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Eucalyptus reforestation induces soil water repellency

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Abstract. There is an increasing interest in eucalypt reforestation for a range of purposes in Australia, including pulpwood production, carbon mitigation and catchment water management. The impacts of this reforestation on soil water repellency have not been examined despite eucalypts often being associated with water repellency and water repellency having impacts on water movement across and within soils. To investigate the role of eucalypt reforestation on water repellency, and interactions with soil properties, we examined 31 sites across the south-west of Western Australia with paired plots differing only in present land use (pasture *v.* plantation). The incidence and severity of water repellency increased in the 5–8 years following reforestation with *Eucalyptus globulus*. Despite this difference in water repellency, there were no differences in soil characteristics, including soil organic carbon content or composition, between pasture and plantation soils, suggesting induction by small amounts of hydrophobic compounds from the trees. The incidence of soil water repellency was generally greater on sandy-surfaced (<10% clay content) soils; however, for these soils 72% of the pasture sites and 31% of the plantation were not water repellent, and this was independent of measured soil properties. Computer modelling revealed marked differences in the layering and packing of waxes on kaolinite and quartz surfaces, indicating the importance of interfacial interactions in the development of soil water repellency. The implications of increased water repellency for the management of eucalyptus plantations are considered.

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Introduction

There is strong interest in eucalypt reforestation, within Australia (Gavran 2013) and internationally (Booth 2013), for timber and pulp wood production and catchment water management (Townsend *et al*. 2012) and increasingly as a carbon mitigation strategy via carbon sequestration or bioenergy production (Wu *et al*. 2008; Mitchell *et al*. 2012; Harper *et al*. 2014). Given the possible scale of activity that may develop, it is important to understand implications for soil and water sustainability (Cowie *et al*. 2006; Payne 2010; Sochacki *et al*. 2013). Although implications of reforestation have been considered in terms of water yield (Jackson *et al*. 2005; Gerbens-Leenes *et al*. 2009), water quality (Diaz-Chavez *et al*. 2011) and soil carbon storage (Cowie *et al*. 2006; Harper *et al*. 2012), the impacts on soil water repellency have not been specifically considered, either in terms of ongoing site management in eucalypt plantations or as part of the sustainability criteria for bioenergy plantations (Scarlat and Dallemand 2011). This is despite the reported association of eucalypts with water repellency in plantation-grown *Eucalyptus globulus* in the Iberian Peninsula (Doerr *et al*. 1998; Ferreira *et al*. 2000; Rodríguez-Alleres and Benito 2011) and in natural forests in Australia (McGhie and Posner 1980; Crockford *et al*. 1991; Prosser and Williams 1998; Harper *et al*. 2000).

Across southern Australia, large areas (~10 Mha) of formerly eucalypt-dominated lands cleared for agriculture experience varying degrees of water repellency (Blackwell 2000; Harper *et al*. 2000). It is within these regions that much of either the existing or the planned eucalypt reforestation for carbon mitigation will occur (Mitchell *et al*. 2012).

Water repellency generally develops because of the formation of hydrophobic coatings on soil particles and aggregates (Wallis and Horne 1992; Doerr *et al*. 2000), and this reduces water infiltration rates. Even for porous soils, where water may be able to occupy the larger pores, the individual grains will not be in contact with the water, so that infiltration is inhibited. Alternatively, the hydrophobic material may occupy the pores rather than coating individual grains, which also results in reduced wettability. On a hydrophilic surface, water spreads over the soil in a continuous film, but on a hydrophobic surface the water forms into beads on the soil surface (Doerr *et al*. 2000). Water repellency is broadly related to a soil's surface area and is thus more likely to occur on sandy-surfaced soils (Harper *et al*. 2000), although there are reports on soils with more clayey textures (McGhie and Posner 1980). The occurrence of water repellency is also commonly linked to the surrounding vegetation (DeBano 1981; Wallis and Horne 1992), and although in some situations it can be exacerbated by wildfire (DeBano 1981), this effect is not always consistent (Doerr *et al*. 1996).

Water repellency has several implications for soil management. Water repellency reduces the infiltration capacity of soils and is often associated with increased runoff and erosion (Witter *et al*. 1991; Ferreira *et al*. 2000; Shakesby *et al*. 2000; Doerr *et al*. 2003; Coelho *et al*. 2005). Preferential flow patterns can be established because of the presence of water repellency, which through finger-flow increases the likelihood of harmful substances being leached into groundwater (Bauters *et al*. 1998). Within agricultural regions, water repellency is often associated with poor crop yields due to uneven wetting of the soil and poor germination (Blackwell 2000).

Given the widespread extent of both existing and planned eucalypt reforestation in southern Australia, the association of this species with water repellency (McGhie 1980; Ferreira *et al*. 2000; Shakesby *et al*. 2007), and reforestation occurring in a region in which water repellency has been extensively reported on agricultural lands (McGhie 1980; Harper *et al*. 2000), this study aimed to (*i*) quantify the effect of *E. globulus* reforestation on the degree of water repellency in the soils of south-western Australia compared with other land uses (agriculture and natural bush land); (*ii*) investigate possible relationships between soil properties and water repellency through statistical analysis and simulations of interactions between particle surfaces and waxes; and (*iii*) explore the likely implications for plantation and water-resource management.

