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Soil wettability in forested catchments in South Africa; as measured by different methods and as affected by vegetation cover and soil characteristics

D.F. Scott*

CSIR, Division of Water, Environment and Forestry Technology, P.O. Box 320, Stellenbosch, 7599, South Africa

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Abstract

Earlier studies in South Africa had shown that water repellency in the soils of timber plantations was associated with a greater risk of overland flow and soil erosion on mountain slopes. This paper reports on a follow-up study to determine how prevalent water repellent soils are in the forestry areas of South Africa, and to what extent this phenomenon is associated with specific vegetation types. Soils from a representative series of forestry sites around South Africa were sampled from beneath each genus or plantation type and the range of local vegetation types. These soils were dried at low oven temperatures and then subjected to a series of tests of soil wettability, namely, water drop penetration time, infiltration rate, critical surface tension and apparent advancing contact angle as determined by the equilibrium capillary rise test.

Water repellency is common in dried soils from timber plantations. The dominant variation in repellency is explained by the different vegetation types: soils beneath eucalypts are most repellent, followed by those beneath wattle (*Acacia* species), indigenous forest and pine. Soils beneath grassland and fynbos scrub were least likely to show repellency, perhaps because regular fires remove plant litter and thus the potential for hydrophobic substances to develop. Soil characteristics explained very little of the variation in repellency. Organic carbon content was weakly correlated with higher repellency, but organic carbon content and soil texture added little explanation to models that first accounted for variation in vegetation type and point of origin. These results are broadly the same regardless of which method of measuring repellency was used. However, the critical surface tension test was far superior to the others in terms of information gained, speed, efficiency and statistical utility of the resultant scores.

Keywords: Soil wettability; Water repellency; Critical surface tension

1. Introduction

Earlier studies in South Africa had shown that severe wildfire in some pine-afforested catchments induced water repellency in the soils, and that the degree of repellency was positively related to fuel loads during the fire (Scott and VanWyk, 1990). This repellency was associated with a greater risk of overland flow and increased soil erosion. It was also apparent that severe water repellency in soils was not confined to burned sites, and that the degree of repellency was linked to vegetation type (Scott, 1991; Scott and Schulze, 1992; Scott, 1994). Therefore the objective of this study, undertaken in 1989, was to determine how prevalent water repellent soils were in the

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* Tel.: +27-21-888-2407; fax: +27-21-888-2684.
E-mail address: dscott@csir.co.za (D.F. Scott).

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forestry areas of South Africa, and to what extent this phenomenon was associated with specific vegetation types and soil characteristics.

1.1. Background to the study

In most soil physical studies soils are assumed to be completely wettable because of the strong attraction between the soil particles and water molecules (DeBano, 1981). It is not uncommon though for some soils to show resistance to wetting, i.e. that they are water repellent, hydrophobic or hard-to-wet. This condition may be noticeable in the dry state only with certain soils or at all stages of wetting (DeBano, 1981).

In most cases water repellency in soils can be attributed to coatings on the soil particles of hydrophobic substances of organic origin. One of the more common sources of these organic skins are fungal mycelia (Bond and Harris, 1964; Jex et al., 1985) which are particularly noticeable in lawns and pastures as the so-called "fairy-ring" phenomenon, causing dry circles of grass where the soils are non-wettable (DeBano, 1981; Dekker and Ritsema, 1996). Water repellency is also commonly associated with certain vegetation types or plant species, such as citrus orchards (Jamison, 1946; Bishay and Bakhati, 1976) and some Californian desert plants, where repellency is confined within the drip zone of the plants (Adams et al., 1970), to chaparral vegetation (DeBano et al., 1967; Holzhey, 1969) and some eucalypts (Bond, 1964; McGhie and Posner, 1980; Burch et al., 1989; Doerr et al., 1996).

If water repellency is caused by a coating on soil particles it follows that soils with a low specific surface area (surface area per unit of mass), i.e. coarse textured soils, should develop the phenomenon more readily. Thus sand is often particularly repellent, as found in Florida (Jamison, 1946), Australia (Roberts and Carbon, 1972), Egypt (Bishay and Bakhati, 1976) and the Netherlands (Ruyten and de Goede-Hiensch, 1988), and as observed in the coastal sands of Zululand and the Cape Flats in South Africa. Other factors positively related to the degree of water repellency are the amount of organic matter in the soil (Van't Woudt, 1959; Scholl, 1971), the age of the vegetation (period since last fire) through controlling the build-up of plant litter on the soil (Teramura, 1980), and the dryness of the soil (Gilmour, 1968; Singer and Ugolini, 1976; Grelewicz and Plichta, 1983) which may result in the seasonal appearance of water repellency. Finally, as mentioned earlier, soil heating, such as may occur during fire, has been found to intensify water repellency in the soil (DeBano and Krammes, 1966; Dyrness, 1976; John, 1978; Shakesby et al., 1993).

In this study, representative soils from the main timber-growing areas in South Africa were sampled from beneath plantations of different timber genera and the adjacent natural vegetation, and subjected to a range of standard wettability tests. Results from these tests are presented, some comment is made on the various tests used and the implications of the results are discussed.

2. Methods

2.1. Soil wettability and its measurement

Wetting is a complex phenomenon, the theory of which is dealt with in the chemistry and physics of surfaces. Water repellency or soil wettability is not an absolute state; factors such as surface chemistry, surface roughness and porosity may all influence perceived repellency, which also varies with soil wetness and temperature, and possibly also atmospheric humidity (Hammond and Yuan, 1969; King, 1981). Hence the wettability of a soil is not static.

Consequently, there is no single complete method for measuring repellency. There is no universally accepted or absolute measure of repellency, and results obtained from different studies are therefore not necessarily directly comparable. Relative scales, such as the repellency index proposed by Watson and Letey (1970) and used in this study, may be set so as to be meaningful for a particular sample of soils and thus may differ between different studies.

For these reasons, and in the light of earlier experience in measuring water repellency, this study employed a battery of tests of soil wettability, rather than a single test, as different tests highlight different aspects of the repellency and a fuller picture of soil wettability is presented by multiple measures. The intention in using a range of tests of wettability was not to repeat previous comparisons of techniques, but

Table 1
The origin and some properties of a range of soils from forestry regions in South Africa. The mean of organic carbon content and derived specific surface area are shown with their standard errors in brackets. The location codes cross-refer to Fig. 1 and the text (S.F. = State Forest)

