Available online at www.sciencedirect.com

SCIENCE DIRECT®

Journal of Hydrology 319 (2006) 295–311

Journal of Hydrology

www.elsevier.com/locate/jhydrol

Effects of differing wildfire severities on soil wettability and implications for hydrological response

S.H. Doerr[a,*], R.A. Shakesby[a], W.H. Blake[b], C.J. Chafer[c], G.S. Humphreys[d], P.J. Wallbrink[e]

[a]*Department of Geography, University of Wales Swansea, Singleton Park, Swansea SA2 8PP, UK*
[b]*School of Geography, University of Plymouth, Drake Circus, Plymouth PL4 8AA, UK*
[c]*Science and Research, Sydney Catchment Authority, Cordeaux Office, PO Box 323 Penrith 2751, NSW 2560, Australia*
[d]*Department of Physical Geography, Macquarie University, North Ryde, Sydney, NSW 2109, Australia*
[e]*CSIRO Land and Water, P.O. Box 1666, ACT 2601, Australia*

Received 22 October 2004; revised 13 June 2005; accepted 28 June 2005

Abstract

Fire-induced or enhanced soil water repellency is often viewed as a key cause of the substantial increases in runoff and erosion following severe wildfires. In this study, the effects of different fire severities on soil water repellency are examined in eucalypt forest catchments in the Sandstone Tablelands near Sydney, burnt in 2001 and 2003. At sites affected by different fire severities and in long-unburnt control sites, repellency persistence was determined in situ and in the laboratory for surface and subsurface soil samples ($n=846$) using the Water Drop Penetration Time (WDPT) test. All long-unburnt samples were found to be water repellent, with severe to extreme persistence (>900 s) being dominant for surface (0–2.5 cm) and slight to moderate persistence (10–900 s) for subsurface (2.5–5 cm) soil, indicating naturally very high 'background' levels of repellency. In contrast to the generation or enhancement of repellency usually reported following forest fires of similar severity in previous studies, burning caused widespread destruction of repellency. The mineral soil depth to which repellency was destroyed (0.5–5 cm) was found to increase with burn severity. Below this charred wettable layer, persistence of pre-existing water repellency increased. Two years after the fire, the frequency of extreme repellency persistence was reduced in the surface and subsurface. However, recovery to pre-fire repellency levels had not been achieved.

The associated hydrological impacts of these fire effects are more complex than simply the enhancement of overland flow, runoff and soil erosion with increasing fire severity. For forest fires sufficiently severe to remove foliage and ground litter above already repellent soil, a more severe burn, in which there is destruction of surface soil repellency, would result in lower runoff response compared to a burn insufficiently severe to destroy surface repellency. During storms intense enough to saturate the wettable surface rapidly, this layer may, however, be removed by overland flow, with potentially severe implications for soil fertility and seedbed survival, post-fire ecosystem recovery, and downstream sedimentation and water quality.

The results demonstrate that existing fire severity classifications are not well suited to predicting fire impacts on soil hydrological responses and highlight the need for a new fire severity evaluation scheme. A scheme encompassing not only

---

* Corresponding author. Tel.: +44 1792 295147; fax: +44 1792 295955.
E-mail address: s.doerr@swansea.ac.uk (S.H. Doerr).

doi:10.1016/j.jhydrol.2005.06.038

foliage and ground cover status, but also changes to surface and subsurface soil hydrological properties, would provide a better prediction of the immediate hydrological effects of wildfires on catchments such as flash flooding and erosion, and also of their time-to-recovery than current classifications allow. Such a scheme could prove invaluable given the future increase in fire frequency and severity predicted for many regions.

Keywords: Soil water repellency; Water repellence; Hydrophobicity; Wildfire; Fire severity; Fire frequency; Flooding; Erosion; Eucalyptus

1. Introduction

Fire-induced soil water repellency (hydrophobicity) is commonly viewed as one of the main causes of the substantial increases in hillslope runoff and erosion observed following wildfire (e.g. Sartz, 1953; Swanson, 1981; Morris and Moses, 1987; Scott and Van Wyk, 1990; Shakesby et al., 1993; Andreu et al., 1996; Inbar et al., 1997; Robichaud and Brown, 1999). Forestry personnel have often noted the presence of repellency after fire and, in studies conducted primarily in chaparral shrubland and coniferous forests in the western USA, repellency was found to be induced, or considerably intensified, by wildfire. These studies showed that repellency was typically either absent or relatively weak prior to burning or in unburnt control sites, and strongly enhanced in the topsoil or in the soil just below it after the fire (DeBano, 2000a,b). In a detailed laboratory study, DeBano and Krammes (1966) demonstrated that the soil temperature reached during burning was critical in determining post-fire soil wettability. They heated slightly repellent Californian chaparral soil for 5–20 min and found that repellency changed little at soil temperatures below 175 °C, increased considerably at 175–200 °C, and was destroyed at 280–300 °C. That 'the heat during a fire markedly changes and intensifies water repellency' (DeBano, 1981:5) became an accepted axiom for wildfires in general. DeBano (1991) suggested that heating any wettable soil with more than 2–3% organic matter would induce repellency. Whilst the general applicability of the latter has yet to be established, destruction temperatures for repellency between 250 and 350 °C have been confirmed in laboratory studies for soil samples from chaparral and coniferous forest from the western USA (Savage, 1974; Scholl, 1975; DeBano et al., 1976; Robichaud and Hungerford, 2000), Australian eucalypt forests (Doerr et al., 2004) and Spanish pine stands (García-Corona et al., 2004). When longer heating times were used, changes in repellency occurred near the lower end of this temperature range (DeBano and Krammes, 1966; Doerr et al., 2004). Heating is thought to induce or increase repellency by (i) volatilization of certain organic compounds in the litter and topsoil and their subsequent condensation onto soil particles (DeBano and Krammes, 1966), (ii) polymerization of organic molecules into more hydrophobic ones (Giovannini and Lucchesi, 1983), (iii) improved bonding of such substances to soil grains (Savage, 1974), and (iv) the melting and redistribution of waxes from interstitial organic matter onto soil aggregates and mineral grains (Franco et al., 2000). Elimination of repellency around 300 °C is probably caused by the volatilization and combustion of organic compounds (DeBano et al., 1976; Chandler et al., 1983). With depletion of oxygen during a fire, organic compounds are pyrolized rather than combusted (oxidized). In such cases, the temperature at which repellency is destroyed may be as high as 500–600 °C (Bryant et al., in press).

Many post-fire hydrological studies of the last few decades, including those in eucalypt forests, have suggested that moderate or high repellency levels result from burning (e.g. O' Loughlin et al., 1982; Mitchell and Humphreys, 1987; Shakesby et al., 1993). High repellency levels, however, can also be found in unburnt terrain (see reviews by DeBano, 2000b; Doerr et al., 2000a), and the aforementioned laboratory studies have shown that heat-induced changes to repellency can vary greatly depending on pre-fire repellency levels and fire severity (or, more specifically, the associated soil temperatures and their duration). For example, even in unburnt or long-unburnt locations, soils under a range of eucalypt species exhibit some of the highest reported repellency levels (Crockford et al., 1991; Burch et al., 1989; Doerr et al., 1998; Scott, 2000). In studies examining the effects of forest fires, it is thus not always clear whether the repellency levels observed are actually a product of the burn.

Wildfires near Sydney, Australia, during the southern hemisphere summers of 2001 and 2003 affected large areas of native eucalypt forest at variable levels of fire severity (Shakesby et al., 2003; Chafer et al., 2004), providing an opportunity to examine the effects of different fire severities on soil water repellency in otherwise undisturbed eucalypt terrain. This paper reports on surface and subsurface wettability measurements carried out both in situ and on homogenized bulk soil samples in the laboratory in order to establish the (i) 'background' levels of water repellency in long-unburnt soils, and (ii) effects of burning on the water repellency levels for eucalypt catchments in this region affected by different fire severities. Results are discussed in the context of post-fire studies conducted elsewhere and evaluated regarding their implications for soil hydrological response.

2. Study region

The study was carried out in the Nattai Tablelands 70 km south–west of Sydney (Fig. 1), burnt by an extensive wildfire over a two-week period beginning in late December 2001. This area was chosen because fire severity had been variable, some long-unburnt forest patches escaped burning, a detailed fire history was available, and, being Sydney's principal water supply catchment, much of the area has been protected by legislation from logging and other anthropogenic disturbance for over 30 years (Chafer et al., 2004).

