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Spatial and temporal variability of soil water repellency of Amazonian pastures

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Abstract. Fire is commonly used to establish and maintain pastures in the Amazon. Fire is also known to induce soil water repellency but few published data exist for the humid tropics. The objectives of this study were to characterise the intensity and spatial variability of water repellency on previously burned pasture soils in the Amazon, and its effect on the nutrient status of the forage grass *Brachiaria brizantha* (Hochst.) Stapf. Surface soils of pastures and forests in north-western Mato Grosso, Brazil, were found to exhibit soil water repellency using MED and WDPT tests. Soil water repellency was found only within 0–0.01 m of the mineral soil surface, with soil below 0.01 m found to be hydrophilic in all cases.

Spatial variability of repellency was high for both pasture and forest soils. For pasture soils, soil water repellency was strongest on recently burned pastures, which exhibited some extremely high values (MED >8 M). Repellency decreased rapidly with time following burning. Increasing soil water repellency was associated with decreasing N : P ratios of *B. brizantha* above-ground biomass ($r^2 = 0.66$, $P = 0.004$). These findings indicate that soil water repellency and pasture productivity are inversely related. Since pasture abandonment fuels continued deforestation, disrupting the processes causing pasture degradation may lead to more sustainable land use in the Amazon.

Additional keywords: hydrophobicity, *Brachiaria brizantha*, burning, N : P, Oxisol, Ultisol.

Introduction

Over 75% of Amazonian deforestation in the past 30 years has been directed towards the establishment of pastures (Fearnside 1996). The productivity of Amazonian pastures declines within 4–8 years of establishment, frequently resulting in abandonment (Buschbacher *et al*. 1988; Serrão and Toledo 1990; Kauffman *et al*. 1998). The often indiscriminate use of fire in pasture management contributes to pasture degradation in the Amazon (Serrão and Toledo 1990).

Fire is one of the key causative factors of soil water repellency (e.g. DeBano *et al*. 1970; Savage *et al*. 1972; Doerr *et al*. 1996; DeBano 2000; Robichaud and Hungerford 2000). Burning accompanies deforestation and is used every 2–3 years during pasture establishment (Kauffman *et al*. 1998). The burning has the potential to cause the build-up of a water repellent soil layer. This has been suggested to occur via the translocation of volatilised water repellent organic compounds into the soil profile, which condense in cooler soil layers and coat soil aggregates (DeBano 2000). Soil water repellency has been observed to persist over months (Huffman *et al*. 2001) and years (Shakesby *et al*. 1993). The breakdown and re-establishment of soil water repellency as soil is wetted and dried has not been extensively studied (Shakesby *et al*. 2000).

The interrelationship of soil water repellency and pasture degradation has not caught the attention of land managers. Long-term degradation of Amazonian pastures occurs due to deterioration of soil nutrient levels and soil structure (Fearnside 1979; Serrão and Toledo 1990). In the Amazon, pasture rehabilitation (plowing, fertilising, liming, and replanting) costs approximately US$800/ha, whereas the cost of acquiring new land is roughly US$43/ha for forest land and US$180/ha for pasture land (Fearnside 2001). Disrupting the process of pasture degradation could reduce the rate of deforestation by enabling established pastures to be used for longer periods of time (Serrão and Toledo 1990).

Although much attention has been focussed on soil water repellency in temperate soils recently, few studies of water repellency have been conducted in the humid tropics. Researchers have reported the occurrence of soil water repellency in humid regions of Colombia (Jaramillo *et al*.

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2000) and India (Singh and Das 1992). In addition, the dynamics of soil water repellency over time and its relation to nutrient cycling are poorly understood.

We investigated soil water repellency on pasture, forest, and cropped soils in north-western Mato Grosso, Brazil. The objectives of this research were to (*1*) identify if soil water repellency exists in soils of the Amazon, and (*2*) characterise the intensity and spatial variability of soil water repellency on pasture soils of the Amazon in relation to: (*i*) time following burning; and (*ii*) plant nutrient status.

