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Surface runoff and soil erosion under eucalyptus and oak canopy

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ABSTRACT: To assess potential differences in stormwater runoff and sediment yield between plots of blue gum eucalyptus (*Eucalyptus globulus*) and coast live oak (*Quercus agrifolia*), we measured runoff, sediment yield, water repellency and soil moisture at eight paired sites. Eucalyptus has been associated in many studies worldwide with elevated soil water repellency and increased runoff, a likely contributor to soil erosion. To better understand these connections and their relationship to land cover, there is a need for studies employing either rainfall simulators or natural rainfall. Our research employs the latter, and was subject to contrasting hydrologic conditions in the two years of the study. Fieldwork was conducted from October 2006 to February 2008 in the San Francisco Bay Area of central California. During the 2006–2007 winter wet season, runoff was significantly higher under eucalypts than at paired oak sites, and in the early phases of the season was connected with elevated water repellency. However, sediment yield at all sites during the 2006–2007 hydrologic year was below the detection limit of the Gerlach sediment collection traps, possibly due to a limited wet season, and only appeared as suspended sediment captured in overflow buckets. Intensive rainfall events in January 2008 however created substantial runoff of sediment and litter with significantly greater yield at oak sites compared to paired eucalyptus sites. Water repellency likely had little effect on runoff during these events, and the primary cause of greater erosion under oaks is the thinner cover of leaf litter in comparison to eucalyptus. Our study is limited to undisturbed sites with intact litter cover that have not experienced recent wildfires; if disturbed, we would expect a different picture given the propensity for crown fires of eucalypts, enhancement of rainsplash erosion, and the likely greater potential for stream-connected sediment yield from post-disturbance soil erosion events. Copyright © 2015 John Wiley & Sons, Ltd.

KEYWORDS: eucalyptus; litter; runoff; sediment yield; soil moisture; water repellency

Introduction

Many resource managers and ecologists have long suspected that *Eucalyptus* trees introduced in coastal California and elsewhere impact landscapes by inhibiting growth of native plants, reducing forage area for insects, birds and animals, and clogging coastal aquatic habitat with increased sedimentation (WESCO, 1993). Eucalypts in coastal California are currently under management for fire control (East Bay Regional Park District (EBRPD), 2013) and habitat.

Several studies worldwide have looked at their hydrologic impacts (e.g. Ferreira *et al.,* 2000; Keizer *et al.*, 2002; Doerr *et al.,* 2006). Shakesby *et al.* (2000) associated eucalypt-induced elevated soil water repellency with reduced aggregate stability, reduced infiltration, increased rainsplash detachment, enhanced overland flow and increased soil erosion. Studies have documented hydrologic responses including changes in infiltration rates and erosion rates on eucalypt versus control vegetation on plot scales ranging from 0.24 m^2 to 500 m^2 (Keizer *et al.*, 2002).

Shakesby *et al.* (2000) however caution that while elevated water repellency increases erosion risk, it does not directly translate to increased erosion due to wide variations in local conditions such as cracks, pipes and patches with low water repellency. Furthermore not all studies show an increase in soil erosion under eucalypts: semi-arid sites of Portugal, Morocco and Tunisia showed no greater water repellency under *Eucalyptus* than under native evergreen species of *Quercus*, and this led to no significant increase in overland flow and erosion rates, though the results in that study were complicated by variations in grazing pressure (Coelho *et al.,* 2005).

Methods

We examined paired (either contiguous or within 100 m of each other) patches of an *Eucalyptus globulus* and *Quercus agrifolia* in San Francisco (SF) Bay Area locations, similar to Lacey *et al.* (1989) except that we used natural precipitation instead of rainfall simulators. This close proximity helped ensure that runoff and sediment yield from each eucalypt and oak pair was measured under similar physical conditions of slope, aspect, rainfall intensity and volume, and soil type. Eight suitable sites were identified, four in Tilden Park in the EBRPD, one in the Presidio of San Francisco and three within the Marin Open Space District in Marin County (Figure 1). No sites were subject to grazing or recreational land use impacts, and all had intact litter cover, and were selected for minimal potential disturbance by humans. The SF Bay Area has a Mediterranean

