* (1988) or more recently by Roy & McGill (2000). However, the extraction led to hydrophilic behaviour for all those dried topsoils with a water contact-angle below the threshold value of 78° . Further, although the data are scattered, we observed a slight positive relationship between the water contact-angles and the amounts of materials extracted by isopropanol–water (Figure 4). Except for the GEL topsoil, the water contact-angle after extraction decreased significantly as a function of the amount of material extracted (Figure 4). However, we also validated the crucial effect of the extracted organic products on soil hydrophobicity by recording the water advancing contact-angle of quartz (Fontainebleau sand) as a function of adsorbed organic materials, previously extracted by isopropanol–water from the GEL topsoil (i.e. the sample where the role of the extracted products seems the lowest). The results showed that the very hydrophilic quartz surfaces became hydrophobic with a very small amount of extracted materials ($< 1 \mu\text{g}$ of extracts g^{-1} sand) (Figure 5). Moreover, the water contact-angle increased up to a plateau value corresponding to that of the GEL topsoil before extraction. Similar results have been reported by Tschapek *et al.* (1973), who analysed the complete change of the quartz surface from hydrophilic to hydrophobic before and after humic acid adsorption.

If we assume that the materials extracted by isopropanol–water were coatings on the topsoil sites, we can compute the

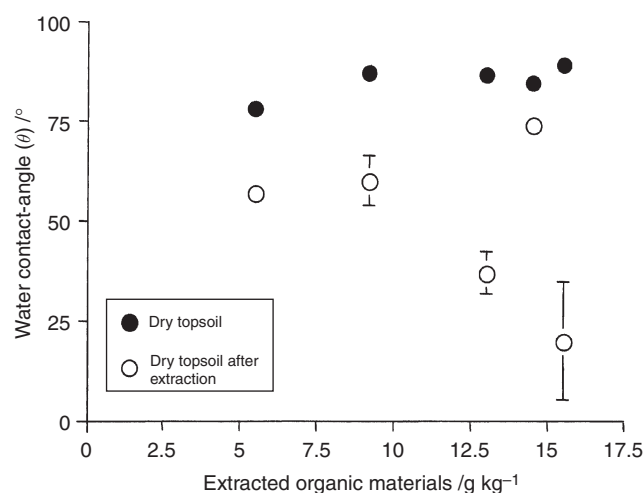


Figure 4 Water contact-angle (θ) (capillary rise) of the 30°C -dried soil samples, before and after extraction with isopropanol–water, as a function of mass of organic materials extracted.

contact-angle of the organic coatings using Cassie's law (Cassie & Baxter, 1944), as follows:

$$\cos \theta_{(\text{before extraction})} = \cos \theta_{(\text{after extraction})} + \cos \theta \text{ of the organic coatings.} \quad (2)$$

The results showed that the water contact-angle of the coatings ranged from 100.5° (GEL topsoil) to 157° (AZO topsoil),

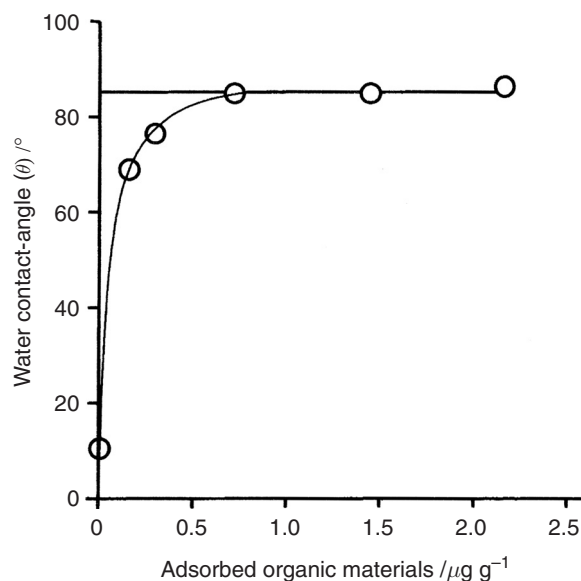


Figure 5 Water contact-angle (θ) (capillary rise) of quartz as a function of adsorbed organic materials previously extracted with isopropanol–water from the GEL topsoil. The horizontal line corresponds to the water contact-angle value of the dried GEL topsoil before isopropanol–water extraction.