Materials and methods

Site description

Thirteen pasture sites in the municipality of Castanheira, Mato Grosso, Brazil (10°52′S, 58°29′W), were classified by the length of time since the pasture was last burned, and included pastures on small and large landholdings. All pastures were established at least 4 years prior to the study. Three of these sites had been burned within 1 week of the time of measurement, with time since burning for the remaining pastures ranging from 1 to 10 years. Two forest sites and 2 agricultural sites were selected for comparison. Sites for all land uses were on locations with similar soil characteristics and slopes less than 5%. Forest and cropped sites were selected based upon proximity to pasture sites. All sites were located within a 15-km radius. Pasture soil and forage characteristics for pastures not recently burned are presented in Table 1.

Soils in the study area are predominantly Ultisols and Oxisols with an ustic moisture regime. Ultisols sometimes have a water repellent layer close to or at the soil surface (van Wambeke 1992). Rainfall is approximately 2 m/year, with a 4-month dry season that extends from May to August.

Pasture sites were all planted to *Brachiaria brizantha* (Hochst.) Stapf, a bunch grass that is the most commonly planted forage grass in the study region as well as in the tropical Americas (Keller-Grein *et al.* 1996). Pasture soils in the study region are P-limited, having average soil P levels of 4 mg/kg (Mehlich-I) at 0–0.05 m depth.

Soil water repellency measurements

The strength of soil water repellency was assessed *in situ* at the mineral soil surface using the Molarity of an Ethanol Droplet (MED) test (Watson and Letey 1970; King 1981; Doerr 1998) after carefully removing all loose organic material. Solutions of ethanol and distilled water ranging in concentration from 0 M to 8 M were prepared in 0.5-M increments. Drops of increasing ethanol molarity were applied to the mineral soil until the surface tension of the solution was sufficiently low to permit infiltration within 3 s (Doerr 1998). Measurements were made during the dry season in June 2002 following 6 weeks without rainfall. The strength and spatial variability of soil water repellency at 2 different spatial scales were assessed by making 5 measurements within 9 microsites (0.1 by 0.1 m) located every 2 m along a downslope-oriented transect (Doerr *et al.* 1998).

The relevant soil physical property determined by the MED test is the strength or degree of water repellency, which is mainly controlled by the surface tension of the solid–air interface, γ_s (Letey *et al.* 2000). γ_s is related to the surface tension of the least concentrated ethanol solution that is rapidly absorbed into the soil (Letey *et al.* 2000; Roy and McGill 2002). Thus, the MED test gives the surface tension of the least concentrated droplet with a contact angle of less than 90° (Letey *et al.* 2000), referred to here as the critical surface tension (CST) (e.g. Scott 2000; Huffman *et al.* 2001) with unit mN/m. CST values were computed from ethanol solution concentrations using the equation given by Roy and McGill (2000). Statistical analysis among sites was performed using the arithmetic mean CST value of all measurements made within a site.

Categories of repellency based on MED values that synthesise scales chosen by King (1981), Doerr (1998), and Doerr *et al.* (2000) are used for qualitative descriptions of soil water repellency status, and are given in Table 2 along with equivalent CST values.

Whereas the MED test is used to assess the strength of soil water repellency, the Water Drop Penetration Time (WDPT) test (Letey 1969; Doerr 1998) is commonly used to determine the persistence of soil water repellency. WDPT measurements in the field proved impractical due to long drop penetration times and ants climbing onto droplets. As such, measurements using the MED test were conducted in the field, whereas the WDPT tests for comparison were conducted in the laboratory following the methodology suggested by Doerr (1998). In order to compare results from these 2 tests, soil adjacent to, but not affected by the MED test was collected from 7 microsite locations that exhibited different strengths of soil water repellency as determined by the *in situ* MED test. Soil samples for the WDPT test were homogenised and air-dried at 28°C for 2 weeks. Since soil water repellency was observed *in situ* to occur only at the mineral soil surface, soil for the WDPT test was collected from the 0–0.01 m depth. A drop of water was placed on the surface of the homogenised soil and the time to infiltration was measured. This was repeated 5 times on each homogenised sample