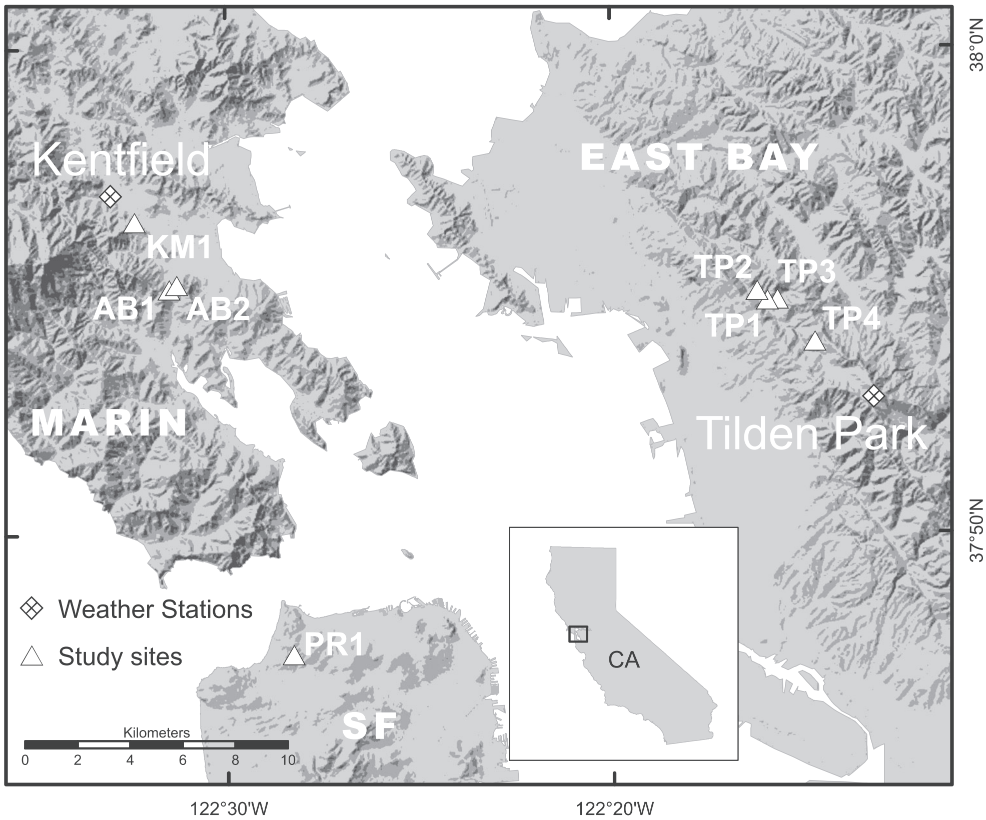

Figure 1. Locations of study sites and reference meteorological stations in the San Francisco Bay Area. TP sites are in Tilden Park, Berkeley located in Alameda County in the East Bay. The PR site is in the Presidio of San Francisco. AB and KM sites are in the Marin County Open Space District, Marin County (source: US Geological Survey, 1997).

climate with about 84% of the precipitation falling almost exclusively as rain between the months of November and March (Table I). Rainfall averages for 1971 to 2000 varied considerably (National Oceanic & Atmospheric Administration [NOAA], 2004) with Kentfield in Marin County receiving roughly double the rainfall of the SF Bay Area and the EBRPD sites (Western Regional Climate Center [WRCC], 2014), but the seasonal summer-dry pattern is consistent. Our study sites consist of *Quercus*- or *Eucalyptus*-dominated woodland patches bounded primarily by grasslands, located in hilly areas upslope of the flatlands surrounding San Francisco Bay. These species were chosen as they occur in similar sites, in summer-dry landscapes with relatively few tree species, with the eucalypt an invasive non-native that has replaced large areas of native oak and scrub vegetation in coastal California during the past century.

