Spatio-temporal patterns of soil water repellency in Portuguese eucalyptus forests and implications for slope hydrology

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Abstract Understanding of the spatial and temporal dynamics of soil water repellency is very limited, despite their importance in determining soil hydrological response. Thus, repeat measurements of *in situ* surface and sub-surface repellency and associated soil moisture content were made on eight occasions over a 16-month period at four sites in *Eucalyptus globulus* plantations of differing stand age (1–10 years) and burn history in north-central Portugal. Key findings are: (a) at all sites, large-scale seasonal variations in repellency occur, which, for the surface soils of the 10-year old site, encompass the transition from entirely wettable to entirely repellent within a period of ≤2 months; (b) when soils are either mostly wettable or mostly repellent, a close inverse relationship with antecedent rainfall and soil moisture exists; however, (c) at other times, no clear relationship between antecedent rainfall and soil moisture is apparent; and (d) the area of soil affected by repellency increases with stand age. The implications of these findings for slope hydrology are discussed.

Key words *Eucalyptus globulus*; overland flow; Portugal; slope hydrology; soil moisture; spatial patterns; temporal patterns; water repellency

INTRODUCTION

Water repellency of soils is a widespread phenomenon (Wallis & Horne 1992), which can reduce soil infiltration capacity, lead to preferential leaching of nutrients (Ritsema *et al.*, 1993), and is thought to enhance runoff responses and soil erosion (Krammes & Osborn, 1968). Its persistence until its breakdown during wet weather, its rate of recovery following the onset of dry weather, and its severity and spatial contiguity, are key factors affecting repellency impacts on slope or drainage basin response to rainfall events (Shakesby *et al.*, 2000; Doerr *et al.*, 2003). The occurrence of repellency is generally thought to follow a seasonal distribution, becoming most extreme during dry periods and declining or disappearing after long wet periods (e.g. Roberts & Carbon, 1971; Crockford *et al.*, 1991). However, conclusive evidence for this distribution is scarce. In addition, its occurrence may not be driven by soil moisture alone (Doerr & Thomas, 2000; Dekker *et al.*, 2001). This paper reports on detailed investigations into the severity and spatio-temporal variations of water repellency in commercial *Eucalyptus globulus* forests in north-central Portugal.

STUDY AREA

The study was carried out at four different sites (Table 1) in *Eucalyptus globulus* stands located in the foothills of the Caramulo Mountains (40°35′N; 8°26′W) in north-central Portugal. This region is highly suited to a study of the seasonal variability of this soil property because: (a) repellency levels under dry summer conditions are amongst the highest reported worldwide (Doerr *et al.*, 1998); (b) earlier work has suggested that the repellency here may vary seasonally (Ferreira *et al.*, 2000); and (c) the wet-Mediterranean climate (annual average rainfall 1379 mm at 190 m a.s.l.) has a strong seasonal pattern with a distinct wet winter (November–February) and a dry, warm summer (June–September). Average monthly temperatures range from 19.8°C in August to 5.8°C in January. Underlain by schist bedrock, the study area is deeply dissected with convexo-rectilinear slopes averaging 20° (Walsh *et al.*, 1995). Soils are shallow (<40 cm depth), stony *Umbric Leptosols* (Pereira & FitzPatrick, 1995) with sandy loam to loamy sand textures (Doerr *et al.*, 1998). Drainage densities are fairly high (4.0 to 4.7 km km^{-2}) and drainage basin response can be very rapid with high peak flows (Walsh *et al.*, 1995). Eucalypts in the area are planted for paper production and are harvested every 9–12 years. These forests are highly flammable and the region has experienced repeated forest fires since the mid-1980s.