Table 1. Soil physical properties (0–0.05 m) and pasture characteristics of sites not recently burned

Site	Bulk density[A]	Clay (%)	Sand (%)	Organic matter (%)	Areal coverage (%) of *B. briazantha*[B]	N : P of above-ground *B. brizantha*	Time since burning (years)
1	1.43 ± 0.19	18.1	66.9	3.31	13.9 ± 3.8	7.8	2
2	1.52 ± 0.07	13.1	83.6	2.66	11.1 ± 1.2	7.0	1
3	1.48 ± 0.11	14.7	81.9	3.59	27.0 ± 6.1	3.0	2
4	1.42 ± 0.09	18.1	76.9	2.66	15.8 ± 2.4	7.0	1
5	1.31 ± 0.02	19.7	75.3	2.58	4.6 ± 1.8	14.0	10
6	1.47 ± 0.07	38.1	51.9	3.59	23.7 ± 1.4	7.0	8
7	1.38 ± 0.14	16.4	78.6	3.5	20.5 ± 4.1	2.3	6
8	1.40 ± 0.06	34.7	55.3	4.48	22.2 ± 2.3	5.1	6
9	1.48 ± 0.09	16.4	70.3	1.68	15.1 ± 1.0	6.2	8
10	1.47 ± 0.18	13.1	83.6	2.51	30.9 ± 0.5	3.7	4

[A]Value ± 1 s.d. ($n = 3$). [B]Value ± 1 s.d. ($n = 2$).

Table 2. Categories of soil water repellency status adapted from King (1981), Doerr (1998), and Doerr *et al.* (2000)

MED range (M)[A]	Water repellency status	CST range (mN/m)[B]
<1.0	Hydrophilic	>55.1
1.0–2.0	Hydrophobic	55.1–47.5
2.0–3.5	Strongly hydrophobic	47.5–40.6
>3.5	Extremely hydrophobic	<40.6

[A]Molarity of Ethanol Droplet (MED).
[B]Critical surface tension (CST).

for locations on the sample not affected by previous drop placement. The mean MED value for the microsite location was used for comparison with mean WDPT results.

Soil and plant analyses

A suite of measurements was made on the 10 sites that had not been recently burned. Soil was sampled at 3 locations on each transect (0–0.05 m depth) using a sharpened steel cylinder (7.1 cm diam.). Bulk density was determined for each of the 3 samples, which were then composited and analysed for physical and chemical parameters using standard methods. Available soil P and micronutrient contents were measured using Mehlich-1 extraction, total N by Kjeldahl digestion, and organic matter by loss on ignition.

All above-ground live plant parts of *B. brizantha* were removed from two 1-m^2 plots in each pasture, homogenised, dried at 70°C for 48 h, weighed, and a subsample was ground. *B. brizantha* samples were analysed for macro- and micro-nutrients using standard methods. Nitrogen was determined by titration against boric acid following digestion in H_2SO_4. Phosphorus was determined following nitric perchloric acid digestion using colourimetry. The diameter of each grass tuft occurring within each 1-m^2 plot was measured following removal of above-ground biomass as a proxy for net primary productivity. This allowed the percent ground cover to be measured objectively, irrespective of grazing pressure. *B. brizantha* was approximately 40% cured at the time of sampling. Collecting plant tissue samples from one species at a consistent physiological stage reduces much of the variability in plant nutrient status (Chapin and Van Cleve 1989).

Results and discussion

The correlations between soil water repellency (mN/m, determined from *in-situ* MED test), potential predictor variables, and pasture productivity variables are presented in Table 3. Potential predictor variables for the pasture soils in this study include time since burning, soil organic matter, and soil texture, whereas the N : P ratio in the above-ground biomass of *B. brizantha* and the per cent ground cover occupied by *B. brizantha* tufts are considered pasture productivity variables potentially related to soil water repellency. CST values were found to be normally distributed. Significant relationships with soil water repellency were only found for the N : P ratio of *B. brizantha*, time since burning, and the percent ground cover. These correlations are considered in further detail in the following sections. Soil water repellency was not found to be significantly related to soil texture nor to soil organic matter in this study (Table 3).