Finding subsite pairs with similar slopes was a primary design consideration as slope is a major component in runoff. Because runoff increases with slope (Assouline and Ben-Hur, 2006), we looked for oak slopes approximately equal to eucalyptus slopes. Mean oak slope was 21.4° while mean eucalyptus slope was 19.1° with a standard deviation of 9.1 for oaks and 8.1 for eucalyptus. Difference in slopes at a site ranged from 1° to 7° with a standard deviation of the difference of 2.9°. In seven cases the slope at sites under oak trees was equal to or greater than the slope of eucalyptus trees and in one case the slope under eucalyptus trees was 1° greater than the slope under oak trees (Table II). Aspect differences ranged from 6° to 67° with a standard deviation of 26.6. As leaf litter acts as mulch and reduces runoff and sediment yield (California Department of Fish and Game (DFG), 2006), we measured litter depths under oak and eucalyptus canopy. Mean oak litter depth was 5 cm while mean eucalyptus depth was 10 cm, with a standard deviation of 2 cm for oak and 4 cm for eucalyptus. No significant surface gravels were detected at any site. Each paired site had equivalent soil classifications, described in Table III.

Table I. Mean annual total precipitation and average air temperature for three NOAA meteorological stations that are located within 5 km of the study sites. Berkeley is near the Tilden Park site, Kentfield is near the Marin sites and San Francisco near the Presidio site

City	Precipitation (mm)	Precipitation falling November–March (%)	Mean temperature (°C)
Berkeley, CA	645	83	18.3
Kentfield, CA	1206	85	21.9
San Francisco, CA	566	84	15.6

Data source: Western Regional Climate Center (WRCC) http://www.wrcc.dri.edu/climate-summaries

Assessing soil water repellency

To assess the degree of soil water repellency of soil under the tree types, we applied a critical surface tension (CST) test. Rather than measuring the soil itself, we used the surface tension of a solution that was able to penetrate the soil *in situ* within three seconds (Crockford *et al.,* 1991). The result was a threshold, a CST value, required to penetrate the soil. We recognize however that recent studies (Dekker *et al.,* 2009; Doerr *et al.,* 2009) have questioned the accuracy of repellency tests with field-moist soils in studies of runoff effects.

Ethanol has less than one-third the surface tension of water at 20 °C, and penetrates soil surfaces more easily than water under hydrophobic conditions (Doerr, 1998). Higher ethanol concentrations lower the surface tension of solution, as shown

Table II. Characteristics of the sites: slope, aspect, distance between oak and eucalyptus plots, and average litter depth

Site name	Slope (deg)			Aspect (deg)			Spacing between oak and eucalyptus plots (m)	Litter depth (cm)			Soil series and USDA great group
	Oak	Eucalyptus	Difference	Oak	Eucalyptus	Difference		Oak	Eucalyptus	Difference	
AB1	32	31	1	220	227	7	41	8	6	2	Tocaloma Haploxerolls
AB2	24	25	1	100	106	6	24	7	13	7	Tocaloma Haploxerolls
KM1	30.5	25	5.5	189	196	7	87	5	7	2	Tocaloma Haploxerolls
TP1	9	9	0	229	296	67	41	7	14	7	Millsholm Haploxerepts
TP2	12	10	2	143	197	54	81	2	8	6	Millsholm Haploxerepts
TP3	25	18	7	264	215	49	62	4	8	4	Los Gatos Argixerolls
TP4	12	12	0	187	175	12	32	3	17	14	Millsholm Haploxerepts
PR1	27	23	4	121	115	6	25	1	8	7	Sirdrak Dystrustepts

in Table IV; these estimates from Doerr (1998) were used in our experiments. The higher the concentration of ethanol in water required to penetrate the ground within three seconds, the more water-repellent the soil (Doerr, 1998). Five repetitions of the test were performed at each subsite, at the mineral soil surface, and averaged to obtain CST for each visit. Measurements were taken roughly twice per month during the 2006–2007 wet season, generally following rain events.