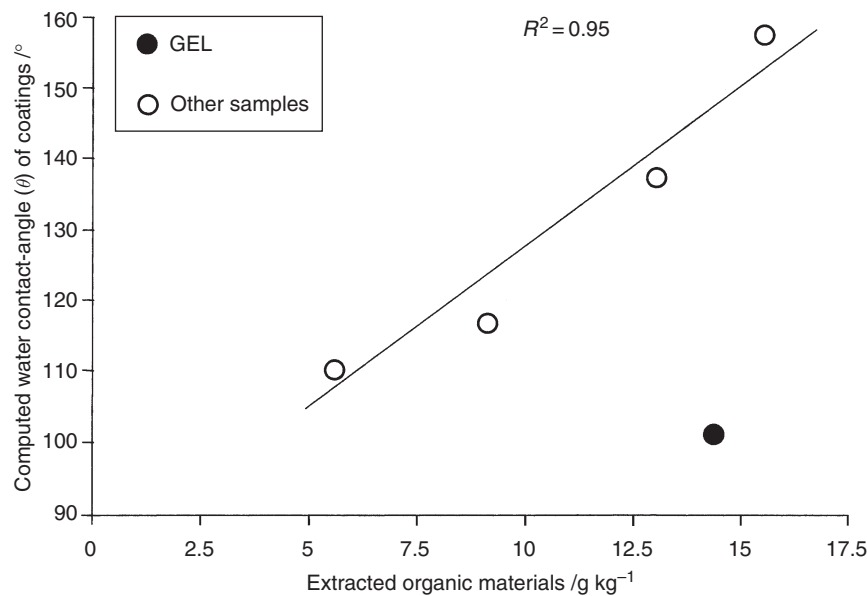


Figure 6 Computed contact-angles (θ) of the organic coatings as a function of the mass of extracted organic materials.

indicating that the assumed organic coatings, extracted by isopropanol–water, were strongly water repellent (Figure 6). In addition, except again for the GEL dried topsoil, the calculated contact-angle of the organic coatings increased as a function of the amount of materials extracted by isopropanol–water (Figure 6).

N_2 specific surface area

Table 4 reports the values of the specific surface area (SSA) measured by applying the BET equation to the N_2 adsorption isotherms of the different topsoils of this study, as well as the values of the part of these SSA associated with their micropores. Clearly, both sets of values were extremely small. Moreover, the data did not show any positive relationship with the clay contents of the samples (Table 1). On the contrary, the topsoil with the largest clay content (AZO: 550 g kg^{-1}) exhibited a SSA more than four times smaller than the soil (CHI) having only 180 g kg^{-1} of clay. However, all the topsoils with $\text{SSA} < 5 \text{ m}^2 \text{ g}^{-1}$ were also very rich in organic carbon

Table 4 N_2 -BET total specific surface area and micropore surface area ($\text{m}^2 \text{ g}^{-1}$) computed using the *t*-plot approach (Rouquerol *et al.*, 1999)

	Total BET surface area	Micropore surface area
CHI	7	1.5
PIC	2.2	0.25
GEL	2.4	0.11
CUE	2.6	0.5
AZO	1.5	0

(Table 1). As discussed by Theng *et al.* (1999), the inconsistencies between the results reported in Table 4 and Table 1 are not really surprising. Indeed, it has often been reported that the BET- N_2 method is inherently unable to provide realistic SSA values (and thus realistic SSA values of micropores) for soil samples rich in organic matter. This observation has been explained by different mechanisms (e.g. de Jonge *et al.*, 2000), but all of them are related to the fact that, at the boiling temperature of N_2 , these molecules are restricted from covering surfaces where strong interactions take place between organic and mineral colloids.

In the framework of the present study, the results listed in Table 4 can therefore be taken as an indirect indication that the increasing hydrophobic behaviour observed after drying (Table 2) is due to coating of minerals by water-repellent organic materials. In the same way, these results also justify our attempt to assess the extent of the organo-mineral interactions by applying Cassie's law to the samples of this study.