Location code	Location	Geology	Soil form and approximate {FAO equivalent soil group}[a]	Organic carbon (%)	Texture class	Specific surface area[b] ($m^2\ g^{-1}$)	Vegetation cover types sampled
1. Biesievlei	Bergvliet S.F., Mpumalanga	Nelspruit Granites	Magwa {Humic Ferralsol}	7.5 (2.6)	Loam	4.57 (0.86)	*Eucalyptus grandis*, *Pinus elliottii*, grassland
2. CP	Cathedral Peak, KwaZulu–Natal Drakensberg	Beaufort Shale	Inanda {Humic Ferralsol}	7.8 (1.1)	Silty clay loam	6.16 (0.46)	*E. grandis*, *Pinus patula*, (2) grassland (2)
3. Cey	Ceylon S.F., Mpumalanga	Timeball Hill Shale	Inanda {Humic Ferralsol}	4.0 (0.7)	Silty clay loam	7.08 (0.14)	*Eucalyptus saligna*, *Pinus taeda*, grassland
4. Jk	Jonkershoek, S.W. Cape	Cape Granite	Sweetwater {Cambic Umbrisol}	6.3 (1.4)	Silty loam	4.55 (0.65)	*Pinus radiata*, *Eucalyptus cladocalyx* fynbos (scrub)
5. MM	MacMac S.F., Mpumalanga	Lyttleton Dolomite	Inanda{Humic Ferralsol}	11.2 (2.1)	Silty clay loam	8.40 (0.52)	*E. saligna*, *P. elliottii* (2), grassland (2)
6. Nt	Ntabamhlope, KwaZulu-Natal Drakensberg	Beaufort Shale	Magwa {Humic Ferralsol}	6.2 (2.2)	Silty clay	8.39 (0.68)	*Eucalyptus fastigata*, *Acacia mearnsii*, grassland
7. Rd	Richmond, KwaZulu-Natal Midlands	Ecca Shale	Inanda {Humic Ferralsol}	10.0 (1.2)	Silty clay	9.08 (0.39)	*E. grandis*, *A. mearnsii*, grassland
8. Sd	Saasveld, Southern Cape	TMS and Saasveld schist	Nomanci {Cambic Umbrisol}	6.8 (2.0)	Loam	2.47 (0.27)	*P. radiata* (2) native forest (2)
9. WH	Windy Hill, KwaZulu-Natal Midlands	Table Mountain Sandstone (TMS)	Nomanci {Ferralic Cambisol}	6.2 (1.8)	Loam	3.95 (1.43)	*E. grandis*, *P. patula*, *A. mearnsii*, grassland
10. ZC	KwaMbonambi, Zululand Coast	Quaternary coastal sands	Fernwood {Albic Arenosol}	1.2 (0.03)	Loamy sand	0.76 (0.13)	*E. grandis* (2) *P. elliottii*, grassland, native forest (2)

[a] From the South African (SCWG, 1991) and FAO classifications (FAO-UNESCO, 1974).

[b] Estimated from the particle size distribution by a formula given by Hillel (1980).

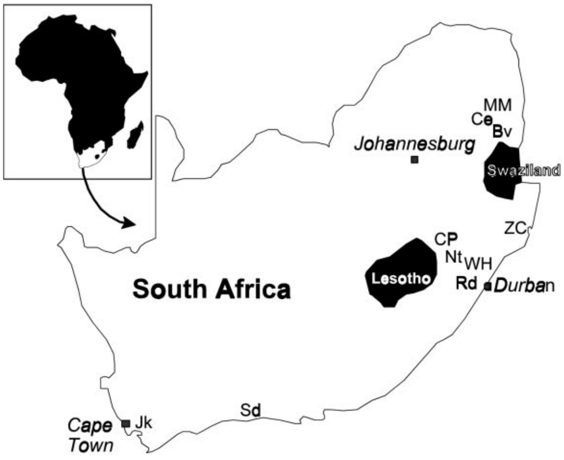


Fig. 1. The locations of the sites in South Africa from which soils were sampled for repellency testing. The location codes are used in Table 1 and the text.

simply to improve the representativeness of the conclusions drawn. To remove any variation caused by differences in initial wetness, all soils were air dried or dried at low oven temperatures (70–100°C). The phenomenon being measured, therefore, is what Dekker and Ritsema (1994) termed "potential repellency". Under the typically sharp seasonal drought conditions of South Africa, though, it is likely that surface soils do reach this air-dry condition in most years.

2.2. Sampling of soils

Soil samples were taken from 10 forestry sites around South Africa that broadly represented most of the major timber-producing soils. At each point, a typically thin cover (<50 mm) of plant litter and duff were removed and a disturbed sample of roughly one kilogram was taken from the top 50 mm of mineral soil. Soil samples were taken from beneath each of the local plantation tree genera as well as beneath grassland or other indigenous vegetation at that location. In the case of plantations, the chosen sites had supported that tree type for at least twenty years. In South Africa the predominant timber plantation trees are eucalypts (mostly *Eucalyptus grandis*), pines (*Pinus patula*, *P. elliottii*, *P. taeda* and *P. radiata*) and black wattle (*Acacia mearnsii*), and all have been established into short vegetation of grassland or scrub (fynbos). The actual timber species grown depends on the geographical location; all cover types are not represented at each location. The native vegetation at each location varies. In the summer rainfall region, i.e. the eastern seaboard and escarpment areas (locations 1–8 in Table 1), the native vegetation is sub-tropical, fire sub-climax grassland, which is seasonal except on the coast. The grasslands are maintained by annual or biennial burning. In the Mediterranean type climatic zone of the Western Cape Province (locations 9 and 10 in Table 1) the native vegetation is fynbos, a fire-maintained sclerophyllous scrub unique to the southern tip of Africa. The fire cycle in fynbos is around 10 years, though highly variable. Throughout the sampling area, native evergreen forest occurs in isolated fire refuge sites. Where forest occurred in close proximity to the sampling points, soils from beneath this cover type were also sampled.

At each of the 10 locations, under as many vegetation types as were represented (Table 1), soil samples were collected as near to each other as possible (usually within 50 m), so as to reduce the variability in soil properties which was not due to the vegetation supported by that soil. Uniformity of soils from one location was determined by observation in the field; at four locations additional samples were taken to account for inclusion of local variations in conditions. In total 38 samples representing different combinations of location, vegetation type and soil were included in the analysis. The origin (location), parent material, soil types, organic carbon content and texture class of the sampled soils are summarised in Table 1. The forestry areas of South Africa are the high rainfall areas; the soils are typically highly leached, freely draining and dominated by kaolinitic and sequioxidic mineralogy. While clay mineralogy was not measured specifically, it is not expected to vary substantially between sites. The general geographic locations of the sample sites are shown in Fig. 1.

2.3. Soil analyses and tests

In the laboratory, the soil samples were passed gently through a 2 mm sieve and dried. Sub-samples were submitted for standard laboratory analyses. Organic carbon was determined by the Walkley–Black method. Particle size distribution was determined by sieving of the sand fraction and the pipette method used to separate coarse (20–50 μm) and fine (2–20 μm) silt fractions from clay (<2 μm). Sieve openings of 0.5, 0.25, 0.106 and 0.053 mm were used to separate coarse, medium, fine and very fine sand fractions. The soils were then subjected to four soil wettability tests. The range of tests used was expected to provide complementary information on soil wettability.

2.3.1. Water drop penetration time

Wettability is most easily conceived of as the speed with which a water drop penetrates a soil, or is absorbed. Anything less than immediate absorption indicates less than perfect wettability. The water drop penetration time test in reality often measures persistence or stability of repellency, as drops which initially are not absorbed may enter the soil after some period of time (Watson and Letey, 1970; DeBano, 1981).

In the first test, water drop penetration time (WDPT) was the time, measured in seconds to a maximum of 300, for a water drop to be absorbed into a smoothed surface of the soil. For each measurement, the mean of six drops across the surface of the prepared soil was recorded.

A second and analogous test used a miniature ring infiltrometer as proposed by King (1981). Here, the time for a known depth of water to infiltrate was measured, and expressed as an infiltration rate (IR). The ring was made from perspex tube with an inside diameter of 25 mm, with the lower end of the ring sharpened so as to displace the soil outwards. Before use the rings were dipped in a solution of paraffin wax in xylene and allowed to dry, thus rendering them water repellent to avoid an edge effect. The ring was pushed 10 mm into the soil surface and a measured depth of water (10 mm) was added. The depth of water absorbed (to a minimum of 5 mm) was divided by the time taken for its absorption (to a maximum of 15 min).