In a few cases ($N = 5$), a solution of 36% ethanol failed to penetrate the ground within three seconds. We assigned these cases to category VI and assumed it would take an ethanol concentration of 50% to penetrate the soil within three seconds.

Precipitation and soil moisture

Daily rainfall totals for each study subsite over the 2006–2007 wet season were obtained from a combination of hourly tipping bucket rain gauge data recorded at two nearby meteorological stations and episodic onsite data from 21 standard 100-mm plastic rain gauges, mounted understory and in nearby clearings. The two meteorological stations were located in Kentfield, Marin County (37.95°N, 122.55°W) and Tilden Park, East Bay (37.88°N, 122.22°W), in both cases close to clusters of study sites, with the furthest site being about 4 km from its nearest weather station (see Figure 1). Manual recordings from the standard rain gauges were obtained following most major rainfall events from October 2006 to May 2007.

We assessed soil moisture in terms of volumetric water content (VWC) by taking soil core samples for bulk density and gravimetry, and electronic measurements with a Campbell Scientific Inc. (CSI) CS616 time domain reflectometer (TDR) probe (Campbell Scientific Inc., Logan, UT) attached to a CR1000 (Campbell Scientific) data logger. Soil cores 200 cm^3 in volume, collected from 0 to 10 cm depth, were weighed wet, dried in a drying oven at 60 °C for 48 hours or in a microwave oven (Foth *et al.*, 1982), then re-weighed to obtain the water content, and volumetric water content derived.

During the early part of the 2006–2007 wet season, gravimetry was the only method available to assess soil moisture as the ground was too hard to insert TDR probes. Once the soil softened up from rainfall we took most of the soil moisture measurements by TDR to a depth of 10 cm, corresponding to our 10 cm core depth. Three TDR measurements were taken at random locations outside of, but within 1 m of, each oak and eucalyptus plot. The three readings were averaged to obtain a TDR reading for each subsite. In rare cases where hard ground could potentially damage the TDR probes, we took only one or two samples.

We derived a generalized TDR calibration curve under a range of moisture conditions by comparing gravimetric core samples against TDR samples taken at the same places and times. The resulting polynomial ($N = 24$, $R^2 = 0.75$) was:

$$y = -0.0005x^2 + 0.0506x - 0.6919 \quad (4)$$

where y represents percent VWC and x represents TDR square wave period in microseconds.

Leaf litter depth

We measured the depth of leaf litter from the estimated bottom of organic matter at the interface with mineral soil to the top of the litter layer with a ruler, to the nearest centimeter. Three measurements were taken per plot, the first near the trap, the second midway up the plot, and the third at the top of the plot.

Table III. Soil characteristics by series (Soil Survey Staff, 2015)

Region	Soil series	Soil classification (USDA soil taxonomy)	FAO	Parent material	Depth (m)
East Bay	Los Gatos	Fine-loamy, mixed, active, mesic Typic Argixerolls	Phaeozem	Sandstone	0.6–1.0
	Millsholm	Loamy, mixed, superactive, thermic Lithic Haploxerepts	Cambisols	Shale and fine-grained sandstone	0.25–0.5
Marin	Tocaloma	Fine-loamy, mixed, superactive, mesic Typic Haploxerolls	Phaeozem	Sandstone and shale	0.5–1.0
San Francisco	Sirdrak	Sandy, mixed, isomesic Humic Dystrustepts	Cambisols	Dunes	1.5 (not residual)

Table IV. Critical surface tension (CST) test – soil water repellency classes (0 = hydrophyllic, I–V hydrophobic; I = slightly, II = moderately, III = strongly, IV = severely, V & VI = extremely), increasing concentrations of ethanol (volumetric) in percentage of de-ionized (DI) water and CST expressed in milli-Newtons per meter

Hydrophobicity class	0	I	II	III	IV	V	VI[a]
Ethanol concentration (%)	0	1	5	13	24	36	50[a]
CST (10^{-3} N m^{-1})	72.1	66.9	56.6	46.3	38.6	33.1	28.5[a]

reproduced after Keizer *et al.* (2002) and Doerr *et al.* (2003).
[a]In these cases it was assumed it would take an ethanol concentration of 50% to penetrate the soil within three seconds.