Methods

Site selection

Soils were sampled in 2001 as part of a study on the effects of *E. globulus* plantations on soil fertility in the south-west of Western Australia (Grove *et al*. 2001; Mendham *et al*. 2002*b*, 2003, 2004; O'Connell *et al*. 2003). Thirty-one sites (Table 1) were selected to span the climatic range (mean annual rainfall 574–1417 mm/year) of *E. globulus* in the region (Grove *et al*. 2001). Sites were defined as a pair of adjacent *E. globulus* plantations and pasture on the same landform element, and were paired on the basis of soil morphology and total nitrogen (N) and phosphorus (P) concentrations as an indicator of site fertiliser history. Adjacent plantation and pasture areas had the same land-use history before plantation establishment. For 10 of the 31 sites, an additional comparison was made with native vegetation ('bushland'), which was dominated by the native trees *E. marginata* and *Corymbia calophylla*. Main properties of each of the 31 sites, including World Reference Base for Soil Resources classifications (FAO 2014), are summarised in Table 1; additional soil and site properties and

Table 1. Summary of major physical and chemical soil characteristics at each of the sites (average across the land uses)
All of the sites had a paired comparison between *E. globulus* plantation (PL) and pasture (PA); sites marked with an asterisk also had a native forest (bushland) comparison. CS, Coarse sand; FS, fine sand; ST, silt; CL, clay

Site	Soil Classification (FAO)	Location (°S)	(°E)	Rain (mm year^{-1})	pH	TN	OC	Exchang. cations (cmol^{+} kg^{-1})				Particle size analysis				Water repellency	
						(%)		Ca	Mg	K	Na	CS	FS	ST	CL	PA	PL
													(%)			(M ethanol)	
Allison	Ferric Acrisol	34.62	117.30	776	5.0	0.41	4.9	2.51	0.74	0.12	0.37	48.2	28.8	5.0	18.0	0.0	0.4
Andrews*	Ferric Acrisol	34.93	118.01	821	4.4	0.22	3.1	1.30	0.57	0.15	0.19	33.3	59.9	2.6	4.2	0.0	1.8
Anning*	Ferric Acrisol	34.95	116.88	1289	4.5	0.35	4.3	2.90	0.62	0.21	0.16	53.3	31.0	5.9	9.8	0.0	1.6
Ayers*	Xanthic Ferralsol	33.81	116.06	946	5.3	0.47	4.9	5.19	1.08	0.37	0.24	26.3	44.4	13.6	15.7	0.0	0.0
Browne	Ferric Acrisol	33.95	116.02	995	4.7	0.34	4.2	1.93	0.32	0.15	0.10	49.4	31.7	6.9	11.9	0.0	0.0
Clarke 1	Ferric Acrisol	33.35	116.77	580	4.8	0.16	1.8	1.02	0.69	0.11	0.17	66.5	22.5	5.0	6.1	0.0	0.0
Clarke 2	Ferric Acrisol	33.36	116.78	580	4.6	0.20	2.8	2.21	0.51	0.16	0.30	67.2	22.8	3.3	6.6	0.0	0.0
Decke 1	Haplic Arenosol	34.22	116.25	964	5.1	0.27	3.3	2.70	0.45	0.20	0.09	40.0	48.8	4.2	6.9	0.0	1.0
Decke 2	Ferric Acrisol	34.23	116.26	964	5.0	0.33	4.2	2.13	0.37	0.19	0.16	45.9	38.2	6.6	9.3	0.0	0.6
East	Haplic Arenosol	34.25	116.21	1023	5.0	0.68	5.5	4.49	0.70	0.22	0.18	28.2	41.6	17.0	13.2	0.2	0.0
Flanagan 1	Xanthic Ferralsol	34.70	116.14	1417	5.3	0.36	5.0	3.04	0.94	0.40	0.24	34.8	30.1	14.3	20.8	0.0	0.0
Flanagan 2	Ferric Acrisol	34.70	116.13	1417	5.2	0.30	3.4	2.00	0.53	0.15	0.09	52.9	27.4	8.4	11.3	0.0	0.0
Geary	Ferric Acrisol	33.71	115.05	1028	5.3	0.38	5.3	3.60	1.20	0.24	0.27	49.7	27.5	5.8	17.0	0.0	0.6
Gibbs*	Haplic Arenosol	33.50	116.52	732	4.9	0.15	2.1	2.29	0.52	0.07	0.07	77.0	19.9	1.0	2.1	0.2	0.2
Hall 1*	Ferric Acrisol	34.47	117.43	645	5.0	0.25	3.3	1.97	0.56	0.12	0.22	52.3	35.4	3.1	9.3	0.0	1.4
Hall 2	Haplic Arenosol	34.49	117.39	661	4.7	0.19	2.6	1.82	0.42	0.09	0.12	55.3	39.3	1.7	3.6	0.2	1.4
Hartridge*	Gleyic Arenosol	34.25	115.35	1086	4.9	0.26	3.6	1.75	0.42	0.15	0.21	71.8	18.3	2.2	7.6	1.6	2.0
Jeffries 1*	Haplic Arenosol	33.60	116.65	640	5.2	0.07	1.6	2.92	0.59	0.10	0.05	83.3	15.3	0.6	0.8	0.0	0.4
Jeffries 2	Haplic Arenosol	33.60	116.64	640	5.0	0.07	1.3	1.91	0.29	0.09	0.07	71.8	24.7	1.1	2.5	0.0	0.0
Lindsay	Haplic Arenosol	34.01	115.79	1007	4.7	0.46	5.0	2.59	1.15	0.58	0.36	18.2	42.7	19.6	19.5	0.0	0.0
Lubcke 1	Rhodic Ferralsol	33.32	116.58	650	5.1	0.16	2.7	1.74	0.39	0.12	0.20	62.9	25.1	2.7	9.3	0.0	0.0
Lubcke 2	Haplic Arenosol	33.32	116.56	650	5.1	0.33	4.4	3.66	0.55	0.17	0.18	52.0	31.0	4.3	12.7	0.0	0.0
Lynch	Ferric Acrisol	34.68	117.50	724	4.5	0.26	3.2	2.01	0.86	0.17	0.19	55.7	31.0	2.8	10.5	0.0	0.0
Moltoni*	Ferric Acrisol	34.37	115.99	1358	4.7	0.26	3.7	2.23	0.38	0.18	0.08	49.9	29.4	6.9	13.8	0.0	0.0
Oates	Ferric Acrisol	33.69	115.51	926	5.4	0.20	2.6	1.82	0.35	0.17	0.18	43.8	47.0	2.9	6.3	0.0	0.0
Patmore 1*	Haplic Arenosol	34.45	116.75	817	4.9	0.13	2.2	3.50	0.83	0.09	0.08	75.0	21.2	0.6	3.2	0.2	0.0
Patmore 2	Haplic Arenosol	34.41	116.82	826	5.0	0.25	4.1	3.82	0.90	0.22	0.11	45.2	42.7	4.6	7.5	0.0	0.8
Robinson*	Ferric Acrisol	34.07	115.11	1226	4.9	0.42	5.0	2.50	0.61	0.22	0.25	44.0	22.1	8.6	25.2	0.0	0.0
South 1	Xanthic Ferralsol	33.20	116.66	685	4.7	0.19	2.6	2.74	0.52	0.18	0.24	59.1	22.6	5.3	13.0	0.0	0.0
South 2	Xanthic Ferralsol	33.21	116.64	681	4.7	0.23	3.7	3.15	0.68	0.29	0.88	45.7	37.1	7.1	10.0	0.0	0.0
Walker	Haplic Arenosol	34.62	118.38	574	4.9	0.10	1.8	2.11	0.46	0.09	0.08	47.7	49.8	0.0	2.6	1.8	2.4