2.3.2. Critical surface tension

Resistance to wetting can be overcome by reducing the surface tension of the fluid. The wettability of a soil thus can be characterised by its so-called critical surface tension (CST) which is the highest surface tension to readily wet the soil (Watson and Letey, 1970). This same method has been termed the molarity of ethanol droplet (MED) test when the molarity of the aqueous ethanol drop rather than its surface tension is reported (King, 1981).

The test measured the CST, being the highest surface tension ($\mathrm{N\,m^{-1}}$) which readily wet the soil. This was measured using a range of aqueous ethanol solutions of varying molarity and hence surface tensions (completely wettable soil will be readily wet at zero molarity of ethanol). Ready wetting was defined as not instantaneous, but a penetration time of between 1 and 2 s. The test was repeated up to six times across the prepared surface and the CST that was representative of the soil recorded.

2.3.3. Liquid–solid contact angle

The wetting angle between a liquid and a solid, formally termed the liquid–solid contact angle, is also used to describe the wettability of the solid's surface. In porous media this contact angle is determined from a capillary tube model and refers to the apparent angle the water meniscus makes with the pore wall (DeBano et al., 1967). In soil-water systems the contact angle is usually assumed to be zero, though laboratory determinations of the apparent advancing contact angle seldom show this for even readily wettable soils.

The fourth test was measurement of the apparent advancing contact angle by the equilibrium capillary rise method of Letey et al. (1962). Prior to being packed with soil, glass columns, 500 mm long with an inside diameter of 25 mm, were coated with a thin film of paraffin wax and then air-dried to make the glass water repellent. Detailed but unreplicated measurements of the rate of capillary rise of water were taken (up to the assumed equilibrium height reached at 24 h), as these data give a good indication of the effects of water repellency on the hydraulic properties of a soil.

The first three tests were repeated three times on sub-samples of each soil, but the capillary rise tests were performed only once for each soil of which a large enough sample was available. For the first three tests, soil samples were placed in small bowls and the surface smoothed by gentle patting with the bottom of a glass beaker to reduce the gross roughness of the surface. Another measure of repellency, the repellency index (RI) was derived by dividing WDPT by

Table 2
Simple correlations between five measures of water repellency and some potential predictor variables for a sample of South African forestry soils. Repeat and auto-correlated comparisons have been omitted (RI, repellency index = WDPT/CST; NS, not significant, i.e. $\alpha \geq 0.1$; $^{**}\alpha < 0.01$)

Key: Pearson's ρ/probability $>|\rho|$ under H_o: $\rho = 0$ / (number of observations)

	WDPT	CST	ACA	IR	RI
CST (critical surface tension)	−0.88** 122	1			
ACA (apparent contact angle)	0.78** 41	−0.76** 41	1		0.79** 41
Height of capillary rise of water	−0.76** 41	0.74** 41		0.62** 41	−0.77** 41
IR (infiltration rate)	−0.67** 123	0.78** 122	−0.67** 41	1	−0.66** 122
Specific surface area of soil	−0.14 NS 123	0.26** 122	−0.07 NS 41	0.14 NS 123	−0.14 NS 122
Sand fraction	−0.06 NS 123	−0.02 NS 122	−0.10 NS 41	−0.14 NS 123	−0.08 NS 122
Clay fraction	−0.14 NS 123	0.26** 122	−0.01 NS 41	0.14 NS 123	−0.14 NS 122
Organic carbon content	0.49** 123	−0.52** 122	0.44** 41	−0.41** 123	0.52** 122

the CST (Letey et al., 1975). This index has meaningless units, but combines the results of the two tests to provide an extended range of repellency ratings along a single axis.

2.4. Data analysis

The repellency scores for the various soils were analysed by the general linear model (GLM) procedure of the SAS statistical package (SAS Institute, 1985). The GLM procedure is appropriate for unbalanced designs and allows the use of continuous and class variables as predictor or explanatory terms. The unbalanced design resulted from the unequal numbers of and different types of vegetation at each sampling location. Harper and Gilkes (1994) showed that the combination of numerous soils characteristics better explains the variation of repellency than single variables, and that multi-variable regression could be used successfully to predict the risk of repellency at the scale of a regional soil survey. Therefore, as a retrospective exercise, multiple regression analysis was also performed on the repellency scores using organic carbon and soil texture variables as predictor terms. After both types of analyses the model residuals were checked for random distributions.

Analysis of variance and regression analysis were performed on the dependent variables CST and ACA only. The WDPT scores provide little discrimination amongst all non-wettable soils: the distribution of this variable tends to be strongly bi-modal with large numbers of either low or very high scores for wettable or non-wettable soils with few scores in the middle of the scale. Similarly, the derived RI has a strong bi-modal distribution. The infiltration rate (IR) scores were all concentrated at the low end of the scale and provided little discrimination between the various samples (Figs. 2–4). These variables, WDPT, RI and IR, have distributions that are far from normal, that could not be normalised by transformations and were, therefore, not used in the analyses of variance and regression modelling.

3. Results

3.1. Simple correlations between variables

The correlations between the different measures of repellency in soils (the dependent variables) and between these measures of repellency and some possible predictor variables are of interest (Table 2) as