METHODS

At each of the four sites, *in situ* repellency was assessed at the soil surface and at depths of 10 and 20 cm for 60 points, allocated on a 10 m × 18 m grid with 2 m intervals. This was carried out on eight occasions over a 16-month period (August 2000, and February, April, May, June August, October and November 2001), providing a total of 1440 measurements per site. To enable necessarily destructive repeat measurements to be undertaken, around each grid point a clockwise pattern of sampling (diameter 1.2 m) was adopted. Repellency was assessed following removal of leaf litter and humus, using the % ethanol method as described in Doerr *et al.*, (1998). Water drops with increasing ethanol content were applied to the soil until the solution was concentrated enough (i.e. surface tension low enough) to overcome repellency and at least 3 of 5 droplets of the same concentration infiltrated within 3 s

Table 1 Study site characteristics.

Stand: age[*]	height (m)	Land management history	Aspect	Slope angle (°)	Altitude (m a.s.l.)	Litter depth[†] (cm)
10 years	8–10	Seedlings planted in undisturbed soils	NNW	8.0	430	10.4
5 years	5–8	Regrowth from stumps from previous harvest	NW	6.5	430	7.8
1 years	1–2	Seedlings planted in deep ploughed soils	SSE	10.8	260	0.6
9 months	1–2	Regrowth from stumps after fire in March 00	ESE	7.4	180	3.9

[*] Estimated age with respect to 1 January 2001.

[†] Average values (n = 480).

Table 2 % Ethanol concentration increments and descriptive classes used in this study.

% Ethanol	0	1	2	3	5	8.5	13	18	24	36	50	>50
Class	Wettable	Low		Moderate				Severe		Extreme		

(Crockford *et al.*, 1991). Ethanol concentrations used and associated descriptive classes are given in Table 2. Volumetric soil moisture was assessed at each repellency measurement point using Time Domain Reflectometry (TDR). Daily rainfall data were collected at a gauge at 200 m a.s.l., <3 km from the study sites.

RESULTS AND DISCUSSION

The results presented in Fig. 1 and Table 3 demonstrate that: (a) the spatial frequency of repellency has a seasonal distribution (% of repellent points); (b) that repellency is at its most extreme during dry periods, but declines or disappears when soil moisture is high; and (c) that repellency is re-established as soils dry out. For example, for the surface soils of the 10-year old eucalyptus site, the spatial frequency of repellency varies from 0% (i.e. all samples wettable), to 100% (all samples repellent),