correlations with the Australian Soil Classification (Isbell 1996) are described in Grove *et al*. (2001). The sites are representative of those where *E. globulus* has been established on farmland across this region and, apart from the rainfall gradient, encompass major Soil Orders (14 Acrisols, 10 Arenosols, and 7 Ferralsols), and broad dynamic ranges of clay content (0.7–23.8%) and soil organic carbon (SOC, 1.3–6.0%) (Table 1).

The pastures in the study were established 30–74 years before sampling, following the development (e.g. deforestation, fertilisation, seeding) of natural forest or woodland. Pasture sites were managed according to standard agricultural practices in the region (Squires and Tow 1991) and were dominated by annual species, such as subterranean clover (*Trifolium subterraneum*) and capeweed (*Arctotheca calendula*), along with a range of grasses. In this region, agricultural crops such as wheat (*Triticum aestivum*) or oats (*Avena sativa*) are grown irregularly (every 5–10 years) in the pasture sites after tillage to ~0.1 m depth. Sampled areas of native vegetation were typical for the region, with a jarrah (*Eucalyptus marginata*) overstorey and a diverse understorey of perennial shrubs and non-woody, grass-like species as well as winter annuals and some geophytes (Grove *et al*. 2001).

The sampled plantations had been established 5–8 years earlier. Surface soils in the plantations had not been disturbed since being under pasture except along the planting rows, which had been deep-ripped at the time of planting (Grove *et al.* 2001). Only one site had mounding present; however, soil samples were taken from inter-row locations to ensure that the data were not biased.

Soil sampling

Within each site, soils were evaluated to ensure that soil properties were matched for the contrasting land-use types (pasture, plantation, bushland). Soil was sampled along a 40-m transect, and transects were at least 20 m from the boundary between land-use types to avoid any edge effects. Within transects, plots (each 6 m by 10 m, $n = 4$ per transect) were established for sampling soils. Within each plot, six surface-soil samples were collected and then bulked for analysis. For both plantation and pasture, surface soil samples were taken to a depth of 0.2m at intervals of 0–0.1 and 0.1–0.2 m at each site. For the 10 sites where a comparison with natural bushland could be made, samples were taken from 0–0.05 and 0.05–0.1 m. In addition to the surface-soil samples, deeper samples to 1 m depth were taken from one hole per replicate at the subset of 10 sites with the 3-way land-use comparison. Here, the depths sampled were 0–0.05, 0.05–0.1, 0.1–0.2, 0.2–0.3, 0.3–0.5, 0.5–0.7 and 0.7–1.0 m.