The bedrock comprises mainly quartzitic Hawkesbury Sandstone and stream incision has produced canyons and gorges with intervening ridges and gently-sloping plateaux (denoting more resistant sandstone beds). In the study reach, ridge tops typically lie close to c. 500 m a.s.l., while the valley floor extends to below 300 m. Soils range in texture from sands to sandy loams, except in some sheltered locations, where sandy clay loams occur. On ridge tops, the vegetation comprises open dry eucalypt woodland, with *Eucalyptus sieberi* and *Corymbia gummifera* and an associated *Proteaceae* and *Myrtaceae* shrub understorey. *E. deanei* and *Corymbia eximia* become dominant downslope and on moist valley floors. The climate is humid temperate with moist summers and cool winters and no marked dry season. The long-term mean annual rainfall is

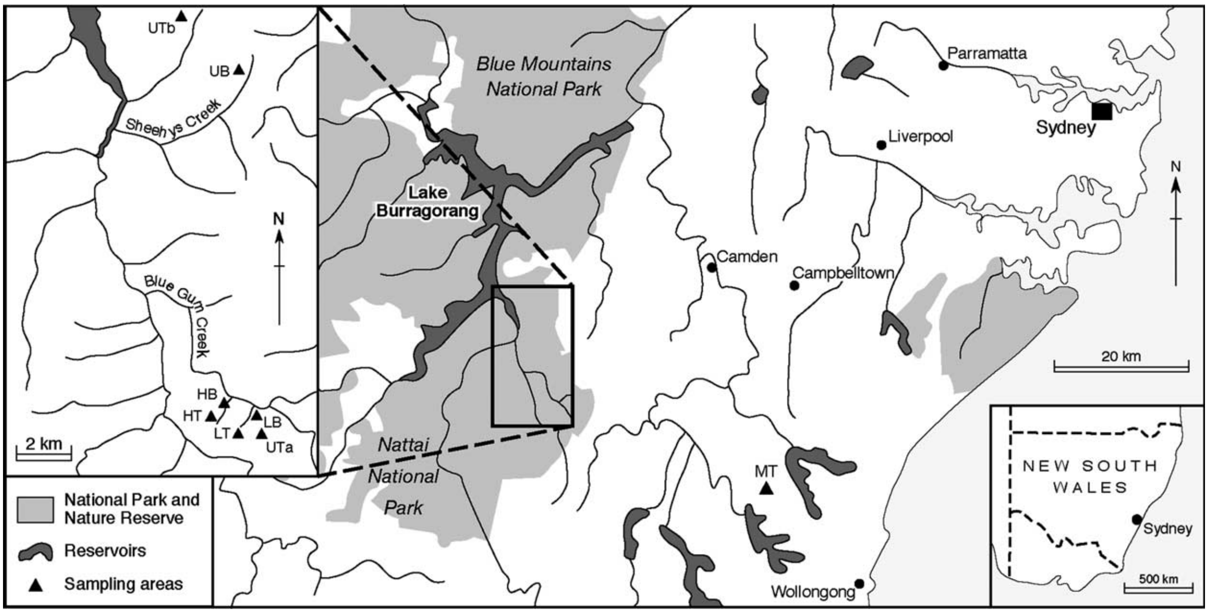


Fig. 1. Study region with study site locations.

900–1000 mm, with extremes of 400 and 1600 mm. There is a late summer rainfall maximum and a minimum in August–September (Bureau of Meteorology, 1991).

3. Research design and methods

3.1. Classification of fire severity for the study area

A fire severity analysis, based on the degree of vegetation and ground fuel destruction (e.g. Chandler et al., 1983; Moreno and Oechel, 1989), was undertaken by the Sydney Catchment Authority using multi-temporal satellite imagery and field-based measurements (Chafer et al., 2004). SPOT satellite images were obtained for the study region relating to the immediate pre-fire and post-fire periods. The Normalised Difference Vegetation Index (NDVI) for the two images was calculated and a difference image of the two dates computed, which provided direct comparison of burnt and unburnt states, allowing calculation of fire severity (Chafer et al., 2004). From these and pre-existing data on the pre-fire fuel load (i.e. above-ground vegetation and litter), the amount of fuel available and burnt in the study area and the fire severities were estimated and cross-checked with on-site post-fire ground examinations (Table 1). The latter consisted of sampling 342 GPS-located sites scattered over most of the burnt area in the Sydney region and fire damage to the vegetation was assessed according to the descriptions in Table 2. The site differential NDVIs were extracted into a GIS with a resulting classification accuracy of $>87\%$ (Chafer et al., 2004) as determined by the assessment method described in Congalton and Mead (1983). A six-class fire severity scheme (unburnt, low, moderate, high, very high, extreme) was derived (Table 1).

3.2. Study sites, soil sampling and sample preparation

Two small catchments on the western side of Blue Gum Creek with similar slopes, aspects and vegetation, but differing burn severities from the December 2001 fire, formed the main study sites (Fig. 1). Catchment H (63 ha) was affected mainly by moderate to extreme, and catchment L (89 ha) mainly by low to moderate fire severity. Catchment characteristics are summarized in Table 2. To ensure that post-fire erosion effects would not affect the investigation, at the onset of fieldwork in May 2002 sites were selected in low-angle slope positions (<10 °) in ridge-top (sample codes HT and LT) and "base of slope" locations (sample codes HB and LB). The steeper slopes were avoided as signs of post-fire erosion were evident. In addition, sampling was restricted to sites with an undisturbed ash layer and/or downslope of obstacles providing protection from erosion and deposition (e.g. logs and rock outcrops) (cf. Leitch et al., 1983). Long-unburnt sites with similar soil and vegetation characteristics to these catchments were sampled to determine likely pre-fire 'background' repellency levels. Only one suitable 'control' site (UTa) near the burnt catchments could be found, but two further comparable long-unburnt sites were selected north of the catchments (sites UTb and UB; see Fig. 1). Sampling at these control sites

Table 1
Fire severity and estimated intensity rating for eucalypt-dominated sclerophyll vegetation communities in south–eastern Australia (modified from Chafer et al., 2004)

Severity rating	Fire intensity[a] (kWm^{-1})	Max. flame height (m)	Typical severity characteristics
Low	<500	1.5	Only ground fuel and shrubs <2 m burnt
Moderate	501–3000	5.0	All ground fuel and shrub vegetation <4 m consumed by fire
High	3001–7000	10.0	All ground and shrub vegetation consumed by fire and lower tree canopy <10 m scorched
Very high	7000–70,000	10–30	All green vegetation including tree canopy to 30 m, and woody vegetation <5 mm diameter consumed by fire
Extreme	70,000–100,000+	20–40	All green and woody vegetation <10 mm diameter consumed by fire

[a] The fire intensity index, as defined by Byram (1959).

Table 2
Characteristics and sampling dates for all study sites

Site code[a]	UTa and b	UB	HT	HB	MT	LT	LB
Site name	Ridgeroad a and b	Sheehys Creek	Catchment H		Cataract	Catchment L	
UTM coordinates	S (a) 34° 14′ 12″ (b) 34° 06′ 12″ E (a) 150° 29′ 35″ (b) 150° 28′ 14″	S 34° 08′ 00″ E150° 29′ 23″	S 34° 13′ 21″ E 150° 28′ 53″	S 34° 3′ 11″ E 150° 29′ 35″	S 34° 18′ 4″ E 150° 46′ 8″	S 34° 13′ 56″ E 150° 29′ 26″	S 34°13′ 47″ E 50°30′19″
Dominant vegetation[b]	*E. creba*, *globoidea*, *punctata*; *B. serrata*	*E. eugenoides*, *piperita*, *gummifera*, *sieberi*; *A. linifolia*	*E. creba*, *globoidea*, *punctata*; *B. serrata*	*E. deanei*, *piperita*; *C. eximia*	*E. sclerophylla*, *piperita*, *seiberi*; *B. serrata*	*E. creba*, *globoidea*, *punctata*; *B. serrata*	*E. deanei*, *piperit*; *C. eximia*
Last wildfire	1968 (a), 1965 (b)[c]	1965	Dec. 2001	Dec. 2001	Jan. 2003	Dec. 2001	Dec. 2001
Burn severity	not known	not known	moderate–extreme	moderate–extreme	moderate–high	low–moderate	low–moderate
Sampling date	April 2001	Jan. 2003	April 2001, Jan. 2002, Feb.2003	April 2001	Jan. 2003	April 2001	April 2001
Soil texture (∼0–2 cm)[d]	87.4, 12.0, 0.6	81.9, 16.8, 1.3	91.4, 8.3, 0.3	91.3, 8.3, 0.5	82.3, 16.4, 1.3	89.0, 10.4, 0.5	78.7, 19.0, 2.3
Soil texture (∼2–5 cm)[d]	86.8, 12.4, 0.8	78.7, 19.4, 1.9	89.5, 9.9, 0.6	83.1, 15,2, 1.6	82.5, 16.0, 1.5	82.5, 15.8, 1.7	76.5, 21.2, 2.3

[a] First letter denotes, U: long-unburnt, H: higher burn severity, L: lower burn severity, R: recent burn; second letter denotes T: ridge-top position, B: base of slope position.