Soil water repellency and pasture burning

Pasture soils in the study area were found to exhibit a range of soil water repellency at the soil surface during the dry season. Soil water repellency was found only within 0–0.01 m of the mineral soil surface, with soil below 0.01 m found to be hydrophilic in all cases. Soils of recently burned pastures exhibited extreme water repellency (Fig. 1), including some point measurements where repellency exceeded an MED value of 8 M (CST <28.6 mN/m) (Table 4). It should be noted that the most intense repellency reported in a review paper by Doerr *et al.* (2000) corresponds to a MED value of

Table 3. Simple correlations and significance of relationships between soil water repellency and pasture soil and forage properties

Values are for the Pearson's correlation coefficient (*r*) (first value) and *P*-values (second value). Number of observations (*n*) = 13 for CST *v*. time since burning; *n* = 10 for all other comparisons

	CST[A]	N : P[B]	Time since burning	Per cent ground cover	Clay fraction	Sand fraction
N : P	0.81					
	0.004**					
Time since burning	0.69	0.39				
	0.010**	0.27				
Per cent ground cover	−0.61	−0.81	−0.18			
	0.062*	0.004**	0.61			
Clay fraction	0.12	0.13	0.45	0.15		
	0.73	0.72	0.19	0.69		
Sand fraction	−0.25	−0.16	−0.45	−0.05	−0.94	
	0.48	0.66	0.19	0.89	0.000**	
Soil organic matter	−0.37	−0.31	−0.07	0.37	0.61	−0.49
	0.29	0.39	0.84	0.29	0.062*	0.15

*P < 0.1; **P < 0.01.
[A]Critical surface tension determined from the Molarity of Ethanol Droplet Test (MED).
[B]Nitrogen : phosphorus ratio for *Brachiaria brizantha* above-ground biomass.

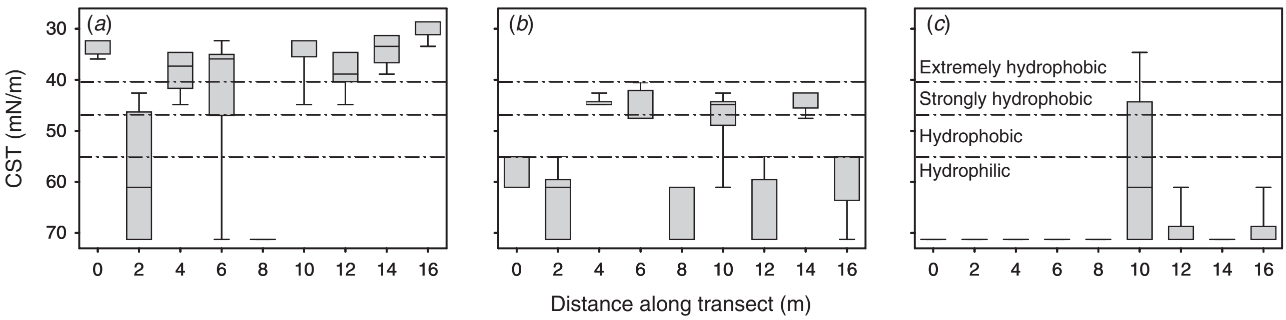

Fig. 1. Soil water repellency on representative pasture transects for varying lengths of time following burning: (*a*) <1 month, (*b*) 1 year, (*c*) >10 years. Repellency expressed as critical surface tension (CST). Boxes indicate the positions of the 25th and 75th percentiles; the bar inside the box shows the median value and the whiskers show the 10th and 90th percentiles. Dashed lines indicate qualitative soil water repellency classes.