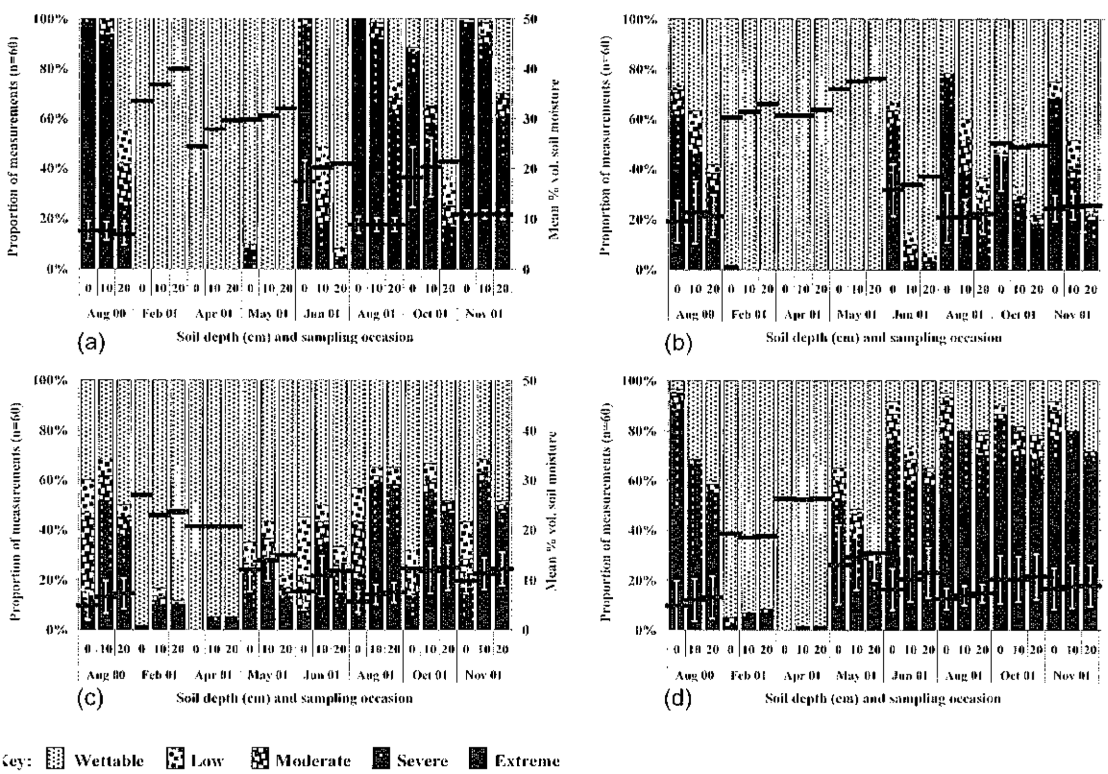

Fig. 1 Spatial frequency of repellency at each site and depth on each sampling occasion shown by percentage of measurement points in each repellency class. Mean % vol. soil moisture (horizontal bars) and one std dev. (vertical lines) are superimposed on the compound bars. (a) 10 years, (b) 5 years, (c) 1 year, (d) 9 months.

Table 3 Variations in the percentage of points at which repellency was recorded (for all depths combined and for each depth separately) at the four sites in relation to mean soil moisture (for all depths combined) and 2-week and 8-week antecedent precipitation.

(a) 10-year old *Eucalyptus globulus*

Date	Mean % vol. soil moisture (n = 180)	Antecedent precipitation (mm)* 2-week	8-week	% of repellent points all depths (n = 180)	0/10/20 cm (n = 60)
Feb 01	36.7	241–305	763–764	0	0-0-0
May 01	30.7	62	244–279	3	10-0-0
Apr 01	27.2	43	536	0	0-0-0
Oct 01	19.9	72–76	138	63	88-65-37
Jun 01	19.4	4	176	52	100-48-8
Nov 01	10.9	3	237	89	100-98-68
Aug 01	8.8	5	57	91	100-98-75
Aug 00	7.3	6	95	85	100-100-55

(b) 5-year old *Eucalyptus globulus*

Date	Mean % vol. soil moisture (n = 180)	Antecedent precipitation (mm)* 2-week	8-week	% of repellent points all depths (n = 180)	0/10/20 cm (n = 60)
May 01	37.2	130–138	298–301	0	0-0-0
Feb 01	31.5	141	767	1	2-0-0
Apr 01	31.1	64	536	0	0-0-0
Oct 01	24.7	75	136	35	47-35-22
Jun 01	17.1	4	176	30	67-15-7
Nov 01	12.5	3	237	50	75-52-23
Aug 01	10.6	15	67	58	78-60-37
Aug 00	10.5	6	94	59	73-63-42

(c) 1-year old *Eucalyptus globulus*

Date	Mean % vol. soil moisture (n = 180)	Antecedent precipitation (mm)* 2-week	8-week	% frequency of repellent points all depths (n = 180)	0/10/20 cm (n = 60)
Feb 01	24.4	276–337	743–755	10	2-17-12
Apr 01	20.6	125	572	3	0-5-5
May 01	13.6	31–34	251	33	35-43-22
Oct 01	12.1	90	115–125	50	32-67-52
Nov 01	11.0	0	242	54	43-68-52
Jun 01	10.0	0	172	43	45-50-33
Aug 01	6.7	1–12	52	62	57-65-65
Aug 00	6.2	7–9	96–98	59	60-68-50

(d) Recently burnt 9-month old *Eucalyptus globulus*

Date	Mean % vol. soil moisture (n = 180)	Antecedent precipitation (mm)* 2-week	8-week	% of repellent points all depths (n = 180)	0/10/20 cm (n = 60)
Apr 01	26.3	125	556	1	0-2-2
Feb 01	18.9	148	760	7	5-7-8
May 01	14.3	30–32	242–253	48	65-48-52
Oct 01	10.3	54	115	83	90-82-78
Jun 01	9.9	0	172	77	92-73-65
Nov 01	8.6	3	237	82	92-82-72
Aug 01	6.8	6	57	85	95-80-80
Aug 00	5.8	8–9	99	75	97-68-60