[b] A: *Acacia*; B: *Banksia*; C: *Corymbia*; E: *Eucalyptus*.

[c] Percentage sand, silt, clay; average of three measurements on each of five samples using a Coulter Lasersizer LS230.

[d] Controlled hazard reduction burns may have affected site UTa in 1971 and 1993, and site UTb in 1985.

was carried in similar slope positions to those of burnt sites (ridge-top: UT; base of slope: UB). A fire in January 2003 provided the opportunity to investigate an additional site only a few days after burning and before any post-fire rainfall. This site (MT), located c. 30 km south–east of the study catchments (Fig. 1), lies in a ridge-top position subjected to moderate to high burn severity, intermediate to severity levels found in catchments H and L.

To explore the longevity of fire effects on soil wettability, repeat sampling for laboratory repellency testing was conducted at the severely burnt site HT approximately one and two years (13 and 25 months) after burning, in ridge-top positions not previously sampled.

At all burnt sites, areas 4–6 m^2 in extent that were undisturbed by erosion were selected and, at three positions at least 0.3 m apart, ash was carefully removed to expose the mineral soil surface. Repellency was then determined, as described below, at the surface of (i) the ‘charred’ mineral topsoil soil (dark colour) and (ii) the underlying uppermost ‘un-charred’ soil layer (pale colour), and the depth of the boundary between them recorded. Charred surface soil material (usually 1–2 cm thick) and ‘un-charred’ subsurface soil (usually to 5 cm depth) was then placed in sealed plastic bags. Samples generally felt dry when collected, but were also subjected to air-drying for several days within a day of sampling, and then carefully passed through a 2 mm sieve to homogenize the material and remove stones and large organic debris. Before laboratory analysis, samples were conditioned at 20 °C and 45–55% relative humidity to ensure that repellency levels would not be affected by changes in atmospheric conditions (Doerr et al., 2002).

Sampling procedures at long-unburnt sites were similar to those at burnt sites after litter and organic material had been carefully removed. As fire-induced changes in colour were absent, soil material was taken from depths of 0–2 and 2–5 cm to match broadly the sampling depths at burnt sites. Further processing was carried out as described above. Re-sampling of site HT one and two years after burning (respectively, codes HT-03 and HT-04) was carried out as for the first post-fire sampling programme, except that time constraints permitted only laboratory analysis.

3.3. Water repellency determination and data analysis

Water repellency was measured using the Water Drop Penetration Time (WDPT) technique (Wessel, 1988; Doerr, 1998) at field sites and in the laboratory. (The only exception was site UT, for which only laboratory testing was carried out due to time constraints during sampling.) In the field, three drops of water (~80 µl each) were placed on the soil at each sampling point. Where all drops infiltrated in ≤5 s, the soil was classed as wettable (Bisdom et al., 1993). Where all drop penetration times exceeded 5 s, the soil was classed as water repellent. Where all three drops did not penetrate in the same time category, the soil was classed as intermediate. At a few sampling points, soils were noticeably damp and the results were accordingly rejected as soil moisture might have exceeded the critical threshold at which repellency disappears (Dekker et al., 2001). Excluding 14 moist samples, a total of 438 surface and 425 subsurface points were classified as being wettable, intermediate or repellent.

Laboratory analysis using the WDPT test under controlled atmospheric conditions (20 °C, 45–55% relative humidity) allowed a more standardized and detailed discrimination of samples into different degrees of repellency. Three drops of distilled water (~80 µl each) were carefully placed onto the sample surface and the time for complete droplet penetration noted using WDPT time intervals extended from those used by Bisdom et al. (1993) (Table 3). These allow classification into essentially arbitrary, but widely used repellency persistence classes, with associated descriptive repellency ratings ranging from wettable (WDPT≤5 s) to extremely repellent (WDPT>3600 s). Unlike measures of water repellency severity (i.e. apparent overall soil surface tension, γ_s) as determined by, for example, contact angle, capillary rise or Critical Surface Tension (CST) measurements (Letey et al., 2000), repellency persistence is a relative measure indicating how long repellency persists in the contact area of a water droplet. Although none of the above methods reflects accurately the extent to which infiltration of rainfall or overland flow generation is affected by a given repellency level in field soils (Doerr et al., 2003), repellency persistence as determined by the delay of water droplet infiltration (i.e. WDPT) is considered the most hydrologically relevant of the above (Wessel, 1988). The median WDPT class of the three drops was taken as representative of the sample repellency level (Table 3).

A methodological issue worth highlighting is the discrepancy of field and laboratory WDPT results (Figs. 2 and 3). The proportions of wettable and repellent samples differ between these sample sets. Potential factors leading to different repellency levels include: (i) differing soil moisture contents amongst field samples, (ii) laboratory data represent an average WDPT of a bulked soil layer, whereas field testing was conducted on the surface of an in situ layer, (iii) laboratory samples underwent homogenization and removal of >2 mm mineral and organic matter associated with sieving. As laboratory treatments provide a greater degree of sample standardization and thus better comparability of datasets, statistical analysis was performed using laboratory WDPT results. These also allowed discrimination in different degrees of water repellency. The Kolmogorov–Smirnov two-sample test (Matthews, 1981) was used, unless stated otherwise, to test the significance ($p<0.05$) of differences in water repellency presence and, where appropriate, also in degrees of repellency between sample populations from (i) different burn severities, and (ii) different times since burning.

Table 3
WDPT class increments used (upper time limit in seconds) and corresponding descriptive repellency persistence rating

WDPT classes (s)	≤5	10, 30, 60	180, 300, 600	900, 1800, 3600	10,800, 18,000, >18,000
Repellency rating[a]	wettable	slight	strong	severe	extreme

[a] after Bisdom et al. (1993).

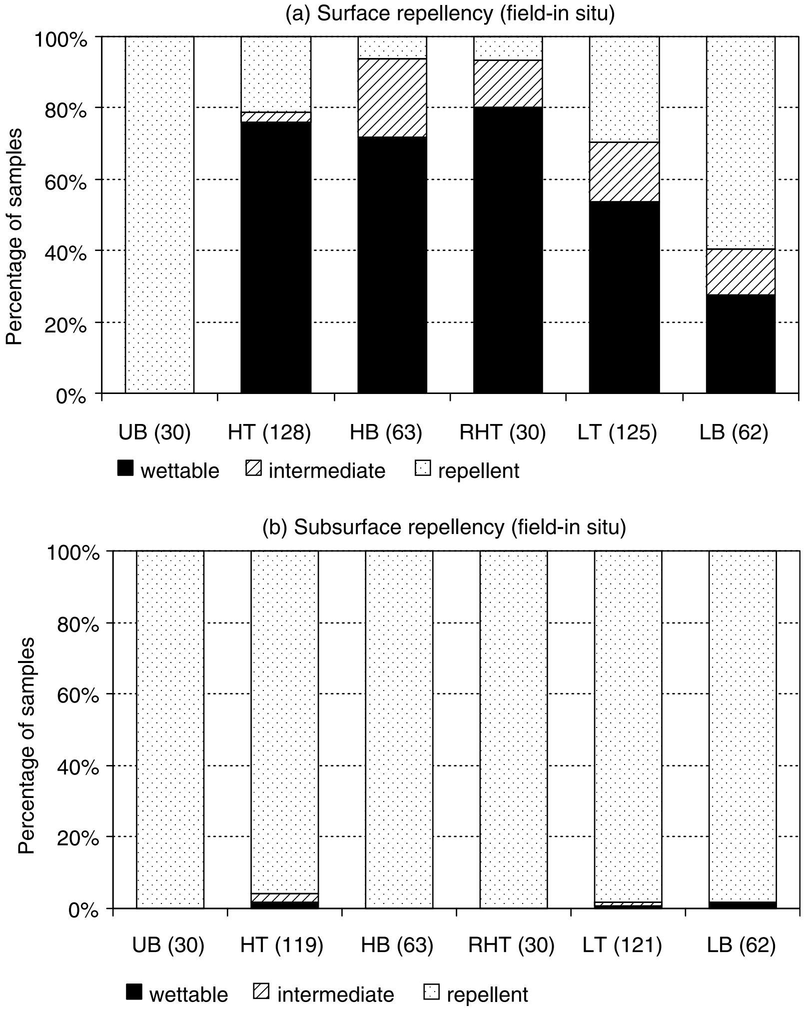


Fig. 2. Water repellency presence or absence measured in situ in the field for (a) surface and (b) subsurface soils. (Note that no data were collected at site UT.) The figure in brackets following the sample site code denotes the number of samples taken. See Table 2 for site codes and further sample details.