Table 4. Soil water repellency as measured *in situ* (MED) for pasture, forest (F), and cropped (C) sites

Site	Time since burning (years)	Mean MED (M)[A]	Max. MED (M)	Mean CST (mN/m)[B]
1	2	1.1 ± 1.6	6.5	60.1 ± 1.9
2	1	1.4 ± 1.1	3.5	54.9 ± 1.5
3	2	1.4 ± 1.3	4	55.8 ± 1.7
4	1	1.1 ± 1.2	4	58.1 ± 1.7
5	10	0.2 ± 0.8	5.5	68.1 ± 0.8
6	8	1.3 ± 1.2	3.5	56.7 ± 1.7
7	6	2.2 ± 1.2	5.5	48.3 ± 1.3
8	6	0.9 ± 1.0	4.5	58.9 ± 1.5
9	8	0.5 ± 0.7	2.5	64.1 ± 1.4
10	4	1.8 ± 1.8	6	54.3 ± 2.0
11	0	4.3 ± 2.7	>8	42.5 ± 2.2
12	0	2.8 ± 1.6	5.5	44.8 ± 1.8
13	0	2.7 ± 1.8	7	46.5 ± 2.6
F1	–	4.3 ± 1.8	6.5	39.3 ± 1.6
F2	–	6.3 ± 1.6	>8	34.1 ± 2.0
C1	–	0.3 ± 0.6	2	67.6 ± 1.6
C2	–	0.6 ± 0.8	2	63.4 ± 2.0

[A]Molarity of Ethanol Droplet value ± 1 standard deviation.
[B]Critical surface tension value ± 1 standard error of mean, computed from MED as per Roy and McGill (2000).

approximately 7 M. Analysis of variance (ANOVA) between recently burned pastures and pastures not recently burned showed that repellency is strongest on the 3 recently burned pastures ($P = 0.002$, Fig. 2).

Fire-induced hydrophobicity on pastures may result from transfer of hydrophobic organic compounds from aboveground biomass to the soil (DeBano *et al*. 1970). Once the hydrophobic material is present, either translocated from burning biomass or present as organic matter/exudates, extreme hydrophobicity can result from the heating and 'fixing' of these compounds (Savage *et al*. 1972).

Temperatures in the 200–250°C range may enhance soil water repellency (DeBano *et al*. 1976). Temperatures just above the soil surface during grass fires have been found to be in the 200–250°C range, briefly reaching

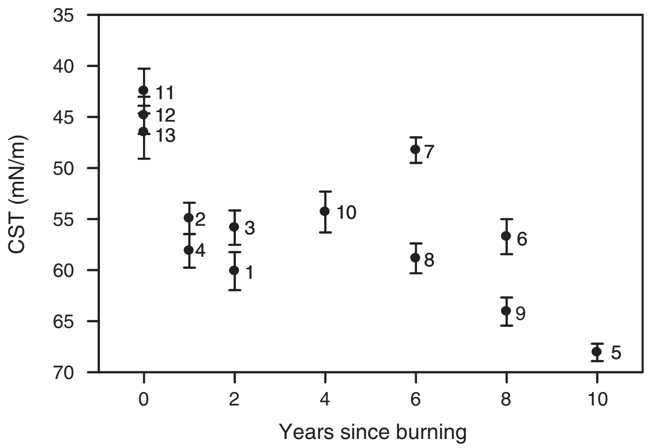

Fig. 2. Soil water repellency *v.* time since burning. Repellency expressed as critical surface tension (CST). Error bars represent standard error of the mean. Data points are labelled by site number (Tables 1 and 4).

a maximum temperature of about 300°C (Scotter 1970). However, soil surface temperatures may exhibit considerable spatial variability due to non-uniform fuel biomass and environmental conditions (Tothill and Shaw 1968). Variability in the pasture-fire fuel load (e.g. live *B. brizantha* and its litter), combined with variations in fire temperatures could lead to the high spatial variability of soil water repellency observed for recently burned pastures (Fig. 1*a*).