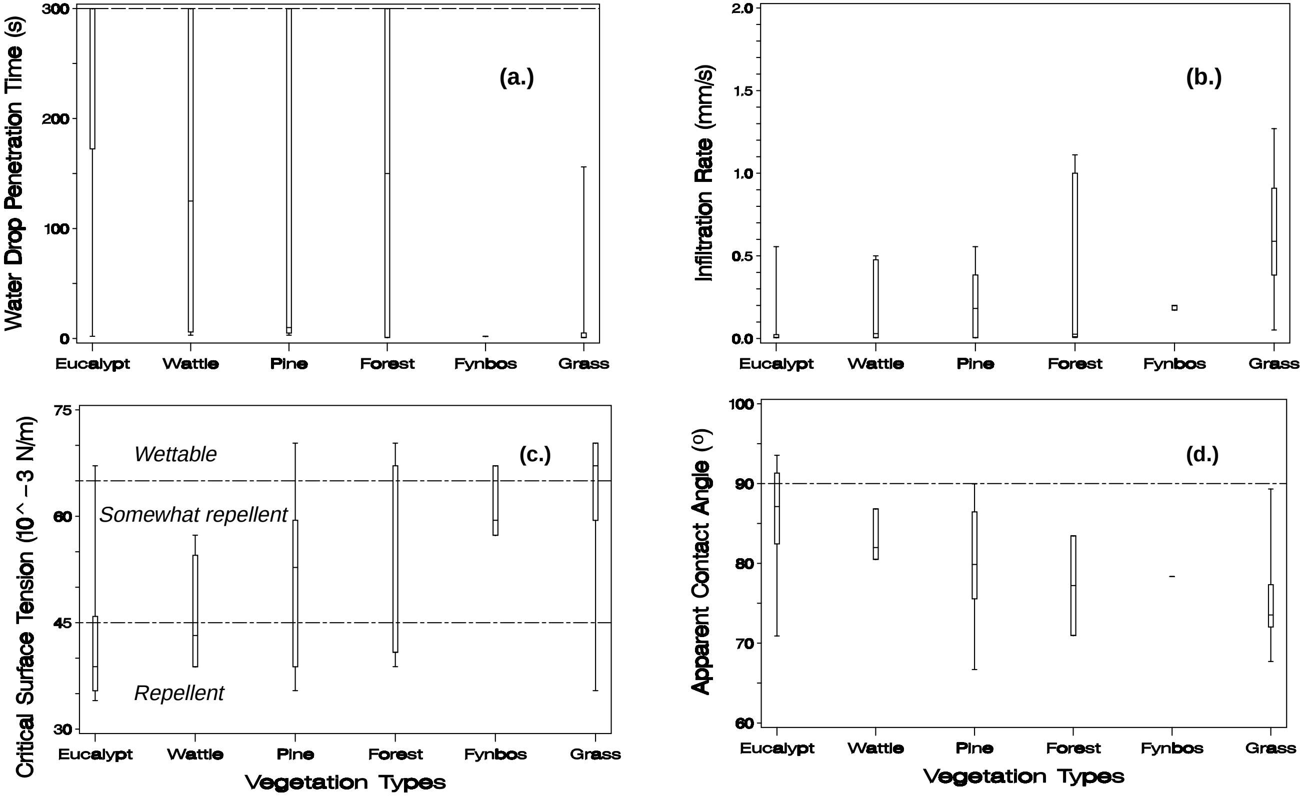


Fig. 2. The water repellency of soils in the forestry regions of South Africa, as measured by four different tests and summarised by vegetation types. (a) Lower values of water drop penetration time, (b) infiltration rate, (c) critical surface tension and (d) higher values of apparent contact angle indicate stronger repellency. Boxes define the 25th and 75th percentiles positions, the bar inside the box shows the median score and the whiskers the 10th and 90th percentiles.

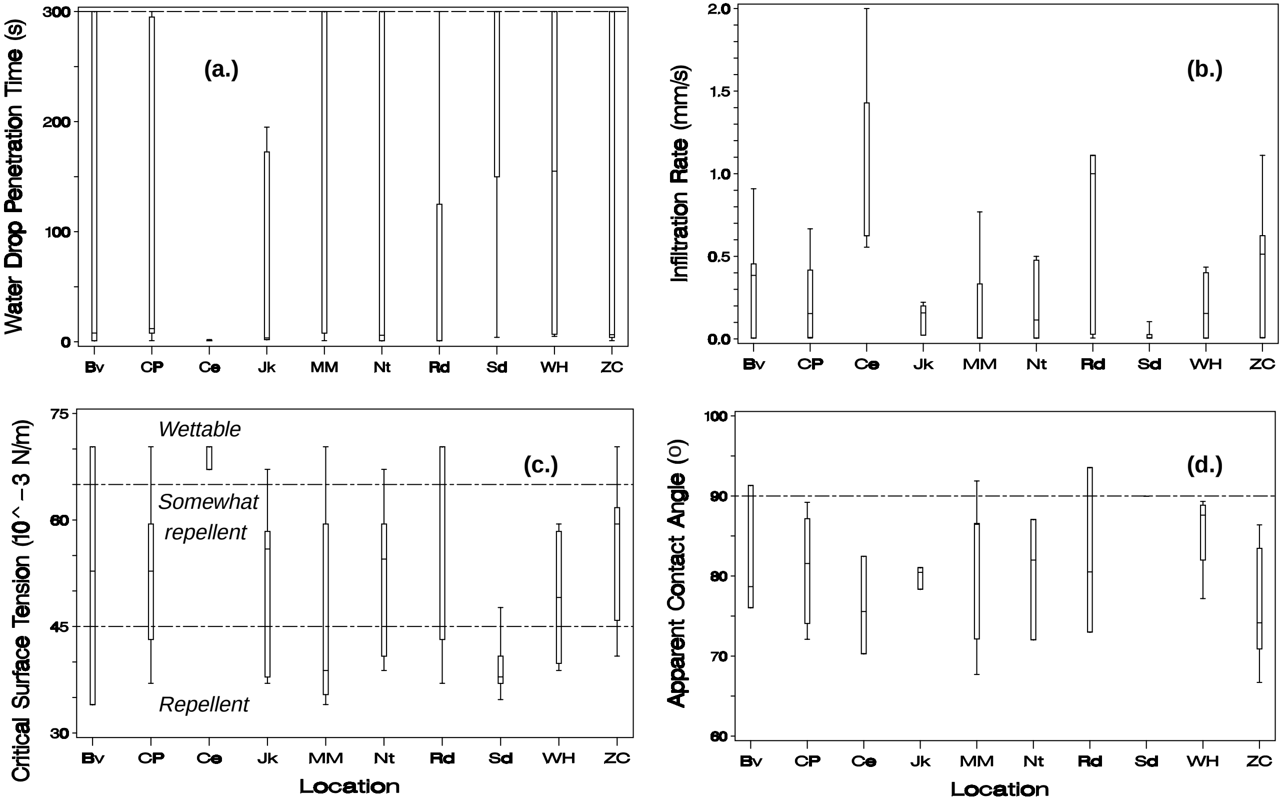


Fig. 3. The water repellency of soils in the forestry regions of South Africa, as measured by four different tests and summarised by the origin (location) of samples. Boxes define the 25th and 75th percentiles positions, the bar inside the box shows the median score and the whiskers the 10th and 90th percentiles.