4. Results

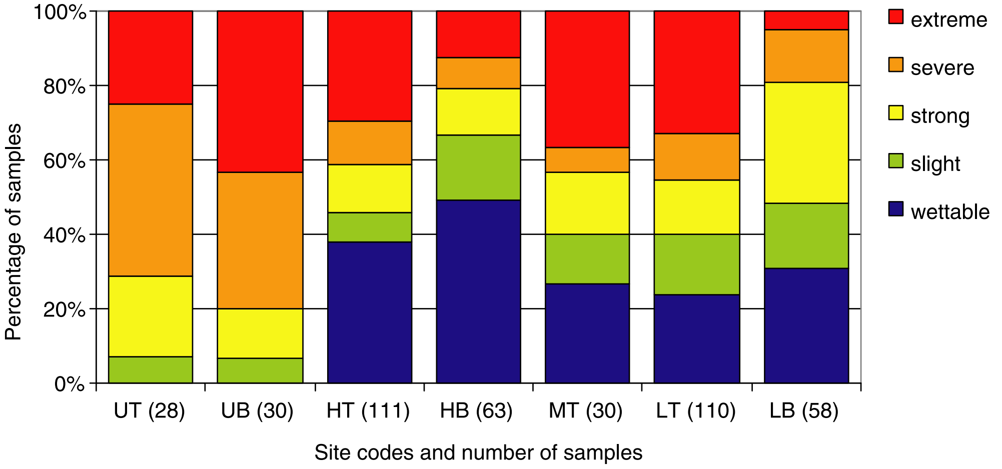
4.1. Water repellency of long-unburnt soils

All surface and subsurface soil areas tested in the field at the long-unburnt site (UB) exhibited water repellency (WDPT > 5 s, Fig. 2). The more detailed laboratory analysis (including the samples from site UT) confirmed the dominance of repellency identified in the field, with all surface samples from long-unburnt locations being repellent and severe to extreme persistence being dominant (Fig. 3(a)). Subsurface soil material was also dominantly repellent (UT, 96%; UB, 93%) (Fig. 3(b)). Overall, subsurface repellency persistence is significantly lower ($p < 0.05$) than that of surface soil, with slight to strong repellency being most frequent.

4.2. Water repellency of burnt soils

For in situ field testing, 27–80% of burnt surface samples were wettable, contrasting with the ubiquitously repellent nature of surface soil at

(a) Surface repellency (lab.)



(b) Subsurface repellency (lab.)

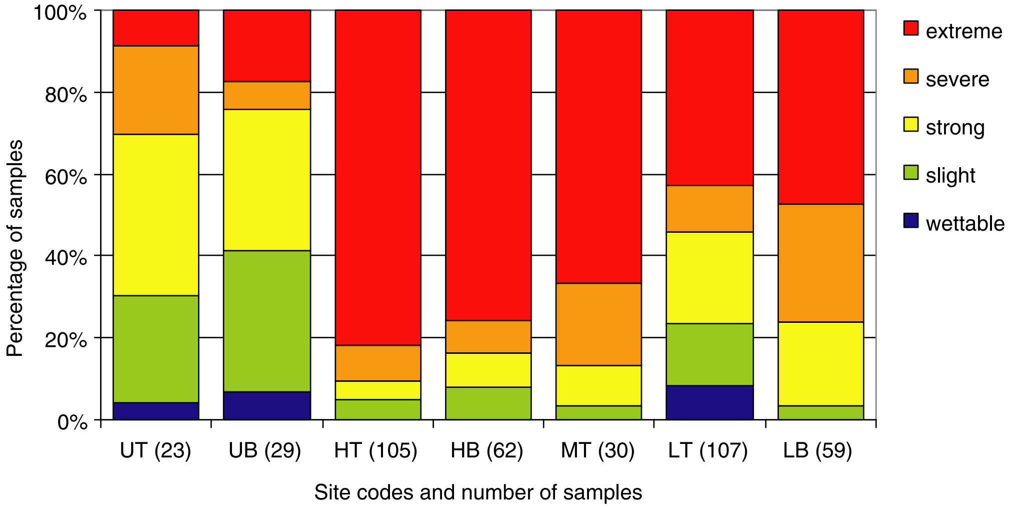


Fig. 3. Frequency distribution of different water repellency persistence levels for all sites measured on air-dry (a) surface and (b) subsurface samples under controlled laboratory conditions. The figure in brackets following the sample site code denotes the number of samples taken. See Table 2 for site codes and further sample details.

the long-unburnt sites (Fig. 2(a)). The laboratory results are broadly similar, although the overall frequency of wettable samples was somewhat lower (24–49%; Fig. 3(a)). Even for laboratory data, the greater frequency of wettable soil conditions compared to unburnt sites is significant ($p<0.05$) for sites burnt in 2001. For the site burnt in 2003 (MT), the frequency of wettable samples is similar to that of the 2001 burnt sites (see Fig. 3), but for this site, possibly as a result of its smaller sample size, frequency of wettable conditions is not significantly different from unburnt sites ($p<0.05$). On the basis that long-unburnt sites are representative of pre-fire conditions at the burnt sites, the results imply that burning has caused a significant reduction in surface repellency occurrence. Moreover, considering those surface samples for which burning has not destroyed repellency, there is no significant difference ($p>0.05$) between their repellency persistence and that of unburnt

Table 4
Data relating to sampling depth of interface between charred (dark) and 'un-charred' (paler coloured) soil layers at burnt sites. Individual measurements were recorded to the nearest 0.5 cm.

Site code	HT	HB	MT	LT	LB
Burn severity	moderate–extreme	moderate–extreme	moderate–high	low–moderate	low–moderate
Average interface depth (cm)	2.00	1.40	0.87	1.20	1.10
Depth range (cm)	0.5–10.0	0.5–4.0	0.5–5.0	0.5–5.0	0.5–5.0
Standard deviation	1.41	0.92	0.83	1.03	0.77
Sample size	127	63	30	126	63

samples, indicating that for burnt surface soils retaining repellency, burning hardly affected persistence levels. In contrast, as regards presence of subsurface repellency, burning apparently had little effect (no significant difference compared to unburnt sites; $p > 0.05$), but as regards persistence, extreme repellency occurrence significantly increased at the 2001 burn sites compared to unburnt sites (Fig. 3(a) and (b))

4.3. Effect of fire severity on water repellency

As regards repellency presence, 72–80% of in situ measurements in catchment H (moderate–extreme burn severity) showed wettable conditions, whereas in catchment L (low–moderate burn severity), considerably fewer (27–54%) were in that category. At site MT (moderate–high burn severity), 80% of sampling points were wettable (Fig. 2(a)). For subsurface soil virtually all (98–100%) measurements indicated repellency (WDPT > 5 s) irrespective of fire severity (Fig. 2(b)). The laboratory results show a similar trend: significantly reduced repellency levels ($p < 0.05$) for surface soil in catchment H compared with catchment L. Surface soil at site MT (intermediate fire severity) has a similar proportion of wettable samples to sites LT and LB, but repellency is not significantly different to either the higher or lower fire severity sites (Fig. 3(a)). For subsurface samples (Fig. 3(b)), a significant decrease ($p < 0.05$) in repellency persistence is evident between respective sites of relatively high (HT, HB), intermediate (MT) and low (LT, LB) fire severities. Thus, for example, extreme repellency is present in 82 and 76% of samples at sites HT and HB, 67% at site MT, and only 43 and 47% at sites LT and LB, respectively (Fig. 3(b)).

4.4. Depth of charred layer

Depths of charring (Table 4) ranged from 0.5 to 5.0 cm, except for one point at site HT (10 cm). Average charring depths were significantly greater ($p < 0.05$, Student's *t*-test) for the more severely burnt (sites HT, 2.0 cm; HB, 1.4 cm) than for respective slope positions in the less severely burnt catchment (sites LT, 1.2 cm; LB, 1.1 cm). At the 2003 burn site (MT), the average depth was 0.9 cm.

4.5. Longevity of fire imprint on water repellency

Laboratory WDPT results from the exploratory re-sampling at the most severely burnt site (HT) 13 and 25 months after the fire (HT-03 and HT-04) are given in Fig. 4. For surface soil material (Fig. 4(a)), despite some variation being evident between sampling dates, neither the frequency of wettable nor of extremely repellent samples changes significantly from one measurement date to the next and the relative frequency of repellency occurrence (i.e. samples with WDPT > 5 s) does not change significantly with time ($p > 0.05$). There is, however, a reduction in the frequency of extreme repellency over time, which is significant if the first and last sampling dates are compared ($p < 0.05$). For subsurface soil, the occurrence of extreme repellency progressively reduces with time after burning. This reduction is also significant ($p < 0.05$) between the first and final sampling dates, but extreme repellency for the latter remains significantly more frequent than for likely pre-fire conditions (i.e. those represented by laboratory results from unburnt sites UT and UB; Fig. 4(b); $p < 0.05$).