The decreasing hydrophobicity in the pastures with time after burning may signify that soil water repellency is a very transient phenomenon. Rainfall can destroy the repellent layer via leaching (Ritsema *et al*. 1998), and splash and rill erosion, which may be severe in fire-induced water repellent soils (Eynard and Lal 2002), could result in a spatially variable loss of the repellent layer. In addition, the mechanical destruction of soil water repellency has been observed (Doerr *et al*. 1998; Hallett *et al*. 2001). On one of our sites, shortly after assessing the water repellency on a recently burned and extremely hydrophobic pasture (pasture 11, Table 4), the pasture was disked. Two days following plowing, water repellency was again assessed, and was found to have been completely eliminated (MED = 0.0 for all microsite locations). This was likely due to the mixing of water repellent surface soil (0–0.01 m) with non-repellent soil of the plow layer (0.01–0.25 m).

Brachiaria brizantha and soil water repellency

Total nutrient concentration in plant tissue is a commonly used index of nutrient status, with the ratio of nitrogen to phosphorus used as a sensitive indicator of the relative limitation of plant growth by the 2 elements (Garten 1976; Chapin and Van Cleve 1989; Koerselman and Meuleman 1996). If either N or P is limiting, growth of *B. brizantha* is limited (Logan *et al*. 2000). A declining N : P ratio may indicate degradation of systems used to produce high-N products such as beef and milk. A decreasing N : P ratio of *B. brizantha* leaf tissues was associated with increasing soil water repellency ($r^2 = 0.66$, $P = 0.004$) (Fig. 3). This may indicate either that (*1*) soil hydrophobicity influences nutrient uptake, or (*2*) P was selectively retained over N during and after burns. Water repellency may interfere with mass transport of mobile nutrients such as nitrate, while exerting a lesser influence over diffusive transport, the primary transport mechanism for phosphate. N-limitations due to pyrodenitrification resulting from repeated burning of biomass (Sanhueza and Crutzen 1998) are also a concern for pasture productivity. Retention of P over N in Amazonian pasture agroecosystems following fires has been observed (Kauffman *et al*. 1998).

The areal coverage of *B. brizantha* was determined for unburned pastures in relation to soil water repellency (Fig. 4). Since *B. brizantha* exhibits a bunching growth habit, only 4.6–30.9% of soil was found to be occupied by *B. brizantha* tufts (Table 1), with bare soil occupying the remaining area. The association between *B. brizantha* coverage and soil water repellency (Fig. 4, $P = 0.06$) may be due to the increased hydrophobicity-inducing potential of a pasture with greater biomass, or preferential occupation of less water repellent soil by *B. brizantha*. No correlation was found between areal coverage of *B. brizantha* and time since burning (Table 3).

Forest and cropped soils

A brief survey of soil water repellency was conducted in primary forests and plots containing annual crops (Table 4). The mineral soil surface in forests had strong or extreme soil water repellency, while exhibiting high spatial variability (Fig. 5). Occasional hydrophilic points within generally hydrophobic microsites were identified (Fig. 5*b*). ANOVA indicated that the strength of repellency was greater on forest soils than on pasture soils ($P = 0.006$). Soil water repellency on forest soils is likely due to leaching of hydrophobic organic acids from decomposing forest litter (Doerr *et al*. 1998). Logging, which is estimated to affect 15 000 km^2/year in the Amazon (Nepstad *et al*. 1994), would likely reduce soil water repellency on forest soils affected by mechanical disturbance of the soil surface by equipment or falling trees.

Soils in cropped plots were not water repellent (average MED = 0.5, Table 4). Cultivation using hoes would likely redistribute any water repellent soil throughout the upper 0.25 m, diluting its effect.

On the MED test

The 2 most common tests for measuring soil water repellency are the MED and the WDPT tests (Doerr *et al*. 2000). Comparisons between the MED test and other methods for