Our results should be partly explained using the hypothesis that air-drying increases the exposure of water-repellent substances at the interface between organic matter coatings and interstitial pore fluids. Following Ma'shum & Farmer (1985) and Roy & McGill (2000), we hypothesized that removal of water promotes interactions between polar functional groups, which in turn increase the exposure of non-polar alkyl chains. This change in conformation in organic matter coatings is due to the fact that non-polar moieties of water-repellent substances exposed at the interface between solid and fluid phases in soil are structurally flexible (Roy & McGill, 2000). Shrinkage, which is particularly pronounced in the volcanic soils studied (Poulénard *et al.*, 2002), should also explain the capillary rise data from wet to dry soils,

sorptivity being a function, in a complex way, of porosity, initial water content and liquid-pore contact-angle (e.g. Benavente *et al.*, 2002).

Conclusions

The combined application of extraction and analysis of water-repellent products, capillary rise measurements and N₂ adsorption isotherms leads to a consistent approach to the water repellency phenomena in the Ecuadorian páramos soils. The development of water repellency follows the decrease of water content on drying. This result, linked to the dramatic erosion, by flotation of water-repellent topsoil aggregates observed by Poulenard *et al.* (2001), shows the need to prevent strong drying processes on the surface of páramos soils.

After moderate drying, the water contact-angle determined from capillary rise was large, within a narrow range from 85° to 89° for most soils studied. This characterizes strong hydrophobic behaviour, except for the CHI topsoil which was partially hydrophobic ($\theta = 78^\circ$). These water contact-angles decrease strongly after extraction of organic materials by isopropanol-water. The abundance of long-chain fatty acids and waxes in topsoil horizons contributes to the development of water repellency after drying. Part of the variability of the hydrophobic behaviour seen between samples comes from differences in the lipid content. Nitrogen specific surface area data and the application of Cassie's law suggest that these water-repellent organic materials occur as coatings. The results presented are insufficient to permit the identification of the respective effect of hydrophobic organic matter and soil moisture on the hydrophilicity/hydrophobicity balance of these soils. Nevertheless, they emphasize the strong relationships between the contribution of aliphatic organic compounds to water repellency and the drying process, at least for very porous and very organic-rich Andisols.