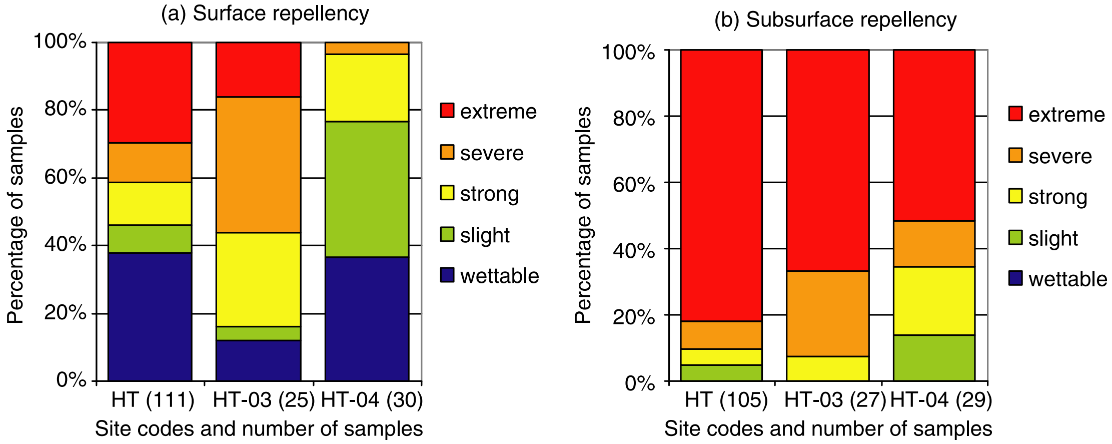


Fig. 4. Frequency distribution of different water repellency levels measured under controlled laboratory conditions on air-dry (a) surface and (b) subsurface samples obtained from site HT during the first sampling occasion in 2002 (HT-02), and then 13 (HT-03) and 25 (HT-04) months later. The figure in brackets following the sample site code denotes the number of samples taken. See Table 2 for site codes and further sample details.

5. Discussion

5.1. 'Background' water repellency in the absence of fire

Water repellency at the long-unburnt sites is both ubiquitous (Fig. 2) and dominated by severe to extreme persistence (Fig. 3) in contrast to the typically lower and spatially more heterogeneous repellency reported from long-unburnt soil in coniferous (e.g. Huffmann et al., 2001; Hubbert et al., in press; Mataix-Solera and Doerr, 2004) and deciduous type forests (Reeder and Jurgensen, 1979; Doerr et al., 2000b; Buczko et al., 2002). As regards long-unburnt eucalypt stands, the dominance of highly repellent conditions observed in this study may not, however, be atypical, as such conditions have also been reported from eucalypt stands elsewhere in Australia (e.g. Burch et al., 1989; Crockford et al., 1991; Doerr et al., 2004), South Africa (Scott, 2000) and Portugal (Doerr et al., 1998). In some cases, such repellency might conceivably have accrued because of fires in the more distant past, but high repellency levels have also been shown to develop without fire in formerly wettable soil under eucalypts in less than two years (Doerr et al., 1998). Furthermore, extreme repellency is known to develop in soils under other vegetation types not exposed to fire including grassland in the Netherlands (Dekker et al., 2001) and alpine tundra in Norway (Doerr et al., 2000b). These findings suggest that the high level of repellency observed here is a natural soil condition occurring independently of fire.

5.2. Effects of fire and differing fire severity on water repellency

Burning appears to have led to the widespread destruction of surface repellency (Figs. 2 and 3) and caused little change in its persistence where it was not destroyed, but significantly increased the persistence of subsurface repellency (Fig. 3). Destruction of surface repellency contrasts with the findings of most previous studies in forested terrain where burning has usually been shown to induce or enhance repellency (e.g. Brock and DeBano, 1990; Dyrness, 1976; Campbell et al., 1977; Reeder and Jurgensen, 1979; Sevink et al., 1989; McNabb et al., 1989; Huffmann et al., 2001; MacDonald and Huffmann, 2004; Mataix-Solera and Doerr, 2004). Outside of forested terrain, surface repellency destruction appears to be common for fires in Californian chaparral, which are often comparatively 'hot' (see review by DeBano, 2000a). The destruction of repellency has been shown in laboratory studies to occur above a soil temperature threshold of 250–350 °C for a wide variety of soils (e.g. DeBano et al., 1976; Robichaud and Hungerford, 2000; García-Corona et al., 2004) including also sample material from site UT in this study (Doerr et al., 2004). This suggests that a soil temperature of at least 250–350 °C was been reached in parts of the study area. In some forest fires studied, fire severity appears to have been too low to heat soil above the critical threshold (e.g. Sevink et al., 1989; Doerr et al., 1998). This applies also to most prescribed forest burns, which are usually timed specifically to result in low fire severity and thus limited soil heating (e.g. McNabb et al., 1989). In some studies, however, terrain affected by high fire severity has also been examined, but instead of surface repellency being destroyed, it was enhanced (e.g. Reeder and Jurgensen, 1979; Huffmann et al., 2001; MacDonald and Huffmann, 2004). This discrepancy with the current study may be due to the following reasons. First, it is possible that in these studies both the ash and any thin wettable mineral soil material may have been removed prior to in situ repellency testing or sampling. If, however, the wettable soil layer was more substantial, as in this study, this is unlikely. Second, oxygen depletion may have occurred in the soil in some cases, for example, during the combustion of comparatively dense duff layers typical of some pine stands and the temperature threshold for repellency destruction may consequently have been up to 200 °C higher than 250–350 °C (Bryant et al., in press), allowing repellency to persist. Third, it is feasible that although fires were classed as severe, soil temperatures remained below the critical threshold for repellency destruction despite sufficient oxygen availability for combustion of hydrophobic compounds. This scenario may apply to some of the case studies carried out in coniferous forests in the drier regions of the western USA, where rapid burning of the typically relatively thin litter and duff layer would have allowed only limited heat flux into the soil, compared to regions where ground fuel accumulation is more substantial (David Scott, pers. comm.). Where the second or third scenario applies, it would suggest that although existing burn severity classifications may be valuable in reflecting the degree of vegetation destruction, they may not be a good indicator of the soil temperatures reached during a burn when applied in isolation. A further compounding factor may be that the widely used ‘Fire Burn Intensity Classification’[1] (USDA, 2000), designed to categorise fire effects on soils, designates ‘medium’ to ‘high’ water repellency in the topsoil as an indicator of ‘high fire intensity’, whereas ‘low’ or ‘absent’ repellency indicates ‘low fire intensity’. Applied in isolation, this classification may have contributed to some erroneous fire severity classifications as repellency absence, according to USDA (2000), would indicate a light rather than a very severe burn during which surface repellency would have been eliminated. Thus, in cases where the pre-fire soil water repellency status can be established, the post-fire water repellency can be a useful indicator of the temperature reached in the soil during burning (Doerr et al., 2004) and thus of fire severity. Where the pre-fire status, however, is not known or highly variable, post-fire soil water repellency conditions cannot be used with confidence in fire intensity classifications.

As regards the fires having no significant effect on repellency persistence for those surface samples in burnt areas retaining their repellency, we suggest that pre-fire persistence was already so high that soil heating did not lead to the increase typically observed in most previous studies in forests. Similarly, very high pre-fire repellency was thought to be the reason why no increase in repellency could be observed after a fire in commercial *Eucalyptus globulus* stands in Portugal (Doerr et al., 1998). The increase in subsurface repellency persistence measured here, however, is in accordance with observations made in many previous studies (e.g. Huffmann et al., 2001; Mataix-Solera and Doerr, 2004; MacDonald and Huffmann, 2004), which suggest translocation of hydrophobic substances into the subsoil (DeBano et al., 1976) and/or the structural alteration of certain organic compounds already present (Doerr et al., 2004).

---

[1] The terms ‘fire intensity’ and ‘fire severity’ are sometimes used in a loose and exchangeable sense. Fire intensity, however, as defined by Byram (1959), is a specific measure of the heat rate released per unit length of the fire front, whereas fire severity describes the impact of the fire on some aspects of the ecosystem (Hartford and Frandsen, 1992). Fire severity classifications therefore may vary depending on which aspect of the ecosystem is being considered. The USDA (2000) classification is strictly speaking a fire severity (rather than intensity) classification, with a specific focus on fire effects on soils.