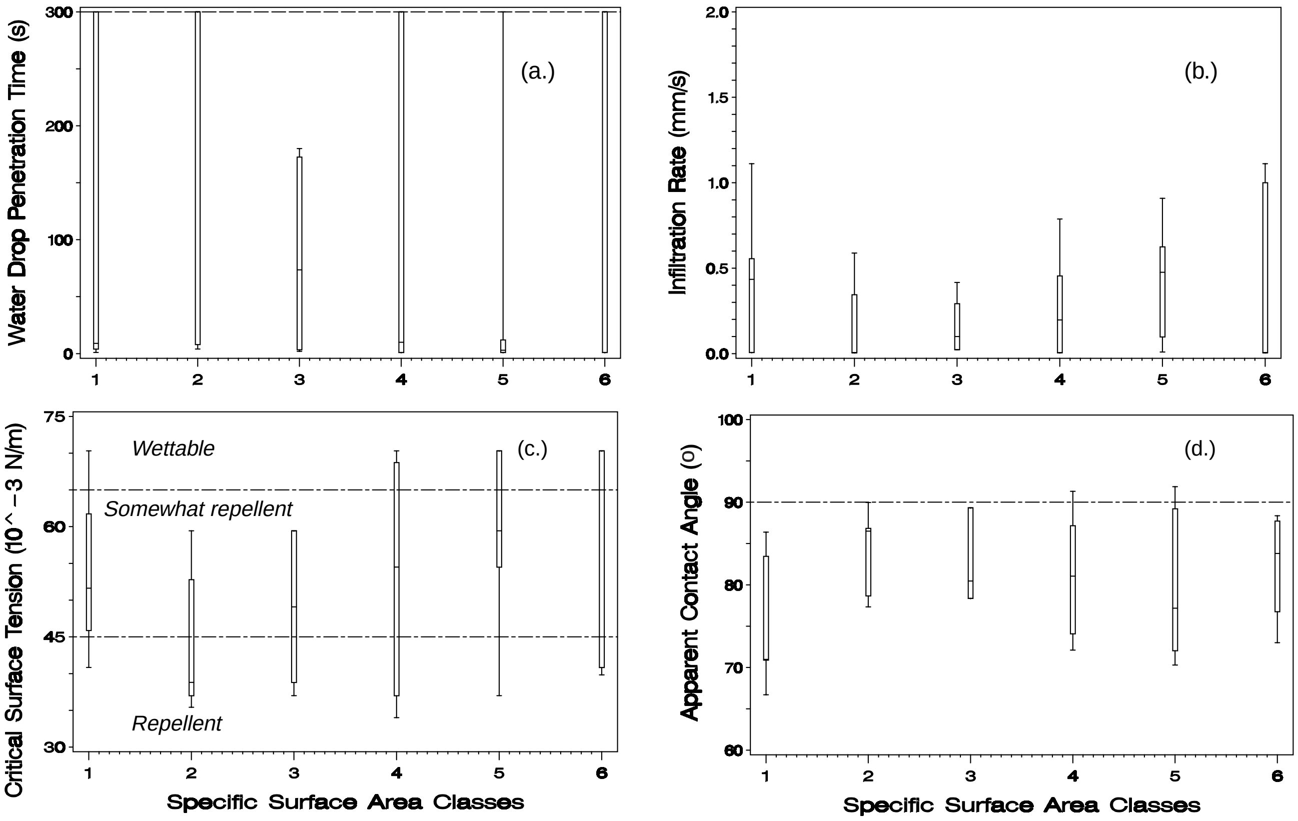


Fig. 4. The water repellency of soils in the forestry regions of South Africa, as measured by four different tests and summarised by classes of specific surface area. Class 1 are the coarsest soils (loamy sands) and Class 6 the heaviest (silty clays)—see text for details.

Table 3
The results of the analysis of variance of two measures of water repellency for a large sample of South African forestry soils (NS, not significant; * ($\alpha > \mathrm{F}) < 0.05$; ** ($\alpha > \mathrm{F}) < 0.01$)

Dependent variable	Model R^2	Source of variation	df	Mean square	*F*	$\alpha > F$
Critical surface tension (109 obs., 5 missing values)	0.91	Locations	9	754	7.1	**
		Vegetation (treatments)	5	1 281	12.1	**
		Replication within experimental units	76	38	0.4	NS
		Sand content	1	462	4.4	*
		Residual error	17	106		
Apparent contact angle (36 obs., 2 missing values)	0.65	Locations	9	70	[a]	
		Vegetation (treatments)	5	113	3.05	*
		Residual error	19	37		

[a] Test not valid without replication.

surveys of this scope are seldom undertaken. Good, though not perfect, correlations were obtained between the different measures of repellency, indicating that while all methods may show a soil to be repellent different methods often highlight either different aspects of or provide more information on the soil's response to wetting.

Based on the hypothesis that repellency is the result of a coating on the soil particles of a hydrophobic organic substance, soil with a low specific surface area (coarse texture) is expected to have a greater likelihood of being repellent. In this study the relationship between texture and repellency is very weak; in the few cases where the correlation is significant the correlation coefficient is nonetheless close to zero (Table 2). Similarly, the proportion of sand in a soil was not correlated with the repellency rating. In short, it was found that soils of any texture could be water repellent. The level of organic carbon was positively related to the repellency rating, displaying significant correlations with all measures of repellency (Table 2).

3.2. Repellency scores

The results of the four tests of soil wettability are summarised by vegetation type in Fig. 2, by sampling locations in Fig. 3 and by soil surface area class (texture) in Fig. 4. In each figure the same plotting symbol is used; the bottom and top of the boxes define the 25th and 75th percentile positions, the bar inside the box shows the median score, while the ends of the whiskers show the 10th and 90th percentile positions. In all the plots it is apparent that, generally, there are a wide range of scores within most of the plotting categories. Though there are minor differences between the results of the different tests, the same general pattern of water repellency emerges.

In Fig. 2a, the WDPT scores range across the whole scale for each vegetation type except fynbos (which had few samples). Nonetheless, it is fairly clear that eucalypt soils are generally hard to wet (median WDPT of 300 s) while soils beneath pines, fynbos and grass are seldom repellent (median WDPTs of 10, 2 and 1 s, respectively). A similar result can be interpreted from the infiltration rate scores (Fig. 2b), though here the wettability of soils from beneath pine and fynbos is lower than that of soils from beneath grass. The CST scores provide the clearest picture of differences between soils of different vegetation types (Fig. 2c); there is a steady increase in wettability from the eucalypts to grass. The same pattern is repeated with the ACA test (Fig. 2d) where the median apparent contact angle is 87° for eucalypt soils and falls steadily through the various vegetation types to a median of 74° for grassland soils.

Where the repellency scores are summarised by location (Fig. 3) it is immediately obvious that values have broad ranges at most single locations. The reason for this is that in most cases the different vegetation types at each location induce repellency at various levels. The exceptions are the Cey and Sd locations where the soils are generally wettable or repellent, respectively, as illustrated by the WDPT, IR and CST plots (3a–c).

The results are also summarised by soil "specific surface area" classes. The class boundaries were selected to allow similar numbers of observations in each group: Class $1 < 0.95\ \mathrm{m}^2\ \mathrm{g}^{-1}$, Class $2 = 0.95 - 3\ \mathrm{m}^2\ \mathrm{g}^{-1}$, Class $3 = 3 - 4.2\ \mathrm{m}^2\ \mathrm{g}^{-1}$, Class $4 = 4.2 - 6.4\ \mathrm{m}^2\ \mathrm{g}^{-1}$, Class $5 = 6.4 - 8\ \mathrm{m}^2\ \mathrm{g}^{-1}$ and Class 6 $> 8\ \mathrm{m}^2\ \mathrm{g}^{-1}$. When the repellency results are plotted against these classes (Fig. 4), ranging from loamy sands (Class 1) to silty clays (Class 6), it is again clear that scores vary over a wide range within each texture class. There is no trend across the texture range, and it appears that texture of the soil alone offers little explanation of a soil's likelihood to develop repellency. By the ACA test (Fig. 4d) the Class 2 and 6 soils (loams and silty clays, respectively) are most repellent (median values of 86.5 and 83.4, respectively). By the CST test the Class 2 and 6 soils are again most repellent (median values of 38.8 and 40.8 $\mathrm{N\ m}^{-1}$), while the other four texture classes have median scores clustered between 49.1 and 54.5 $\mathrm{N\ m}^{-1}$.

3.3. Analysis of variance

The results of the analyses are shown in Table 3. Sources of variation, other than the main effects of vegetation and location, are only included in the table of results where they were statistically significant. There was no significant interaction between location (or lithology) and vegetation, so main effects were tested with the residual of the full model. Different results were obtained with the different measures of repellency (Table 3).

In models for both dependent variables (CST and ACA) there was a portion of unexplained variance, though the CST scores were much more successfully modelled, with 91% of the variation explained, as opposed to 65% of the variation in the ACA scores (Table 3). For both dependent variables, vegetation type explained most variance and this was a significant effect in both models (Table 3). Without replication of the ACA measures the test of location effects was not valid. However, it is apparent from the distributions of the ACA variable in Fig. 4d that location is not a source of great variation in the results. The only significant differences between vegetation types in terms of ACA scores, by Duncan's multiple range test, is between the means for the two short vegetation types, grass and fynbos, as opposed to and the other vegetation types, all tree types.