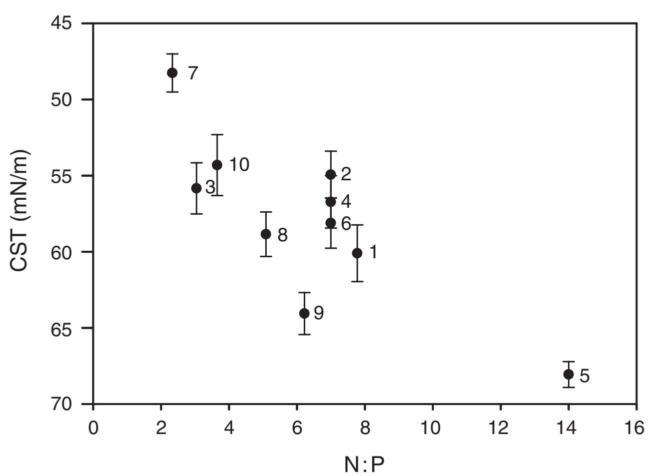

Fig. 3. Soil water repellency *v*. N : P of *Brachiaria brizantha*. Repellency expressed as critical surface tension (CST). Error bars represent standard error of the mean. Data points are labelled by site number (Tables 1 and 4).

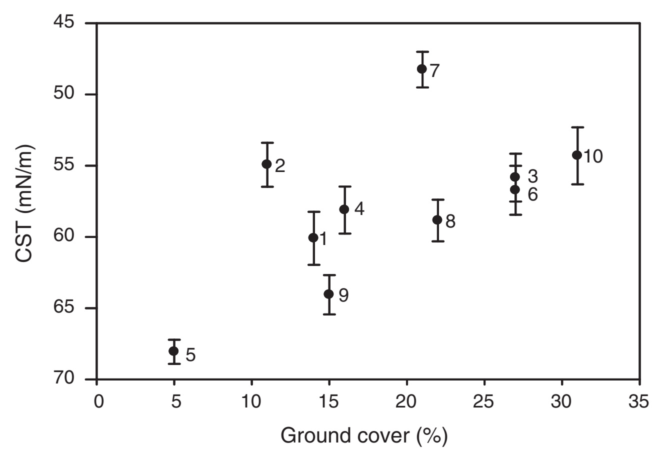

Fig. 4. Soil water repellency *v*. per cent ground cover. Repellency expressed as critical surface tension (CST). Error bars represent standard error of the mean. Data points are labelled by site number (Tables 1 and 4).

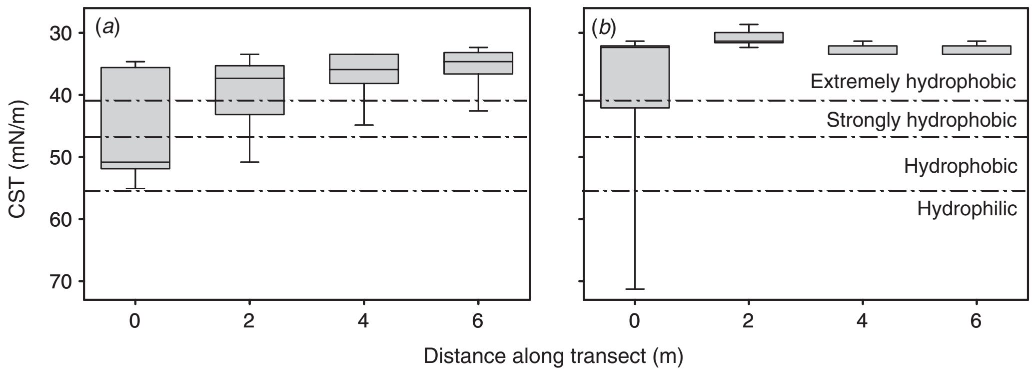

Fig. 5. Forest representative transects. Repellency expressed as critical surface tension (CST). Boxes indicate the positions of the 25th and 75th percentiles; the bar inside the box shows the median value and the whiskers show the 10th and 90th percentiles. Dashed lines indicate qualitative soil water repellency classes.

assessing soil water repellency [e.g. WDPT, apparent contact angle (Letey *et al*. 1962), intrinsic sorptivity repellency index (Wallis *et al*. 1991)] have shown the MED test to produce the most consistent results when applied over a wide range of water repellent soils (Scott 2000; Huffman *et al*. 2001).