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References

- Baldock, J.A. & Nelson, P.N. 2000. Soil organic matter. In: *Handbook of Soil Science* (ed. M.E. Sumner), pp. B25–B84. CRC Press, Boca Raton, FL.
- Batjes, N.H. 1996. Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science*, **47**, 151–163.
- Benavente, D., Lock, P., Angeles Garcia Del Cura, M. & Ordonez, S. 2002. Predicting the capillary imbibition of porous rocks from microstructure. *Transport in Porous Media*, **49**, 59–76.
- Capriel, P. 1997. Hydrophobicity of organic matter in arable soils: influence of management. *European Journal of Soil Science*, **48**, 457–462.
- Capriel, P., Beck, T., Borchert, H., Gronholz, J. & Zachmann, G. 1995. Hydrophobicity of the organic matter in arable soils. *Soil Biology and Biochemistry*, **27**, 1435–1458.
- Cassie, A.B.D. & Baxter, S. 1944. Wettability of porous surfaces. *Transactions of the Faraday Society*, **40**, 546–561.
- Clothier, B.E., Vogeler, I. & Magesan, G.N. 2000. The breakdown of water repellency and solute transport through a hydrophobic soil. *Journal of Hydrology*, **231–232**, 255–264.
- Coulibaly, G. 1984. *Influence des lipides sur les propriétés physiques des sols. Formation de complexes argilo-lipidiques*. Thèse de doctorat, Université de Poitiers.
- DeBano, L.F. 1981. *Water Repellent Soils: A State of the Art*. USDA Forest Service General Technical Report PSW-46, Pacific Southwest Forest and Range Experiment Station, Berkeley, CA.
- DeBano, L.F. 2000. Water repellency in soils: a historical overview. *Journal of Hydrology*, **231–232**, 4–32.
- Dekker, L.W. 1998. *Moisture variability resulting from water repellency in Dutch soils*. PhD thesis, Wageningen University, The Netherlands.
- Dekker, L.W. & Ritsema, C.J. 1994. How water moves in a water repellent sandy soil. 1. Potential and actual water repellency. *Water Resources Research*, **30**, 2507–2517.
- Dinel, H., Schnitzer, M. & Mehuys, G.R. 1990. Soil lipids: Origin, nature, content, decomposition, and effect on soil physical properties. In: *Soil Biochemistry* (eds J.M. Bollag & G. Stotzky), pp. 397–429. Marcel Dekker, New York.
- Doerr, S.H. 1998. On standardizing the 'water drop penetration time' and the 'molarity of an ethanol droplet' techniques to classify soil hydrophobicity: a case study using medium textured soils. *Earth Surface Processes and Landforms*, **23**, 663–668.
- 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. 2000. Soil water repellency: its causes, characteristics and hydro-geomorphological significance. *Earth Science Reviews*, **51**, 33–65.
- Franco, C.M.M., Tate, M.E. & Oades, J.M. 1995. Studies on non-wetting sands. I. The role of intrinsic particulate organic matter in the development of water repellency in non-wetting sands. *Australian Journal of Soil Research*, **33**, 253–263.
- Giovannini, G., Lucchesi, S. & Cervelli, S. 1983. Water repellent substances and aggregate stability in hydrophobic soil. *Soil Science*, **135**, 110–113.
- Horne, D.J. & McIntosh, J.C. 2000. Hydrophobic compounds in sands in New Zealand – extraction, characterization and proposed mechanisms for repellency expression. *Journal of Hydrology*, **231–232**, 35–46.
- Jambu, P., Fustec, E. & Jacquesy, R. 1978. Les lipides des sols: nature, origine, évolution, propriétés. *Science du Sol*, **4**, 229–240.
- 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.
- de Jonge, H., de Jonge, L.W. & Mittelmeijer-Hazeleger, M.C. 2000. The microporous structure of organic and mineral materials. *Soil Science*, **165**, 99–108.
- de Jonge, L.W., Jacobsen, O.H. & Moldrup, P. 1999. Soil water repellency: effects of water content, temperature and particle size. *Soil Science Society of America Journal*, **63**, 437–442.