* Rainfall data given are for a gauge at 200 m a.s.l. Due to differences in altitude, the 10-year, 5-year and 1-year-old sites are predicted (Walsh *et al.*, 1995) to receive an additional 14.5%, 14.5% and 3.8%, respectively, and the recently burnt site a reduction of 1.3% of the rainfall received at this gauge. Inter-site variations in antecedent precipitation occur due to sampling over several days and within-site variations occur when sampling for a given site took more than 1 day to complete and rain fell over the sampling period.

over a period of two months (April–August 2001). The sampling occasions when the soil is predominantly or entirely wettable coincide with the highest mean soil moisture and highest antecedent rainfall (February, April and May 2001) and conversely the periods of greatest spatial frequency are recorded when mean soil moisture and antecedent rainfall are lowest (August 2000 and 2001 and November 2001). Thus, when the spatial frequency of repellency is extremely high or extremely low, it varies inversely with soil moisture and antecedent rainfall.

During the majority of sampling occasions, an increase in the spatial frequency of repellency with stand age was recorded for the three unburnt sites (Fig. 1). This may reflect differences in the rate of supply of repellent substances with age of eucalyptus stand. Doerr *et al.*, (1998) have indicated that eucalyptus litter and root networks are potential sources of repellent substances, both of which increase with stand age in respective thickness and extent. The relatively high spatial frequency of repellency at the burnt site may result from the high stand age prior to burning (10 years) and further input of hydrophobic substances from the burning litter layer (DeBano & Krammes, 1966).

In contrast to the occasions when the spatial frequency of repellency is extremely high or low, at an intermediate level (June and October 2001), a more complex pattern of repellency with soil moisture and rainfall is apparent. At all four sites, repellency extent is greater in October than in June, despite: (a) mean soil moisture being similar or higher in October as in June, and (b) a greater 2-week antecedent rainfall for October than June. For example, at the 10-year old site, mean soil moisture levels are 19.4 and 19.9% vol. in June and October, respectively, 2-week antecedent rainfall is higher in October (72–76 mm) than in June (4 mm) and yet repellency extent is greater in October (63%) than in June (52%). This pattern is further accentuated at 10 and 20 cm depths at each site. Thus for a given soil moisture of 19% vol., repellency extent is greater following recent rainfall than dry antecedent conditions. This apparently anomalous pattern could be explained by the "transition zone" concept in the soil moisture/repellency relationship introduced by Dekker *et al.* (2001). It suggests that between an upper soil moisture threshold (above which soils are repellent) and a lower threshold (below which soils are wettable), soils may be repellent or wettable. Dekker *et al.* (2001) suggested upper and lower thresholds of 23% and 18% vol., respectively, for Dutch surface dune sands, which would be consistent with the 19% soil moisture content discussed above.