Soil analysis

Soils were air-dried and passed through a 2-mm sieve. The <2-mm fraction was analysed for a range of physical and chemical characteristics. Analyses included SOC (Walkley–Black dichromate oxidation technique), Kjeldahl total N and P, exchangeable cations, Colwell (bicarbonate) P and pH (Rayment and Higginson 1992) and particle size analysis using the pipette method and estimation of clay (<2 μm), silt (2–20 μm), fine sand (20–200 μm) and coarse sand (200–2000 μm) (Gee and Bauder 1986).

Characterisation of soil carbon included total carbon by combustion, and carbon composition by ^{13}C cross-polarisation magic angle spinning nuclear magnetic resonance (CPMAS NMR) on a subset of six sites (Mendham *et al*. 2002*b*). The relative amounts of carbon from four broad spectral regions (alkyl, O-alkyl, carbonyl and aromatic) were determined using NMR analysis.

The intensity of water repellency was characterised using the molarity of ethanol (MED) test (King 1981) under standard laboratory conditions on dry-sieved, air-dried soil from <2 m depth. This test uses a series of ethanol solutions at concentrations between 0 and 4 M (increments of 0.2 M), which have different surface tensions. The lowest concentration solution of a droplet (~0.05 mL) with an infiltration time of <10 s is taken as the MED value. Soil samples (~ 50 g) were placed in a Petri dish with a depth of ~1 cm. The MED test was repeated three times on each sample and mean MED values were used in statistical analyses.

Tree measurements

Four tree-measurement plots (average 165 m^2 each) were marked out in each stand in the area where soils were sampled. Tree heights were measured with an electronic clinometer and stem diameters were measured at 1.3 m above the ground. This information was used to calculate the stem conical volume of each stand. The mean annual increment (MAI) in volume over bark (m^3 ha^{-1} year^{-1}) was determined from current total volume and age of the plantation.

Statistical analyses

Our first objective was to evaluate the direct effect of *E. globulus* reforestation on surface-soil water repellency, with a second objective to evaluate covariates of repellency (e.g. soil properties, climate and tree-stand variables).

To evaluate the first objective, we applied a paired Wilcoxon signed-rank test on MED in paired plots within each of the 31 sites. We used this non-parametric test because of a high proportion of zeros in the dataset and related unsuitability of parametric statistical tests. For comparison of bushland, pasture and plantation across 10 sites, we used a Kruskal–Wallis test, which is a non-parametric equivalent of a one-way analysis of variance (ANOVA). In both cases, the individual locations were regarded as replicates and the different land uses as treatments. For the soil depth profiles to 1 m, mean MED values and standard errors were calculated for each sample depth, and the significance of the differences between groups was tested with a one-way ANOVA.

To meet the second objective, we analysed covariates to investigate drivers of repellency at the plot scale ($n = 62$). Repellency (as measured by MED) data contained a large amount of zeros; therefore, we classified data into two groups on the basis of repellency (≥0.1 M MED) *v.* no repellency (0 MED). We then analysed these data using logistic regression. Prior to analysis, we assessed covariates for outliers and collinearity. As expected, soil physical characteristics were highly collinear, so we used silt + clay content as our sole physical soil covariate. Our model set included univariate regressions of all covariates and bivariate additive combinations of land use + all other covariates. For precipitation and soil texture, we considered interactions with land use. We used the Akaike information criterion (AIC) to select models and present all models within 2 AIC units of the best model.

Computer simulations

The surface of sand particles was modelled with a cleaved quartz surface, whereas clay particle surfaces were represented by the gibbsite-like surface of kaolinite. In this preliminary study, hexadecan-1-ol molecules were used as a representative wax. Two systems were constructed by placing sufficient hexadecan-1-ol molecules on model kaolinite and quartz surfaces, respectively, to provide coverage of 2.35 molecules nm^{-2}. The potential energy for each system was calculated with the COMPASS force-field (Sun 1998), which has been shown to perform particularly well in describing hydrophilic–hydrophobic interactions between organic and inorganic surfaces (Henry *et al.* 2005, 2006). During molecular dynamics, electrostatic interactions were calculated using the Ewald procedure, and van der Waals interactions were calculated with an atom-based procedure using a cutoff of 12.50 Å, a spline width of 1.00 Å, a buffer of 0.50 Å and a long-range tail correction. Simulations were performed in the NVT ensemble, equilibrated for 500 ps followed by data acquisition for 4500 ps, using time steps of 1.0 fs. The temperature was maintained at 298 K using the Andersen thermostat (Andersen 1980) with a collision ratio of 1.0.