- Jouany, C. 1991. Surface free energy components of clay–synthetic humic acid complexes from contact angle measurements. *Clays and Clay Minerals*, **39**, 43–49.
- King, P.M. 1981. Comparison of methods for measuring severity of water repellence of sandy soils and assessment of some factors that affect its measurement. *Australian Journal of Soil Research*, **19**, 275–285.
- Knapp, D. 1979. *Handbook of Analytical Derivatization Reactions*. Wiley-Interscience, John Wiley & Sons Inc., New York.
- Körner, C. 1999. *Alpine Plant Life: Functional Plant Ecology of High Mountain Ecosystems*. Springer-Verlag, Heidelberg.
- Ma'shum, M. & Farmer, V.C. 1985. Origin and assessment of water repellency of a sandy South Australian soil. *Australian Journal of Soil Research*, **23**, 623–626.
- Ma'shum, M., Tate, M.E., Jones, G.P. & Oades, J.M. 1988. Extraction and characterization of water-repellent materials from Australian soils. *Journal of Soil Science*, **39**, 99–110.
- Michel, J.C., Rivière, L.M. & Bellon-Fontaine, M.N. 2001. Measurement of the wettability of organic materials in relation to water content by the capillary rise method. *European Journal of Soil Science*, **52**, 459–468.
- Miller, R.H. & Wilkinson, J.F. 1977. Nature of the organic coating on sand grains of nonwetable golf greens. *Soil Science Society of America Journal*, **41**, 1203–1204.
- Nanzyo, M., Shoji, S. & Dahlgren, R. 1993. Physical characteristics of volcanic ash soils. In: *Volcanic Ash Soils: Genesis, Properties and Utilization* (eds S. Shoji, R. Dahlgren & M. Nanzyo), pp. 189–201. Developments in Soil Science 17, Elsevier, Amsterdam.
- Parfitt, R.L. & Wilson, A.D. 1985. Estimation of allophane and halloysite in three sequences of volcanic soils, New Zealand. In: *Volcanic Soils* (eds E. Fernandez Caldas & D.H. Yaalon), pp. 1–8. Catena Supplement 7, Catena Verlag, Cremlingen.
- Podwojewski, P., Poulenard, J., Zambrana, T. & Hofstede, R. 2002. Overgrazing effects on vegetation cover and properties of volcanic ash soil in the páramo of Llangahua and La Esperanza (Tungurahua, Ecuador). *Soil Use and Management*, **18**, 45–55.
- Poulenard, J. 2000. *Les sols des páramos sur couverture pyroclastique: genèse, diversité et propriétés physiques*. Thèse de doctorat, Université de Nancy I.
- Poulenard, J. & Herbillon, A.J. 2000. Sur l'existence de trois catégories d'horizons de référence dans les Andosols. *Compte Rendus Académie des Sciences, Série IIa*, **331**, 651–657.
- Poulenard, J., Podwojewski, P., Janeau, J.L. & Collinet, J. 2001. Effects of tillage and burning on hydrodynamic properties of volcanic ash soil in Ecuadorian páramos. *Catena*, **45**, 185–207.
- Poulenard, J., Bartoli, F. & Burtin, G. 2002. Shrinkage and drainage in aggregates of volcanic soils: a new approach combining mercury porosimetry and vacuum drying kinetics. *European Journal of Soil Science*, **53**, 563–574.
- Poulenard, J., Podwojewski, P. & Herbillon, A.J. 2003. Characteristics of non-allophanic Andisols with hydric properties from the Ecuadorian páramos. *Geoderma*, **117**, 267–281.
- Rouquerol, F., Rouquerol, J. & Sing, K. 1999. *Adsorption by Powders and Porous Solids*. Academic Press, London.
- Roy, J.L. & McGill, W.B. 2000. Flexible conformation in organic matter coatings: an hypothesis about soil water repellency. *Canadian Journal of Soil Science*, **80**, 143–152.
- Roy, J.L. & McGill, W.B. 2002. Assessing soil water repellency using the molarity of ethanol droplet (MED) test. *Soil Science*, **167**, 83–97.
- Savage, S.M., Martin, J.P. & Letey, J. 1969. Contribution of humic acid and a polysaccharide to water repellency in sand and soil. *Soil Science Society of America Proceedings*, **33**, 149–151.
- Savage, S.M., Osborn, J., Letey, J. & Heaton, C. 1972. Substances contributing to fire-induced water repellency in soils. *Soil Science Society of America Proceedings*, **36**, 674–678.
- Serve, L., Piovetti, L. & Longuemard, N. 1983. Dosage des acides et aldéhydes phénoliques par chromatographie liquide haute performance: analyse comparative des sols de hautes montagne et de leurs végétation. *Journal of Chromatography*, **259**, 319–328.
- Soil Survey Staff 1999. *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*, 2nd edn. USDA Agriculture Handbook No 436, NRCS Pocahanta Press, Washington.
- Theng, B.K.G., Ristori, G.G., Santi, C.A. & Percival, H.J. 1999. An improved method for determining the specific surface areas of topsoils with varied organic matter content, texture and clay mineral composition. *European Journal of Soil Science*, **50**, 309–316.
- Tschapek, M. 1984. Criteria for determining the hydrophilicity–hydrophobicity of soil. *Zeitschrift für Pflanzenernährung und Bodenkunde*, **147**, 137–149.
- Tschapek, M., Pozzo Ardizzi, J. & Bussetti, S.G.D. 1973. Wettability of humic acid and its salts. *Zeitschrift für Pflanzenernährung und Bodenkunde*, **135**, 16–31.
- Valat, B., Jouany, C. & Riviere, L.M. 1991. Characterization of the wetting properties of air-dried peats and composts. *Soil Science*, **152**, 100–107.
- Van Oss, C.J. 1996. *Forces interfaciales en milieux aqueux*. Masson, Paris.