The effects of the 2001 fire on repellency were markedly different between catchments H and L, with the higher fire severity characterizing the former causing a significantly greater reduction in the presence of surface repellency than observed in the latter (Fig. 3(a)). In contrast, the fire increased subsurface repellency significantly more in catchment H than in L (Fig. 3(b)). Results at site MT (intermediate fire severity) fit the general pattern of increasing fire severity causing more widespread destruction of repellency at the soil surface and increased persistence for already extensive subsoil repellency. These findings are in accordance with the heating effects on repellency established in the aforementioned laboratory studies and suggest that the number of surface samples subjected to more than 250–350 °C (as indicated by the absence of repellency) increased with fire severity and that subsoil temperatures remained below 250–350 °C at all sites (assuming there was sufficient oxygen for combustion of hydrophobic compounds). Otherwise, soil temperatures would have to have been up to 200 °C higher to eliminate repellency (Bryant et al., in press), as outlined earlier.

Charring depths for the 2001 fire (Table 4) indicate that heating penetrated deeper in catchment H than in L, and in ridge-top compared to 'base of slope' positions. Charring depths for the 2003 burn (site MT) are generally shallower than for both catchments H and L, despite an intermediate fire severity. Although the different fires may not be entirely comparable, the relatively shallow charring depth at site MT warrants further consideration. Whilst above-ground destruction of vegetation, and therefore fire severity, was intermediate between catchments H and L, soil heating at MT must have been relatively shallow or repellency would have been destroyed to greater depths. Possible explanations could be greater pre-fire soil moisture at MT, causing soil temperatures to remain below 100 °C until most soil moisture had been driven off (Chandler et al., 1983), or a comparatively short residence time of the fire resulting in a low net energy transfer to the soil.

5.3. Longevity of fire effects on water repellency

This topic has received surprisingly little attention to date. In North America, Dyrness (1976) reported that fire-induced water repellency persisted until the sixth year in an Oregon pine forest for severely, and 3–4 years for less severely burnt soil. Reeder and Jurgensen (1979) found that 65% of the soils that were repellent after a fire in a mixed species forest in Michigan were wettable a year later. Huffmann et al. (2001) reported from burnt pine stands in Colorado that increased repellency persistence at the surface and depths of 3 and 6 cm after burning was reduced somewhat three months later, but that fire-induced repellency persisted for at least 22 months. Hubbert et al. (in press) examined the effects of a prescribed low-severity fire in a Californian mixed chaparral watershed, which almost doubled the frequency of moderate to extreme surface repellency and halved that of wettable soil (as defined in this study, i.e. WDPT ≤ 5 s). Just over two months later, repellency frequency had returned to pre-fire values. Data from outside the USA are scarce and there are only two studies of which we are aware. Giovannini et al. (1987) reported that the pre-fire soil surface repellency levels (WDPT, 420–460 s) in Sardinian scrub were reduced to 220–240 s after an experimental burn and gradually recovered to pre-fire levels within three years. Cerdà and Doerr (in press) examined the effects of a severe fire over an eleven-year period in eastern Spain and reported that water repellency, which had been destroyed during burning, returned within 3 years under pine vegetation (*Pinus halepensis*). Based on these previous studies, we would have expected a recovery of repellency towards pre-fire levels, but the frequency of wettable surface soil had not changed significantly 1 and 2 years after burning (Fig. 4(a)). The frequency of extremely repellent surface and subsurface conditions, however, was reduced over time.

The observed pattern may be a function of (i) pre-fire repellency levels being comparatively high, and (ii) fire destroying rather than increasing surface repellency with fire-induced changes probably having been too severe to allow recovery to pre-fire soil conditions in only 2 years. Given the potential implications of, and complex interactions between soil wettability, hydrological processes and vegetation recovery discussed in the following section, the longevity of fire-induced modifications to repellency clearly warrants more attention.

5.4. Implications for hydrological response

Increased overland flow, runoff and soil erosion observed following fire have commonly been attributed to fire-induced or enhanced repellency (see review by Shakesby et al., 2000). Any post-fire enhanced hydrological response in the catchments studied here, however, would clearly not have been caused by the de novo creation of water repellency, but primarily by the removal of vegetation and litter from already highly repellent soil, allowing the effects of repellency to become much more prominent, potentially compounded by a further increase in the persistence of subsoil repellency (Shakesby et al., 2003). The presence of high repellency levels also observed under long-unburnt eucalypt stands elsewhere (e.g. Crockford et al., 1991; Burch et al., 1989; Shakesby et al., 1993; Doerr et al., 1998; Scott, 2000) and under a range of other vegetation types (see reviews by DeBano, 2000a; Doerr et al., 2000a) suggests that this scenario is rather more common than currently perceived.

As regards fire severity, increased overland flow, runoff and erosion are usually associated with increased severity (e.g. Campbell et al., 1977; Prosser and Williams, 1998; Wondzell and King, 2003). An increase in the degree of vegetation destruction is certainly a factor here, but an increased occurrence and/or persistence of water repellency associated with greater fire severity has also been implied as a key factor (e.g. Prosser and Williams, 1998; Robichaud and Hungerford, 2000; USDA, 2000; Huffmann et al., 2001). This may, however, be only one type of possible post-fire hydrological response. Amongst burns of moderate and higher severity, as examined in this study, which are typified by the removal of ground litter and much of the aboveground foliage (see Table 1), increased fire severity may actually reduce hydrological response under certain conditions. Without litter and vegetation, a more widespread occurrence of wettable surface conditions associated with greater fire severity would delay runoff (Shakesby et al., in press; Fig. 5(a) and (c)), whereas for less severely burnt areas, where repellency is present also at the surface, virtually instantaneous overland flow would be expected (Doerr and Moody, 2004; Fig. 5(b)). Thus, for example, at the severely burnt site HT, the 78% spatial cover of wettable soil (Fig. 3(a)) extending to 2 cm depth (Table 4) with an estimated pore space volume of 50%, could store the first 8 mm of a rainstorm. Once a wettable surface layer is saturated, however, saturation excess overland flow occurs. Increased pore pressure and decreased shear strength could then cause failure of this saturated layer (Fig. 5(d)), initiating the formation of rills (Wells, 1981) or micro-scale debris flows (Gabet, 2003). These differences in hydrological response can be expected to disappear as vegetation cover is restored and soil wettability approaches pre-fire levels. In the study area, post-fire vegetation recovery has been rapid over the two-year study period resulting in dense tree canopy foliage and the growth of up to 2-m high shrubs despite lower than average rainfall, but remarkably little accompanying change in the proportion of wettable surface soil has occurred.

6. Conclusions

The soils under eucalypt forest in Sydney's main water supply catchment exhibit very high levels of natural 'background' water repellency. Rather than increasing surface water repellency, the extensive wildfires of Christmas 2001 caused the widespread destruction of repellency in the surface soil layer in areas where burn severity was high, and led to a further increase in the persistence of already almost ubiquitous subsurface repellency. Two years after the fire, recovery to pre-fire repellency levels had not been achieved. The commonly used indicators of fire severity, which are based on the degree of vegetation and litter destruction, do not suggest exceptionally severe fire conditions above ground for the catchments examined compared to fires examined elsewhere. Despite this, it seems that topsoil temperatures in these eucalypt stands must have been unusually high, exceeding the established threshold range for repellency destruction. A possible reason for this may be the lack of a duff layer, resulting in a more effective heat transfer into the mineral soil, and a better delivery of oxygen allowing effective combustion of the hydrophobic substances in the topsoil.