Results

For the 0–0.1 m layer in the 31 paired plots, most (81%) of the pasture sites were not water-repellent, with MED values of 0 M (Fig. 1*a*); this percentage decreased to 58% following plantation establishment. The proportion of sites exhibiting water-repellency characteristics (MED values >0 M) was always greater for the plantation sites than the pasture sites (Fig. 1*a*). Indeed, water repellency was significantly greater in plantation than pasture sites ($V = 3$, $P = 0.002$). For the 3-way comparison between bushland, pasture and plantation, the frequency of water repellency was greatest on the plantation sites (Fig. 1*b*), with respective median values for bushland, pasture, and plantation of 0.1, 0.5 and 2.0 M. Using a conservative Kruskal–Wallis test, differences among these land uses were not significant (Kruskal–Wallis $\chi^2 = 3.0$, $P = 0.22$).

For all land uses, water repellency diminished rapidly with depth (Fig. 2). Under the bushland, water repellency appeared to be greater at depth (Fig. 2); however, this effect was not statistically significant. For the 31 paired sites, only one of the plantation sites exhibited any water repellency (0.2 M) in the deeper layer (0.1–0.2 m), with the remainder 0 M at that depth.

For the 0–0.1 m layer, different soil properties had been previously compared between the different land uses (Grove *et al.* 2001; Mendham *et al.* 2002*b*, 2003, 2004; O'Connell *et al.* 2003), and the individual land-use data are not shown here. Soil attributes assessed are summarised in Table 1, with no significant within-site differences for any of the soil physical or chemical properties between paired land uses. Similarity of the particle-size analysis values in the 0–0.1 m layer between the different land uses validates initial site selection and demonstrates that the paired sites were well matched.

There were no differences in the organic matter content between land uses. ^{13}C CPMAS NMR analysis revealed that changes in the relative proportions of carbon from the four spectral regions (alkyl, O-alkyl, aromatic and carboxylic), due to land use at each site, were relatively minor. The main impacts of changed land use were higher O-alkyl material under pasture than native vegetation and plantation ($P = 0.048$) and lower aromatic carbon content under pasture than native vegetation.

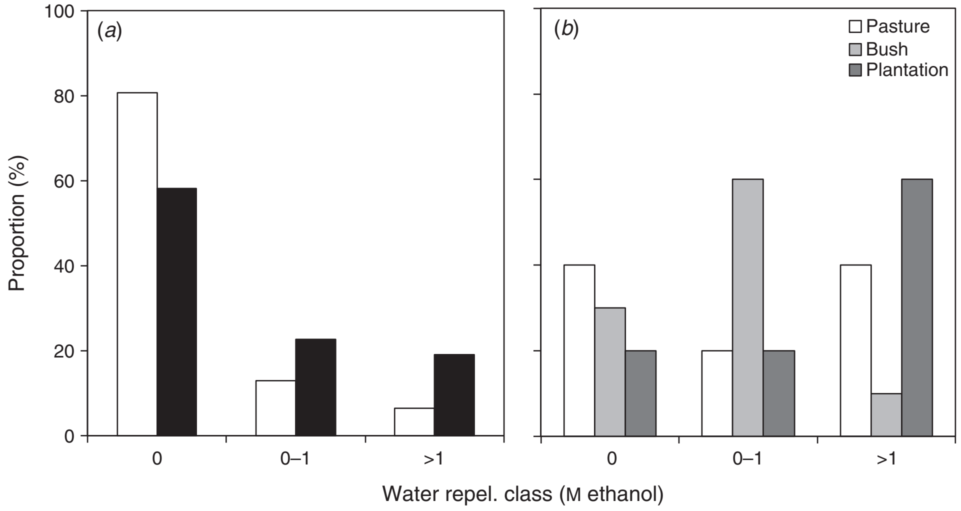

Fig. 1. Proportion (%) of the soils in water repellency classes (M ethanol) of increasing severity for the 0–0.1 m soil layer: (*a*) paired plots under pasture and *E. globulus* plantations ($n = 31$), and (*b*) 3-way comparison of bushland, pasture and *E. globulus* plantations ($n = 10$).

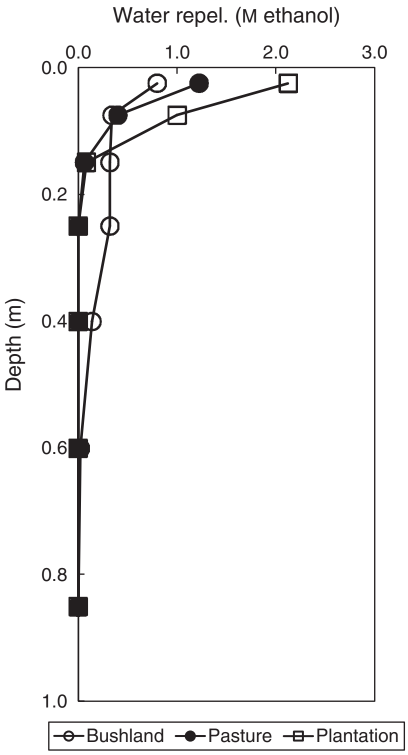

Fig. 2. Mean water repellency (M ethanol) for different depth intervals to 1 m depth, across the three land uses (bushland, pasture and plantation).

On the basis of MED change relative to land use (plantation minus pasture), sites were classified as 'no change' or 'change' (Table 2). Of the 31 sites, 12 had a positive change (mean 0.9 M), 19 had no or small changes (mean –0.02 M).