For the dependent variable CST, location (which generally relates to the geological type) was a secondary but significant effect. Sand content (or specific surface area or clay content individually) provides some additional explanation but is barely statistically significant (Table 3). Organic carbon content, as an additional term, was not a statistically significant predictor. Duncan's multiple range test shows that the mean CST scores for grass and fynbos (63 and 61 $\mathrm{N\ m}^{-1}$, respectively) are significantly higher (i.e. less repellent) than those of the other vegetation types, though the difference between fynbos and pine soils, with a mean CST of 51 $\mathrm{N\ m}^{-1}$, is not significant.

3.4. Multiple regression models

Various possible regression models using the soil variables of organic carbon content (OC), specific surface area (SfA), sand and clay content as possible predictors of ACA and CST were tested. Only OC content was a significant ($\alpha < 0.05$) predictor of ACA, though the model

$$\mathrm{ACA}(^\circ) = 74.3(\pm 2.2) + 0.94(\pm 0.29)\mathrm{OC}(\%)$$

only explains 24% of the variance in the ACA values. CST scores are more successfully predicted by the same group of soils characteristics. The organic carbon and specific surface area were both significant predictor terms in the model

$$\mathrm{CST}(10^{-3}\ \mathrm{N\ m}^{-1}) = 58.7(\pm 2.2) - 2.4(\pm 0.27)\mathrm{OC}(\%) + 1.8(\pm 0.3)\mathrm{SfA}(\mathrm{m}^2\ \mathrm{g}^{-1})$$

which explained 46% of the variance in the CST scores. A similar degree of explanation could be obtained from models where clay or sand content was substituted for surface area, but in all cases it is the OC content that explains most of the variation.

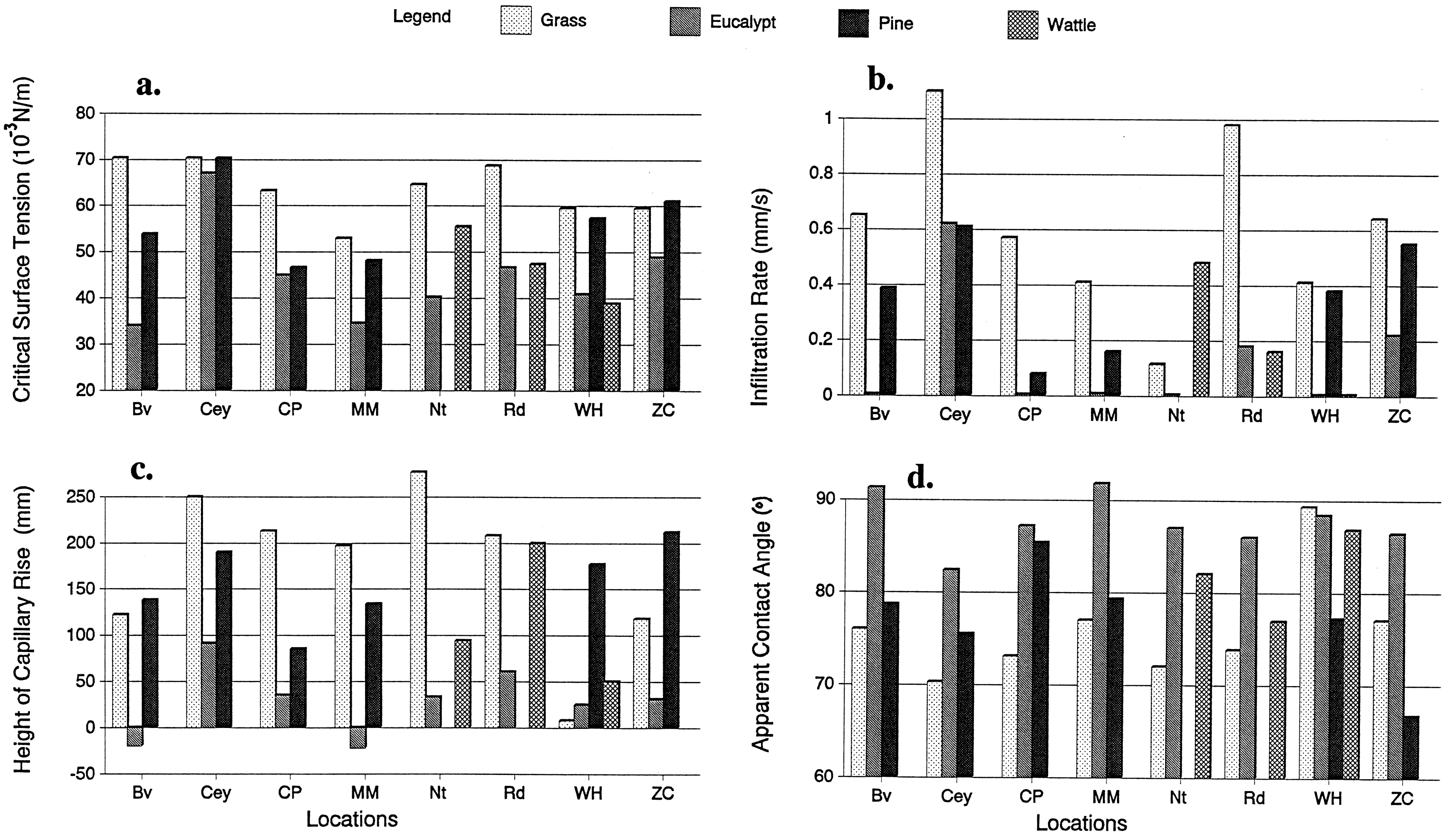
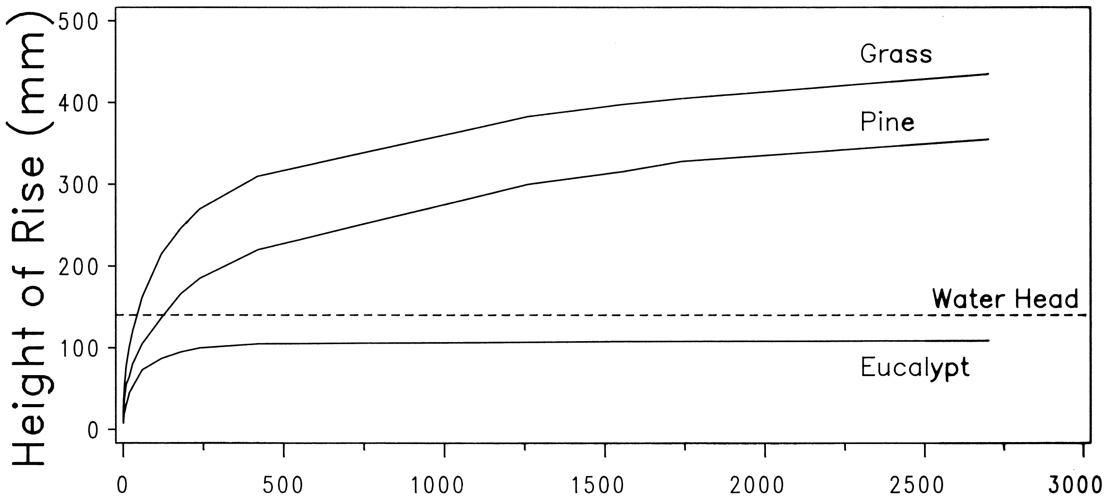