Widespread destruction of surface repellency can have important implications for the generation of overland flow, soil erosion and seedbank maintenance,

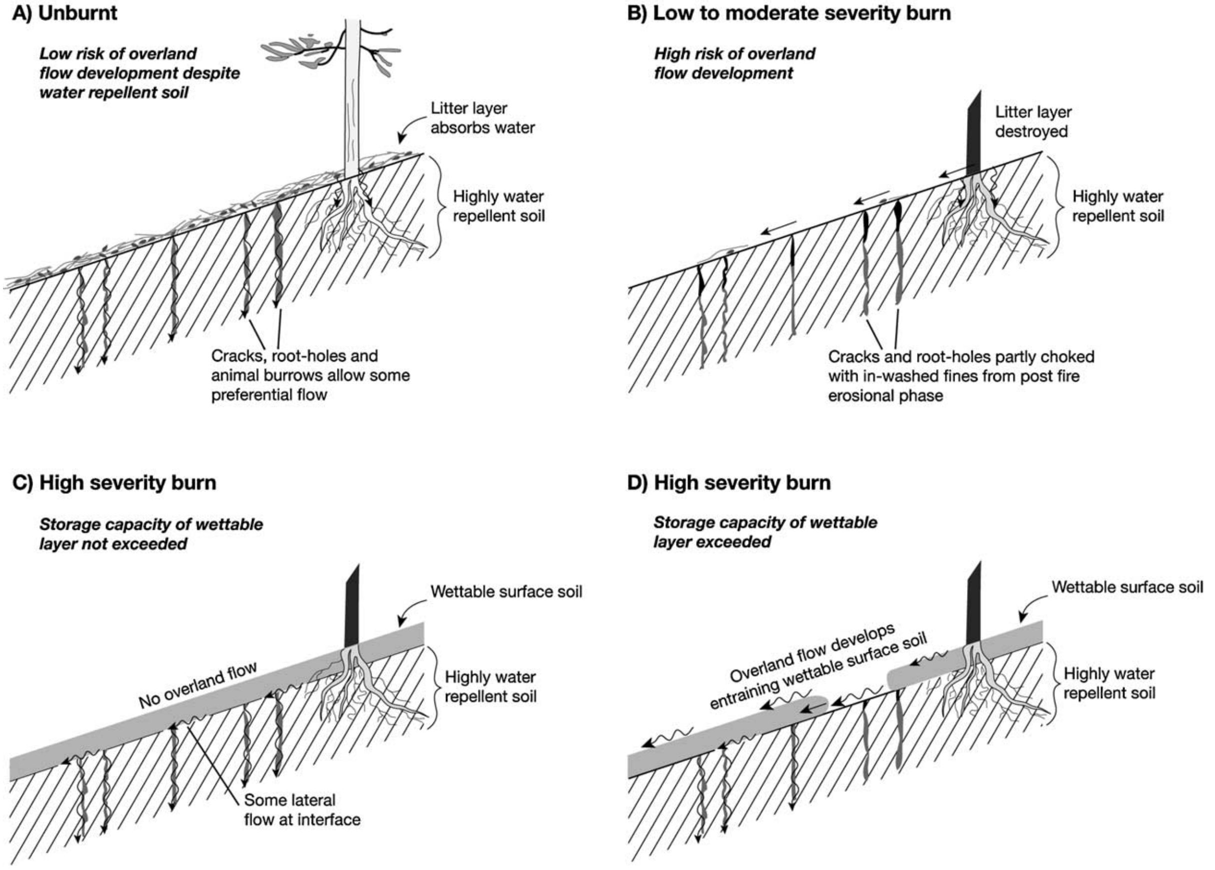


Fig. 5. Hydrological response scenarios of forested terrain with high natural background levels of soil water repellency for (a) unburnt conditions and following fire of (b) low–moderate and (c&d) high burn severity.

and stream and reservoir water quality. The generation of a wettable topsoil layer can be expected to restrict overland flow and associated erosion under rainfall intensities that do not exceed the storage capacity of this wettable layer. However, storms exceeding the storage capacity of this unstable layer may cause its sudden disintegration and the entrainment of this saturated soil material in the developing overland flow.

The hydrological impacts of any fire-induced alterations to repellency will decline under sufficient vegetation and ground litter recovery. Vegetation recovery rates are, however, strongly affected by fire severity and post-fire erosion events. The discrepancy between standard fire severity classifications based on visible aboveground effects and the temperatures reached in the soil as indicated by its diverse effects on repellency status strongly suggest the need for a new fire severity evaluation scheme encompassing not only post-fire foliage and ground cover status, but also changes to surface and subsurface soil hydrological properties. Such a scheme would provide a better prediction of the immediate hydrological effects of wildfires on catchments such as flash flooding and erosion, and also of their time-to-recovery than current classifications allow. This could prove invaluable if the future increase in fire frequency and severity predicted for many regions (McCarthy et al., 2001) actually occurs.

Acknowledgements

This research has been supported by NERC Urgency Grant NER/A/S/2002/00143 and Advanced

Fellowship NER/J/S/200200662 (SHD). Sydney Catchment Authority (SCA), many of their staff, and particularly Glen Capararo, are acknowledged for outstanding logistical support. Joy Hafey and Ben Harrington are thanked for conducting parts of the vegetation survey, as are Victoria Farwig and Zoe Hardiman for assistance with fieldwork and staff at the Wirrimbirra Wildlife Sanctuary for generously providing laboratory and office facilities. GSH acknowledges a financial contribution from Macquarie University. Nicola Jones and Anna Ratcliffe are thanked for drawing Figs. 1 and 5.

References

Andreu, V., Rubio, J.L., Forteza, J., Cerni, R., 1996. Postfire effects on soil properties and nutrient losses. International Journal of Wildland Fire 6, 53–58.

Bisdom, E.B.A., Dekker, L.W., Schoute, J.F.Th., 1993. Water repellency of sieve fractions from sandy soils and relationships with organic material and soil structure. Geoderma 56, 105–118.

Brock, J.H., & DeBano, L.F. (1990). Wettability of an Arizona chaparral soil influenced by prescribed burning. In: Proceedings of a symposium on effects of fire of Southwestern natural resources (Krammes, J.S., technical coordinator). November 15–17, 1988. Tucson, AZ. USDA Forest Service General Technical Report RM-191, pp. 206–209.

Bryant, R., Doerr, S.H., & Helbig, M. The effect of oxygen deprivation on soil hydrophobicity during heating. International Journal of Wildland Fire, 14(4), in press.

Buczko, U., Bens, O., Fischer, H., Hüttl, R.F., 2002. Water repellency in sandy luvisols under different forest transformation stages in northeast Germany. Geoderma 109, 1–18.

Burch, G.J., Moore, I.D., Burns, J., 1989. Soil hydrophobic effects on infiltration and catchment runoff. Hydrological Processes 3, 211–222.

Bureau of Meteorology, 1991. Sydney climatic survey. Australian Government Publishing Service, Canberra pp. 10–15.

Byram, G.M., 1959. Combustion of forest fuels. In: Davies, K.P. (Ed.), Forest fires, control and use. McGraw Hill, New York, pp. 61–89.

Campbell, R.E., Baker Jr., M.B., Ffolliott, P.F., Larson, F.R., Avery, C.C., 1977. Wildfire effects on a ponderosa pine ecosystem: An Arizona case study, USDA forest service research paper RM-191 1977. 21 pp.

Cerdà, A., & Doerr, S.H. The influence of vegetation recovery on soil hydrology and erodibility following fire: An eleven-year investigation. International Journal of Wildland Fire, 14(4), in press.

Chafer, C.J., Noonan, M., Macnaught, E., 2004. The post-fire measurement of fire severity and intensity in the Christmas 2001 Sydney wildfires. International Journal of Wildland Fire 13, 227–240.

Chandler, C., Cheney, P., Thomas, P., Trabaud, L., Williams, D., 1983. Fire in forestry, Volume 1: Forest fire behaviour and effects. Wiley, New York.

Congalton, G., Mead, R.A., 1983. A quantitative method to test for consistency and correctness in photo interpretation. Photogrammetric Engineering and Remote Sensing 49, 69–74.

Crockford, S., Topadalis, S., Richardson, D.P., 1991. Water repellency in a dry sclerophyll forest—measurements and processes. Hydrological Processes 5, 405–420.

DeBano, L.F. (1981). Water repellent soils: A state-of-the-art. United States Department of Agriculture Forestry Service General Technical Report, PSW-46. Berkley, California.

DeBano, L.F. (1991). The effects of fire on soil properties. United States Department of Agriculture Forestry Service General Technical Report, INT-2, 151–156.

DeBano, L.F., 2000a. The role of fire and soil heating on water repellency in wildland environments: A review. Journal of Hydrology 231–232, 195–206.

DeBano, L.F., 2000b. Water repellency in soils: A historical review. Journal of Hydrology 231–232, 4–32.

DeBano, L.F., Krammes, J.S., 1966. Water repellent soils and their relation to wildfire temperatures. International Bulletin of the Association of Hydrological Sciences II, 14–19.

DeBano, L.F., Savage, S.M., Hamilton, D.A., 1976. The transfer of heat and hydrophobic substances during burning. Soil Science Society of America Journal 40, 779–782.

Dekker, L.W., Doerr, S.H., Oostindie, K., Ziogas, A.K., Ritsema, C.J., 2001. Actual water repellency and critical soil water content in a dune sand. Soil Science Society of America Journal 65, 1667–1675.

Doerr, S.H., 1998. On standardising 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., Blake, W.H., Humphreys, G.S., Shakesby, R.A., Stagnitti, F., Vuurens, S.H., et al., 2004. Heating effects on water repellency in Australian eucalypt forest soils and their value in estimating wildfire soil temperatures. International Journal of Wildland Fire 13 (2), 157–163.