Logistic regression revealed significant additive effects of land use and silt + clay (pseudo $R^2 = 0.27$). Plantation was associated with a significant increase in the odds of water repellency occurring (odds = 1.3, z = 2.1, $P = 0.04$) and an increase in clay + silt was negatively associated with odds of repellency (odds = –0.1, z = 2.6, $P = 0.01$). No other covariates were associated with models within 2 AIC units, as corroborated by minimal differences in means (Table 2).

For sites with <10% clay, 28% of those under pasture had some degree of water repellency (>0 M ethanol), whereas 69% of those with plantations were water-repellent (Fig. 3). For the sites with <10% clay, the mean water repellency was 0.22 ± 0.13 M and 0.67 ± 0.19 M for pasture and plantation, with this reflected in the logistic regression and empirical data (Fig. 4). Importantly, SOC content did not vary with regard to change in MED (Table 2). Respective SOC content for pasture and plantation was 2.81 ± 0.25% and 2.75 ± 0.17%, and this difference was non-significant.

When clay + silt content was compared with water repellency across the entire dataset, two broad groups were apparent (Fig. 4). One group demonstrated a decline in water repellency with increasing clay + silt content and mainly comprised plantation samples. By contrast, a group of largely non-repellent observations (0 values of MED) was independent of clay + silt content.

Table 2. Mean (standard error) values for various site, stand and soil attributes (0–0.1 m layer) for sites where water repellency either changed ($n = 12$) or did not change ($n = 19$) across plantation–pasture comparison within site

Type	Attribute	Water repellency	
		No change	Change
	No. of sites	19	12
Site	Annual rainfall (mm year^{-1})	898 (65)	856 (62)
Trees	Mean annual increment (m^3 ha^{-1} year^{-1})	21 (3)	19 (3)
Soil	pH	4.9 (0.1)	4.9 (0.1)
	Total N (%)	0.28 (0.03)	0.26 (0.03)
	Organic carbon (%)	3.5 (0.3)	3.5 (0.3)
	Total P (%)	0.04 (0.01)	0.03 (0.01)
	Colwell P (µg g^{-1})	35 (5)	37 (7)
	Exch-Ca (cmol$^+$ kg^{-1})	2.6 (0.2)	2.5 (0.2)
	Exch-K (cmol$^+$ kg^{-1})	0.2 (0.03)	0.2 (0.02)
	Exch-Mg (cmol$^+$ kg^{-1})	0.6 (0.1)	0.6 (0.1)
	Exch-Na (cmol$^+$ kg^{-1})	0.2 (0.04)	0.2 (0.03)
	Coarse sand (%)	52 (4)	52 (4)
	Fine sand (%)	30 (2)	36 (4)
	Silt (%)	7 (1)	4 (0.6)
	Clay (%)	11 (1)	8 (2)
	Silt + clay (%)	18 (3)	12 (2)

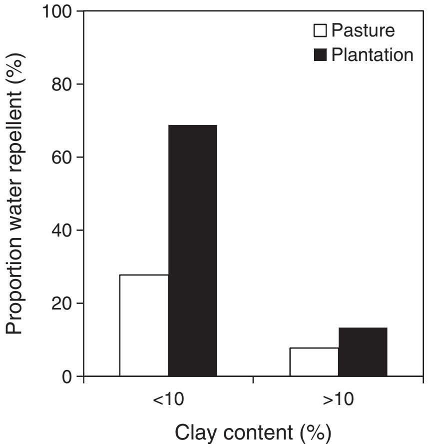

Fig. 3. Proportion of water-repellent soils (>0.0 M ethanol, 0–0.1 m soil layer) for soils with <10% and >10% clay for paired plots under pasture and *E. globulus* plantations.

Modelling

Computer modelling studies were performed to understand the mechanisms by which water repellency can develop on sand and clay particle surfaces. Model surfaces were interacted with long-chain fatty alcohol molecules to explore the configurations and dominant molecular forces. These simulations reveal significant differences in the packing and interaction of wax molecules (fatty alcohols) on clay (kaolinite) and sand (quartz) surfaces (Fig. 5). In particular, even at a relatively low surface coverage (2.35 molecules nm^{-2}), the wax molecules were found to adopt a semi-ordered, tilted packing arrangement on the gibbsite-like surface of kaolinite. Analysis of the functional group interactions provides clear evidence of hydrogen bonding between the hydrophilic head groups of the wax molecules and the OH groups of the clay surface. By comparison, the same coverage on quartz leads to a two-layer arrangement of wax molecules. In the first layer, the molecules are parallel with the sand surface and the interaction between molecules and surface is dominated by van der Waals forces. In the second layer, the molecules are highly disordered and oriented to maximise H-bonding between the head groups of neighbouring molecules.