Three seconds was used as the critical threshold for droplet infiltration in this study. The critical time of infiltration for MED measurements used by researchers varies from as short as 1–2 s (Scott 2000), to 5 s (Buczko *et al*. 2002) or 10 s (Roy and McGill 2000). The original 5-s threshold was chosen 'arbitrarily' (Watson and Letey 1970, p. 843). The standardised method presented by Doerr (1998), which uses 3 s, appears the most appropriate. This provides a time frame that is readily observable without the infiltration being altered by factors such as decay of hydrophobicity (Doerr 1998).

It should be noted that ethanol solutions differing by 0.2-M increments have been used by a number of researchers (e.g. Roy and McGill 2000). However, larger increments are more convenient for measurements because each droplet influences approximately 1 cm^2 of the soil surface that cannot be subsequently remeasured. Hence, whereas smaller increments may imply increased precision, the spatially variable property of interest is best measured within a smaller physical area, especially when one considers that the smaller increments do not necessarily lead to more meaningful interpretations of soil water repellency (e.g. Table 2).

Comparisons with WDPT

Seven comparisons between the WDPT and the MED tests were made (Fig. 6). In general, there was an excellent correlation between the results of these 2 tests. An outlier apparent in Fig. 6 relates to soil from a microsite with an average MED value of 5 M (extremely hydrophobic), which had an average WDPT of 8 s [slightly water repellent as classified by Dekker *et al*. (2001), hydrophobic as classified by Buczko *et al*. (2002)]. This may be an artefact of our measurements, as the spatial heterogeneity means that soil collected for the WDPT may have been less repellent than the soil that was measured with the MED test in the field. Treating this comparison as an outlier and comparing CST values with log-transformed WDPT values yielded an r^2 of 0.98 ($P < 0.001$).

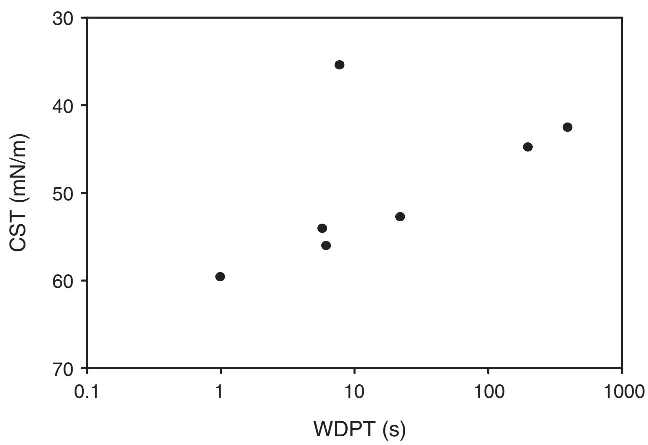

Fig. 6. Comparisons for soil water repellency as assessed by the Water Drop Penetration Time (WDPT) test and critical surface tension (CST) as computed from the Molarity of Ethanol Droplet test.

Conclusions

Soil water repellency is present on Amazonian pasture and forest soils of north-western Mato Grosso, Brazil, during the dry season. The strength of repellency was found to be greatest on recently burned pasture soils, and was generally high for forest soils following 6 weeks without rainfall. The spatial variability of soil water repellency was found to be high on both pasture and forest soils. The rapid decrease in repellency on pastures following burning may be due to a spatial pattern of leaching of hydrophobic compounds coincident with the area between grass tufts, or to erosion of the water repellent layer.

Increasing soil water repellency was found to be associated with a decreasing N : P ratio in above-ground *B. brizantha* tissue, indicating that hydrophobicity may affect biogeochemical cycling of nutrients in pasture agroecosystems. No relationships were found between soil water repellency and the texture or organic matter content of the pasture soils.

High MED values immediately following pasture fires may indicate a possible role of water repellency in pasture degradation. Repellency appears to rapidly dissipate over time following burning of pastures. Disking was found to eliminate soil water repellency on pasture soils.

It remains to be determined if the substances causing soil water repellency in pastures are remnants from the former forest cover on those sites. Further research is needed to determine if soil water repellency is a significant factor in pasture degradation in the Amazon.

Acknowledgments

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