Fig. 5. The effect of vegetation type on four measures of soil wettability, within each of the eight native grassland locations where timber types have been planted. (Note that only a subset of the vegetation types grow at each location.)

a. Cathedral Peak – sandy loam



b. Windy Hill – loamy sand

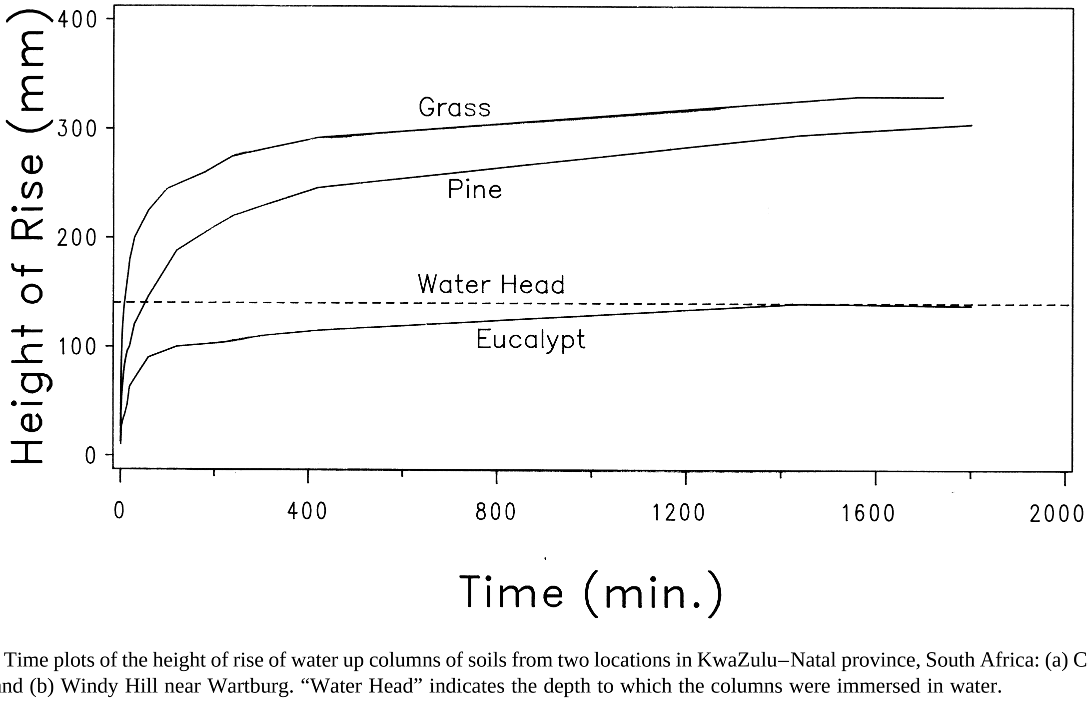


Fig. 6. Time plots of the height of rise of water up columns of soils from two locations in KwaZulu–Natal province, South Africa: (a) Cathedral Peak and (b) Windy Hill near Wartburg. "Water Head" indicates the depth to which the columns were immersed in water.

3.5. The effect of vegetation type

In virtually all areas, as determined by four different measures (Fig. 5), soils under eucalypts were most repellent, with a median WDPT of 300 s, median CST of 0.038 N m^{-1} and median ACA of 87°. Critical surface tension values (Fig. 5a) above 0.065 N m^{-1} would indicate a wettable soil, while values less than 0.045 N m^{-1} indicate a repellent soil. By this classification grassland soils at three locations, **MM**, **WH** and **ZC**, two of which had sandy soils, were somewhat repellent. By contrast, soil from beneath eucalypts at only one location, **Cey**, was wettable, and at two others, **Rd** and **ZC**, the soils were somewhat repellent.

A similar pattern emerges from the results of the other tests. At only one location, **Cey**, did soils from beneath eucalypts have a reasonable infiltration rate, a mean of 1 mm s^{-1} (Fig. 5b), and even this was much lower than in the same soil beneath grassland. Except for one location, **WH**, soils from beneath eucalypts had the highest apparent contact angles, which relates to the very low or negative capillary rise in the eucalypt soils (Fig. 5c and d). A generalised ranking of the repellency developed under different vegetation types (Fig. 5) would be that grassland and fynbos soils are wettable, pine soils are somewhat repellent, soils beneath native forest and wattle vary from somewhat repellent to repellent, and eucalypt soils are repellent.

The soils from fynbos sites are closest to the grassland soils in being least repellent, and they also share the characteristic of being more regularly burned. This regular removal of plant litter may in part explain the weak development of hydrophobic substances. The one grassland soil which had moderate to strong repellency was from the Windy Hill (**WH**) site. This particular soil was coarse-textured and from a fire-refuge site (subject to little burning), allowing a build-up of plant litter over many years.

Typical of the effect of water repellent soil on water movement is the resistance to capillary rise. Amongst other things, capillary rise is dependent on the contact angle between the soil and water. Where this angle is very high, capillary rise will be restricted. The capillary rise curves for the same soils under different vegetation types (Fig. 6a and b) illustrate this effect of contact angle. Actual capillary rise occurs only once water has risen above the level of the water in which the columns are standing. At both sites, Cathedral Peak (a) and Windy Hill (b), therefore, no real capillary rise took place in the eucalypt soils. Despite the positive head, penetration of water into the soil columns did not reach the level of the head over the two days of measurement. This resistance to the entry of water into the soil columns, despite a positive head, was typical of the eucalypt soils. The capillary rise in pine soil samples was also depressed below that of grassland, but to a minor degree.

3.6. The effect of soil texture

It is apparent from the correlations in Table 2, and the results of the analysis of variance (Table 3) and regression that the risk of water repellency is not determined by soil texture, though it may be a minor contributory factor. Some fine-textured soils, such as the silty clay loam from **MM** and the silty clay at **Rd** (Table 1), were highly repellent (Fig. 5). The silty clay loam derived from shales at **Cey** though showed no tendency to repellency (Fig. 5). There was a tendency though for sandy soils beneath grass to show greater repellency than heavier soils beneath grass, e.g. **WH** and **ZC** versus **Nt** and **Rd**.

4. Discussion

4.1. On the different measures of repellency

Water drop penetration time is a useful screening test in that it is a quick and easy test for the presence or absence of repellency. But in soils where repellency is well developed WDPT is unable to provide any distinction between different repellent soils. The related infiltration rate test was similarly unhelpful on the large proportion of repellent soils where there was essentially no measurable infiltration over the duration of the test. This test had the additional disadvantage of requiring a larger soil sample and much more time and effort than the WDPT test. The infiltration rate test might have been more useful for a range of less water repellent soils. The contact angle measurement by means of equilibrium capillary rise was a very demanding test in terms of time, space, equipment and size of soil sample. Because in running the test a head of 150 mm had been imposed on the soil columns, the method provided a very graphic illustration of the effect of repellency on the hydraulic behaviour of the soil, and the height of rise of water was very indicative of repellency in soils of similar texture. However, the derived apparent contact angles have a fairly narrow range (67–94°) and did not provide great discrimination between soils.