Discussion

Effects of land use and soil properties on water repellency

This study has shown that reforestation with *E. globulus* induces water repellency across a range of sites in the south-west of Western Australia (Fig. 1). Although this result is not unexpected given the widespread nature of water repellency on agricultural soils in this region (Blackwell 2000) and previous reports of water repellency associated with eucalypts, it has not been quantified in southern Australia, despite >0.5 Mha of eucalypt reforestation in the last two decades (Gavran 2013). Although water repellency has been previously reported in *E. globulus* plantations in Portugal (Doerr *et al.* 1998; Ferreira *et al.* 2000; Coelho *et al.* 2005; Rodríguez-Alleres and Benito 2011), a feature of those studies was that the different land uses were geographically distant with uncontrolled soil and site differences, whereas in this study, the result is based on paired sites in which these differences are minimised. Indeed, analysis of soil characteristics at paired sites demonstrated no difference in other soil properties, strengthening the conclusion that repellency was induced via eucalypt reforestation. Additionally, our data show that water repellency decreases rapidly with depth (Fig. 2), as previously reported (Barrett and Slaymaker 1989). Further, beyond the 0–0.1 m layer, the effect of land use on water repellency disappeared. This observation is counter to prior suggestions that *E. globulus* induces water repellency around the roots of the plant (Doerr *et al.* 1998).

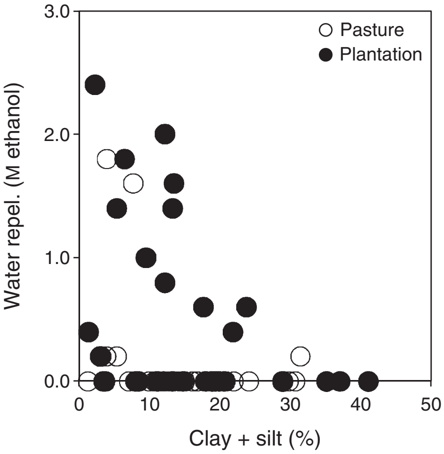

Fig. 4. Change in water repellency (M ethanol) with increasing clay + silt content for soils under pasture and *E. globulus* plantations.

We found the likelihood and severity of water repellency to be much higher on sandy-surfaced soils (Fig. 3) than on more silty or clayey soils. This again mirrors results from agricultural sites in this region (Harper *et al.* 2000; Roper *et al.* 2013). Other studies have also found a negative relationship between the clay content of the soil and degree of water repellency (Crockford *et al.* 1991). The risk of water repellency developing in specific plantations, or parts of plantations, therefore partly depends on soil texture (Harper *et al.* 2000) and this risk can be determined via a pre-establishment soil survey.

Although sandy soils were found to be significantly more susceptible to water repellency (Figs 3 and 4), it should be noted that not all of the soils in the <10% clay class were affected, even following reforestation. Across all sites, a large proportion (42%) did not exhibit water repellency after plantation establishment (Fig. 1), and the only soil properties that differed between the sites where repellency was induced or where it was not were silt and clay contents (Table 2). Additionally, some of the sandy soils, which from previous

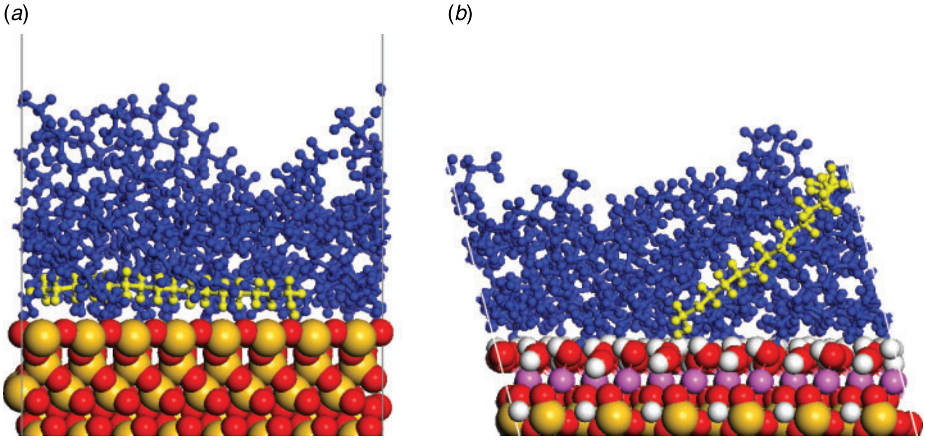

Fig. 5. Structure of wax molecules on (*a*) a sand (quartz) particle surface and (*b*) a clay (kaolinite) particle surface. One wax molecule is coloured bright yellow to highlight structuring of the molecules in the layer adjacent to the particle surfaces.

studies would be expected to be water-repellent, were not repellent, even after the establishment of eucalypts (Fig. 4). This raises important questions regarding the relative importance of the surface chemistry of particles of different soil types and the formation of hydrophobic layers. Further studies could focus on reasons for this variability and the possibility that there is an as-yet unconsidered factor affecting these results.