IMPLICATIONS FOR SLOPE HYDROLOGY

The above results have important implications with respect to the impact of soil water repellency on infiltration and slope runoff processes. In the 1- and 5-year old stands, the presence of a considerable proportion of wettable soils, even when the spatial frequency of repellency is at its recorded maximum, would normally provide numerous sinks to prevent any local overland flow generated on repellent patches from travelling far downslope. This may help to explain why drainage basin responses to rainstorms recorded in areas dominated by younger eucalyptus in the study area were so muted, when runoff responses from small plots were comparatively high (Walsh *et al.*, 1995; Ferreira *et al.*, 2000). In contrast, at the 10-year old site, spatially contiguous repellency was found following dry antecedent weather (surface and 10 cm depth) and near contiguous repellency was recorded at the surface layer of the recently burnt site. In the 10-year-old forest, although surface repellency following long dry periods is indeed high and spatially contiguous, substantial overland flow on slope scales is also unlikely to occur due to: (a) the storage capacity of the thick litter cover which is present under older eucalyptus stands, and (b) the presence of macropores, which may allow preferential flow through the repellent soil matrix. Thus in storms following prolonged dry periods, overland flow responses failed to exceed 3% of storm rainfall, even for small runoff plots in an 8-year old stand in the study area (Walsh *et al.*, 1995). While soil water repellency is unlikely to result in slope-scale overland flow events in unburnt terrain in this environment, its presence may concentrate surface water to enter the soil via the sinks provided by wettable soil patches and macro-pores and may lead to faster, more direct percolation than in wettable-phase conditions. This may help to explain why the streamflow responses following dry conditions in the study area are significantly quicker than following wetter antecedent conditions (Doerr *et al.*, 2003). For the burnt site, the near contiguous repellency is likely to result in enhanced slope-scale overland flow responses to rainstorms following dry periods, due to the absence of litter cover and, possibly, a reduction in the frequency of macropores associated with slopewash.

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REFERENCES

Crockford, H., Topalidis, S. & Richardson, D. P. (1991) Water repellency in a dry sclerophyll eucalypt forest—measurements and processes. *Hydrol. Processes* **5**, 405–420.

DeBano, L. F. & Krammes, J. S. (1966) Water repellent soils and their relation to wildfire temperatures. *Int. Assoc. Hydrol. Sci.* **2**, 14–19.

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.

Doerr, S. H., Ferreira, J. D. A, Walsh, R. P. D., Shakesby, R. A., Leighton-Boyce, G. & Coelho, C. O. A. (2003) Soil water repellency as a potential parameter in rainfall-runoff modelling: experimental evidence at point to catchment scales from Portugal. *Hydrol. Processes* (in press).

Doerr, S. H., Shakesby, R. A. & Walsh, R. P. D. (1998) Spatial variability of soil repellency in fire-prone eucalyptus and pine forests, Portugal. *Soil Sci.* **163**(4), 313–324.

Doerr, S. H. & Thomas, A. D. (2000) The role of soil moisture in controlling water repellency: new evidence from forest soils in Portugal. *J. Hydrol.* **231–232**, 134–147.

Ferreira, A. J. D., Coelho, C. O. A., Walsh, R. P. D., Shakesby, R. A., Ceballos, A. & Doerr, S. H. (2000) Hydrological implications of soil-water repellency in *Eucalyptus globulus* forests, north-central Portugal. *J. Hydrol.* **231–232**, 165–177.

Krammes, J. S. & Osborn, J. (1968) Water-repellent soils and wetting agents as factors influencing erosion. (Proc. Symp. Water-Repellent Soils, 1968), 177–187.

Pereira, V. & FitzPatrick, E. A. (1995) Cambisols and related soils in north-central Portugal: their genesis and classification. *Geoderma* **66**, 185–212.

Ritsema, C. J., Dekker, L. W., Hendrickx, J. M. H. & Hamminga, W. (1993) Preferential flow mechanisms in a water repellent sandy soil. *Wat. Resour. Res.* **29**, 2183–2193.

Roberts, F. J. & Carbon, B. A. (1971) Water repellence in sandy soils of south-western Australia. I. Some studies related to field occurrence. *Division of Plant Industry CSIRO (Australia). Field Station Record* **10**, 13–20.

Shakesby, R. A., Doerr, S. H. & Walsh, R. P. D. (2000) The erosional impact of soil repellency: current problems and future research directions. *J. Hydrol.* **231–232**, 178–191.

Wallis, M. G. & Horne, D. J. (1992) Soil water repellency. *Adv. Soil Sci.* **20**, 91–146.

Walsh, R. P. D., Coelho, C. de O. A., Shakesby, R. A., Ferreira, A. D. J. & Thomas, A. D. (1995) Post-fire land use and management and runoff responses to rainstorms in northern Portugal. In: *Geomorphology and Land Management in a Changing Environment* (ed. by D. McGregor & D. Thompson), 283–308. Wiley, Chichester, UK.