The critical surface tension test had none of the disadvantages of the above tests: it is quick, easy and cheap to run, provided a good range of normally distributed values and a high level of discrimination between soils of different wettability. Because the test is quick and simple it is also easy to replicate and to do repeated measurements. The RI that combines WDPT and CST did not add any value to the CST scores alone because of the strongly bi-modal distribution of the WDPT scores. The different methods used here are reasonably correlated and, by and large, each would have given the same general result in this study. It therefore would make sense, generally, to use just the easiest and most informative CST test.

4.2. Effects of vegetation

The results show that vegetation was the primary determinant of water repellency in a range of different soils. The reason for the differences between the vegetation types was not explored specifically. But two factors are suggested as possible explanations: firstly, the genus-related chemistry of the plant litter itself and, secondly, the fire-free interval during which litter accumulates. The eucalypts are known for the high levels of oils in their leaves and the soil surface below eucalypts typically has a low cover of herbaceous plants. These factors seem to relate to the litter of eucalypts producing organic leachates that inhibit plant growth beneath their canopies, perhaps by means of inducing repellency in the soils. The leachates from the litter of wattle trees (*Acacia mearnsii*) has a less obvious source of hydrophobic substances than the eucalypts, though the ground beneath wattle plantations is, similarly, well known to be fairly bare.

In the case of the native vegetation covers, the period of litter build-up between fires is thought to be a factor. In the indigenous, evergreen forests there is the longest fire-free period during which litter accumulates, while both fynbos and grassland are fire-maintained vegetation types and fires occur at regular intervals. During these fires litter is consumed and this is thought to reduce the potential for hydrophobic substances to develop in the decomposing plant litter. Of these two factors, the chemistry of plant litter appears overall to be more important than the role of a fire-free interval.

4.3. Influence of soil characteristics

The available soil characteristics, organic matter content and texture, were unable to explain the bulk of the variation in repellency (46% of CST and 27% of ACA scores). This was not altogether in contrast to the findings of Harper and Gilkes (1994) where a model incorporating organic carbon and clay content explained just 47% of the variation in WDPT scores; addition of reactive iron as a predictor variable in their model provided a total of 63% explanation of the variation.

Repellency has frequently been associated with coarse textured soils (Jamison, 1946; Roberts and Carbon, 1972; Bishay and Bakhati, 1976; Ruyten and de Goede-Hiensch, 1988). In this study, though, soil texture did not play a big role in determining the risk of repellency. The reasons for this are not clear, though the influence of vegetation was perhaps just much stronger and overshadowed any texture effects. Alternatively, the typically well-developed micro-aggregation in heavier soils might have allowed them to present a lower active surface when wetting from the dry state. Although the role of texture was hardly significant overall, there was evidence that texture does play a role. The sample of indigenous forest soils were generally highly repellent, but were also all coarse, and the only grassland soils to have well developed repellency were those that had a coarse texture.

4.4. Implications of the results

The results indicate that water repellent soils are a common feature of South African forestry soils, at least when in the dry state. Because repellency is more pronounced when a soil is dry, its presence may not always be noticeable in field conditions. Also, it is unlikely that water repellent soils will occur in a continuous layer in the soil. Observations showed that repellency is usually poorly developed or absent at certain spots in a given locality, where infiltration and percolation can occur at high rates. Such points may be alongside rocks, disturbed soil, old root channels or other macropores. Consequently, subsoils may appear to be normally wetted after a rainstorm, while overlying soils are unexpectedly dry.

Channelling of water to preferred pathways as a result of water repellent soils may not lead to surface wash or erosion while there is a reasonable ground cover of plant litter or where the slope is gentle. Ground cover provides added opportunities for rain water to be detained and retained at the point where it falls, reduces the velocity of any surface flow that may develop, and can trap soil which is eroded by rainfall and overland flow.

The most obvious effect of water repellent soils is that they impede infiltration and percolation in the soil, which may result in the generation of overland flow and the restriction of percolation to preferred pathways in the soil profile (Burch et al., 1989; Van Dam et al., 1990; Ritsema and Dekker, 1996). Especially when repellency is highly developed, as observed in soils under eucalypts, water may be channelled to preferred paths for rapid and deep percolation. At depths below those normally classed as the agricultural soil, large and deep-rooting trees can exploit the water which is not available to shallowly rooting plants. Allison and Hughes (1983) found, with the aid of tracers (stable isotopes of oxygen and hydrogen), that rain water on eucalypt savanna in semi-arid South Australia percolated to depths of at least 12 m below the surface, whilst rain on adjacent agricultural lands planted to cereals, with a much lower water use, had not penetrated more than 2.5 m in the same time (17 years). These authors suggest that eucalypts channelled water into root channels that acted as macropores for water transport to the water table.

A similar situation has been observed in an experimental eucalypt planting near Greytown in the KwaZulu–Natal midlands, South Africa. A neutron moisture instrument was used to follow the wetting fronts below ponded water into dry soil. In addition to the slow and gradual wetting from the surface that was expected, there was a simultaneous and rapid increase in wetness at the bottom of the profile (Boden, 1992). In this case the author suggests that large cracks in the soil profile, caused by the desiccating effect of the eucalypt plantation, provided the channels for the rapid transport of water.

Revegetation of sites previously supporting eucalypts may be difficult because of the persistence of water repellency in the soil. Delayed revegetation would leave the site exposed to erosion for longer. There are indications that this has been the case on certain sites cleared of eucalypt vegetation on Table Mountain in the Western Cape Province of South Africa (personal observation).

5. Conclusions

The water drop penetration time and infiltration rate tests did not prove to be very useful, particularly in that they could not distinguish between degrees of stronger repellency, and both produced strongly non-normal distributions. Determining apparent contact angle by equilibrium capillary rise provides an integrated illustration of the effects of repellency on the hydraulic properties of the soil, but the range of ACA scores was narrow, being limited to between 67 and 94° for readily wettable to severely repellent soils. This ACA test is also extremely demanding in terms of time, facilities, effort and size of soil sample. The critical surface tension test was the most useful and efficient of those tried in this experiment. It is quick, easy and cheap to run, provides a good range of normally distributed values and a high level of discrimination between soils of different wettability.

Water repellency is a common feature of the soils of timber plantations in South Africa. Plantations of eucalypts (*Eucalyptus* spp.) and wattle (*Acacia mearnsii*) and indigenous evergreen forest in general, relative to other vegetation types in the forestry regions of South Africa, induce a high level of water repellency in the soil beneath them. Soils of all texture classes are vulnerable to the development of water repellency. This is true for the range of soils sampled, and appears to occur in all the major timber production areas in South Africa.

Strong repellency develops without the heating of soils during fires. Thus these sites have a higher risk of overland flow and soil erosion when the sites are cleared of ground cover, such as after a fire. Soils beneath pine plantations do not have very high levels of repellency, but may have more chance to develop extreme repellency following wildfire than the other plantation types, the soils of which already show high levels of water repellency in the dry state.

Because water repellency is more pronounced when a soil is dry, its presence may not always be noticeable in the field. Also, surface storage of rain water in the plant litter on the forest floor may disguise the fact that infiltration and percolation are impeded. Consequently, water repellent soil may not be a problem until canopy and ground cover are removed during clear-felling, or as a result of a fire. Once surface storage capacity is removed and the soil is exposed to drying, the site is at risk of overland flow occurring during rainstorms, leading to soil erosion and reduced soil water replenishment.

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