Cause of water repellency

There was an increase in water repellency but no difference in total soil carbon content following the establishment of plantations on pasture (Table 1). This could imply either that water repellency is affected by small amounts of the compounds that cause repellency (Doerr *et al*. 2000) or that the composition of the organic matter is important in inducing water repellency. In the latter case, the NMR analysis did show minor differences in O-alkyl material, which was higher for pasture than for plantation or native vegetation, and lower aromatic carbon for pasture than for native vegetation (Mendham *et al*. 2002*a*). The O-alkyl component was attributed to carbohydrate material, which should be largely hydrophilic and therefore lead to decreased water repellency. However, the NMR spectra were insufficiently resolved to rule out the presence of more hydrophobic O-alkyl compounds. For example, Roberts and Carbon (1972) attributed the water repellency in sandy soils to hydrophobic compounds of humic origin. Humic material generally consists of a mixture of large, aromatic-based polymers with phenolic and carboxylic functionality capable of interacting with the surface of soil particles. Alternatively, several studies (Franco *et al*. 2000; Doerr *et al*. 2005; Mainwaring *et al*. 2013) investigated the contribution of wax-containing compounds and particles to the development of water repellency in soils. They suggested that the main components of these waxes were unbranched and branched C_{16}–C_{36} fatty acids and their esters, as well as alkanes, phytanols, phytanes and sterols. Likewise, McKissock *et al*. (2003) reported on a relationship between soil water repellency and aliphatic carbon content, with the carbon attributed to fatty acids. The hydrophilic head groups of fatty acids should have a natural affinity for the polar surfaces of soil particles. However, this interaction results in the hydrophobic tail of the fatty acid projecting from the surface of the particle. If fatty acids are in fact the cause of soil water repellency, then presumably over time there is a build-up of an ordered monolayer of these molecules on the surface of the soil particles. By comparison, the build-up and layering of molecules of humic origin will be much more disordered than that of the fatty acids and may lead to a less uniform hydrophobic surface. Doerr *et al*. (2000) have also suggested that accumulation of hydrophobic material within the soil pores, rather than coating individual grains, may be responsible for reduced wettability. The previous studies imply the involvement of one or both of these mechanisms in the induction of soil water repellency but results here are insufficient to categorically identify either mechanism.

The computer simulations presented in this study clearly indicate different packing and interfacial interactions between wax molecules on clay and sand surfaces, respectively. Even for a low level of coverage (2.35 molecules nm^{-2}), wax molecules on the quartz (sand) surface adopt a multi-layered arrangement. In the first layer, the wax molecules lie flat on the surface, rendering most of the surface hydrophobic. A second, disordered layer forms on top of the first layer, accentuating the hydrophobicity of the first layer. By comparison, wax molecules on a kaolinite (clay) surface adopt a semi-ordered, tilted packing arrangement such that coverage of 2.35 wax molecules nm^{-2} is insufficient to transform the particles completely from hydrophilic to hydrophobic. Consequently, higher levels of wax material are required to render clay particles hydrophobic compared with sand particles.

Further research is required to characterise the amounts and composition of these organic compounds. Determining both the chemical nature of the hydrophobic coating and its physical interaction with soil particles will be important to understanding (*i*) the process of soil water repellency, (*ii*) the variability in soil repellency between sites, (*iii*) the stability/permanency of the coatings, and (*iv*) how to remove the coating or limit its formation. This would identify the specific cause of this phenomenon and help with formulation of amelioration strategies. Further studies could also examine variation in water repellency across different *Eucalyptus* species, which would show whether different species secrete similar compounds. Such studies could also build on what is already known about the chemistry of eucalyptus leaves (e.g. Barton *et al*. 1989).

Implications of water repellency

Water repellency was induced by *E. globulus* at 12 of 31 sites, but the degree to which these differences will correspond to different soil behaviours, such as changes in runoff and infiltration dynamics, is not clear. For some sites, only sub-critical repellency will occur, and the implications of this for plantation management are unknown.

A key question is whether this change in water repellency is significant in terms of plantation- and watershed-management outcomes and the development of sustainability indicators for such projects. Water repellency developed after only 5–8 years of *E. globulus* establishment, and with 20–30-year rotations before reversion to farming (Harper *et al*. 2009), it is possible that more severe repellency will develop and that what has been reported here is an early indication of a developing problem.

There were no measurable effects of soil water repellency on tree growth (Table 2). The most likely impacts of water repellency will occur where these plantations are harvested and regenerated, or where the plantations are returned to agriculture (*i*) after a biomass-producing rotation (Harper *et al*. 2014) or (*ii*) where the sites are deemed unprofitable for a future plantation rotation. The high growth rates and survival of plantations established on farmland are often due to the utilisation of water stored in the soil under shallow-rooted grasses or crops during the previous agricultural land use (Mendham *et al*. 2011; Harper *et al*. 2014). A key consideration in plantation water management is recharging the soil profile after harvest and coppicing to maximise growth in second and subsequent rotations (Mendham *et al*. 2011). Water repellency that has been induced during the first rotation will need to be managed, possibly by manipulating surface micro-topography, so that runoff is captured in localised areas and allowed to infiltrate into the subsoil. This will need to be done to ensure that subsequent rotations are not affected, and to prevent erosion from large-scale water accumulation leading to significant runoff events.

Several studies have shown the induction of water repellency following fire in eucalypt and other forests (Prosser and Williams 1998; Shakesby 2011; Cawson *et al*. 2012). Fire is used to remove debris and convert plantations back to pasture, and the impacts of this on water repellency require resolution.

Finally, water repellency is not currently considered a criterion for biofuel/bioenergy certification (Scarlat and Dallemand 2011); however, the results presented here suggest that it should be considered in the future development of sustainability criteria, given that it is induced by eucalypt reforestation.

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