Doerr, S.H., Dekker, L.W., Ritsema, C.J., Shakesby, R.A., Bryant, R., 2002. Water repellency of soils: The influence of ambient relative humidity. Soil Science Society of America Journal 66, 401–405.

Doerr, S.H., Ferreira, A.J.D., 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. Hydrological Processes 17, 363–377.

Doerr, S.H., Moody, J., 2004. Hydrological impacts of soil water repellency: On spatial and temporal uncertainties. Hydrological Processes 18, 829–832.

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., 2000a. Soil water repellency: its characteristics, causes and hydro-geomorphological consequences. Earth Science Reviews 51, 33–65.

Doerr, S.H., Shakesby, R.A., Walsh, R.P.D., 2000b. Soil hydrophobicity in north-west Europe: Its occurrence and implications for modelling soil hydrological response. British Hydrological Society Occasional Paper 11, 211–218.

Dyrness, C.T., 1976. Effect of wildfire on soil wettability in the high Cascade of Oregon, United States Department of Agriculture Forest Service Research Paper PNW-202, Pacific Northwest forest and range experimental station, Portland, Oregon 1976 pp. 444–447.

Franco, C.M.M., Clarke, P.J., Tate, M.E., Oades, J.M., 2000. Hydrophobic properties and chemical characterisation of natural water repellent materials in Australian sands. Journal of Hydrology 231–232, 47–58.

Gabet, E.J., 2003. Post-fire thin debris flows: Sediment transport and numerical modelling. Earth Surface Processes and Landforms 28, 1341–1348.

García-Corona, E., Benito de Blas, E., Varela, M.E., 2004. Effects of heating on some soil physical properties related to its hydrological behaviour in two north-western Spanish soils. International Journal of Wildland Fire 13, 195–199.

Giovannini, G., Lucchesi, S., 1983. Effect of fire on hydrophobic and cementing substances of soil aggregates. Soil Science 136, 231–236.

Giovannini, G., Lucchesi, S., Cervelly, S., 1987. The natural evolution of a burnt soil: A three year investigation. Soil Science 143, 220–226.

Hartford, R.A., Frandsen, W.H., 1992. When it's hot, it's hot…or maybe it's not! (Surface flaming may not portend extensive soil heating). International Journal of Wildland Fire 2, 139–144.

Hubbert, K.R., Preisler, H.K., Wohlgemuth, P.M., Graham, R.C., & Narog, M.G. Prescribed burning effects on soil physical properties and soil water repellency in a steep chaparral watershed, southern California, U.S.A. Geoderma, in press (available online).

Huffmann, E.L., MacDonald, L.H., Stednick, J.D., 2001. Strength and persistence of fire-induced hydrophobicity under ponderosa and lodgepole pine, Colorado front range. Hydrological Processes 15, 2877–2892.

Inbar, M., Wittenberg, L., Tamir, M., 1997. Soil erosion and forestry management after wildfire in a Mediterranean woodland, Mt. Carmel, Israel. International Journal of Wildland Fire 7, 285–294.

Leitch, C.J., Flinn, D.W., Van De Graaf, R.H.M., 1983. Erosion and nutrient loss resulting from Ash Wednesday (February 1983) wildfires: A case study. Australian Forestry 46, 173–180.

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

MacDonald, L.H., Huffmann, E.L., 2004. Post-fire soil water repellency: Persistence and soil moisture thresholds. Soil Science Society of America Journal 68, 1729–1734.

Mataix-Solera, J., Doerr, S.H., 2004. Hydrophobicity and aggregate stability in calcareous topsoils from fire-affected pine forests in south-eastern Spain. Geoderma 118, 77–88.

Matthews, J.A., 1981. Quantitative and statistical approaches to geography: A practical manual. Pergamon, Oxford.

Climate change 2001: Impacts, adaptation and vulnerability. In: McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., White, K.S. (Eds.), 2001. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge.

McNabb, D.H., Gaweda, F., Fröhlich, H.A., 1989. Infiltration, water repellency, and soil moisture content after broadcast burning a forest site in southwest Oregon. Journal of Soil and Water Conservation 44, 87–90.

Mitchell, P.B., Humphreys, G.S., 1987. Litter dams and micro-terraces formed on hillslopes subject to rainwash in the Sydney Basin, Australia. Geoderma 39, 331–357.

Moreno, J.M., Oechel, W.C., 1989. A simple method for estimating fire intensity after a burn in California Chaparral. Acta Oecologica 10, 57–68.

Morris, S.E., Moses, T.A., 1987. Forest fire and the natural soil erosion regime in the Colorado front range. Annals of the Association of American Geographers 77, 245–254.

O'Loughlin, E.M., Cheney, N.P., Burns, J., 1982. The Bushrangers experiment: Hydrological responses of a eucalypt catchment to fire, First national symposium on forest hydrology, Australian national conference publication, Vol. 86 1982 pp. 132–138.

Prosser, I.P., Williams, L., 1998. The effect of wildfire on runoff and erosion in native *Eucalyptus* forest. Hydrological Processes 12, 251–265.

Reeder, C.J., Jurgensen, M.F., 1979. Fire-induced water repellency in forest soils of upper Michigan. Canadian Journal of Forest Research 9, 369–373.

Robichaud, P.R., Brown, R.E., 1999. What happened after the smoke cleared: Onsite erosion rates after a wildfire in eastern Oregon. Wildland Hydrology June/July, 419–426.

Robichaud, P.R., Hungerford, R.D., 2000. Water repellency by laboratory burning of four northern Rocky Mountain forest soils. Journal of Hydrology 231–232, 207–219.

Sartz, R.S., 1953. Soil erosion on a fire-denuded forest area in the Douglas-Fir Region. Journal of Soil and Water Conservation 8, 279–281.

Savage, S.M., 1974. Mechanism of fire-induced water repellency in soils. Proceedings of the Soil Science Society of America 38, 652–657.

Scholl, D.B., 1975. Soil wettability and fire in Arizona chaparral. Soil Science Society of America Proceedings 39, 356–361.

Scott, D.F., 2000. Soil wettability in forested catchments in South Africa: As measured by different methods and as affected by vegetation cover and soil characteristics. Journal of Hydrology 231–232, 87–104.

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

Sevink, J., Imeson, A.C., Verstraten, J.M., 1989. Humus form development and hillslope runoff, and the effects of fire and management, under Mediterranean forest in N.E. Spain. Catena 16, 461–475.

Shakesby, R.A., Blake, W.H., Doerr, S.H., Humphreys, G.S., Wallbrink, P., Chafer, C.J. Hillslope soil erosion and bioturbation following the 2001 forest fires near Sydney, Australia. In P. Owens, A. Collins (eds) Soil erosion and soil redistribution in river catchments: measurement, modelling and management in the 21st century. CAB International, Wallingford, in press.

Shakesby, R.A., Chafer, C.J., Doerr, S.H., Blake, W.H., Humphreys, G.S., Wallbrink, P., et al., 2003. Fire severity, water repellency characteristics and hydrogeomorphological changes following the Christmas 2001 forest fires. Australian Geographer 34, 147–175.

Shakesby, R.A., Coelho, C., de O, A., Ferreira, A.D., Terry, J.P., Walsh, R.P.D., 1993. Wildfire impacts on soil erosion and hydrology in wet Mediterranean forest, Portugal. International Journal of Wildland Fire 3, 95–110.

Shakesby, R.A., Doerr, S.H., Walsh, R.P.D., 2000. The erosional impact of soil hydrophobicity: Current problems and future research directions. Journal of Hydrology 231–232, 178–191.

Swanson, F.J. (1981). Fire and geomorphic processes. In H.A. Mooney, T.O.M. Bonnicksen, N.L. Christiansen, J.E. Lotan, & W.A. Reiners (eds) United States Department of Agriculture, Forest Service, General Technical Report WO-26, 401–420.

USDA (United Stated Department of Agriculture), 2000. Fire burn intensity classification factsheet, Natural resources conservation service 2000 (http://www.co.nrcs.usda.gov/technical/eng/BURNINTENSITYfactsheet.pdf.).

Wessel, A.T., 1988. On using the effective contact angle and the water drop penetration time for classification of water repellency in dune soils. Earth Surface Processes and Landforms 13, 555–562.

Wells, W.G., 1981. Some effects of brushfires on erosion processes in coastal southern California. In: Davies, T.R.H., Pearce, A.J. (Eds.), Erosion and sediment transport in Pacific Rim Steeplands. International Association of Hydrological Sciences publication, Vol. 132, pp. 305–342.

Wondzell, S.M., King, G.K., 2003. Postfire erosional processes in the Pacific Northwest and Rocky Mountain regions. Forest Ecology and Management 178, 75–87.