These measurements were averaged to obtain a mean litter depth for each plot.

Runoff and sediment collection using Gerlach troughs and overflow buckets

Gerlach troughs were installed to collect runoff and sediment moving downslope during rainfall events. These were designed after Larsen *et al.* (1999) and Utomo M, Afandi, Maryanto, and Arifani (1999), and consisted of 50 cm lengths of plastic rain gutter capped on the ends and fitted with sheet metal lids and approximately 12 cm sheet metal lips on the upslope side to facilitate good contact with the soil surface (Figure 2). The lid kept out direct rainfall interception and prevented sediment kicked up by rain-splash from entering the trough. The downslope side was fitted with a runoff tube leading to a 10 l collection bucket (Figure 3).

We minimized the effects of different slope lengths by limiting plot size (Doerr *et al.,* 2003; Larsen, 2006) to a length of 3 m at the top of each plot, and installed roughly 3 m of plastic garden barrier to direct runoff and sediment from upslope of the plots away from the troughs. Any greater plot length would have extended into slope elements of contrasting shape at several of the sites. With the sides of the plots unbounded as suggested for Gerlach troughs (Hudson, 1993), the 50 cm trap width yielded a plot size of 1.5 m^2.

Measurements were taken after 12 rainfall events from November 2006 through May 2007. Runoff was quantified by measuring the water depth in the overflow buckets and converting to volume. Following each runoff and rainfall reading, we emptied the buckets and rain gauges.

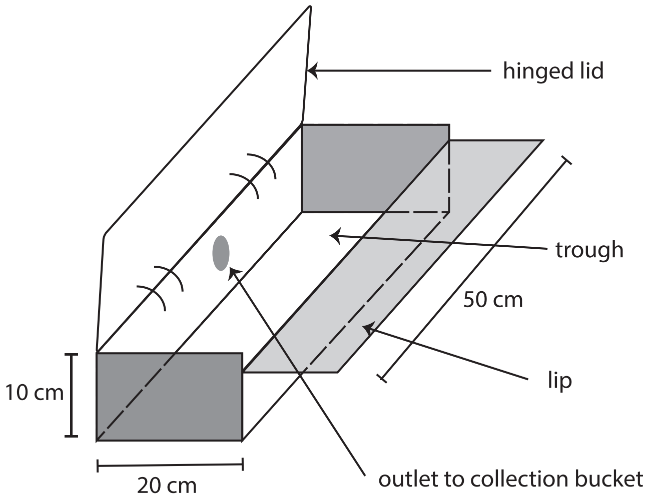

Figure 2. Illustration of a Gerlach trough (reproduced after Utomo M, Afandi, Maryanto, and Arifani, 1999

Figure 3. Gerlach trough and runoff bucket.

Gerlach troughs were observed at each visit for any collected mineral sediment or leaf litter. Measurements were not always available at each site following rainfall due to trap damage, an overturned overflow bucket or other disturbance. To quantify suspended sediment we took grab samples from the runoff buckets by agitating the runoff water to re-suspend settled sediment and taking 60 ml samples (Larsen, personal communication 2006). The sediment was filtered in the laboratory using Whatman #5 filter paper, then dried and weighed. This resulting weight was multiplied by the proportional volume of the bucket to obtain an estimate of total suspended sediment weight. Sediment collected in the Gerlach troughs were collected once at the end of the study in 2008, and analyzed for dry weight for both litter and sediments.

Results and Analysis

While using natural precipitation provides for good spatial coverage of rainfall from above canopy over all plots, we were subject to the vagaries of precipitation, and the first year of the study, focusing on the winter wet season of 2006 to 2007, created no significant sediment runoff, while the second year with much greater precipitation events (Figure 4) created substantial sediment yield yet overwhelmed our runoff capture. Therefore our study focuses on water repellency–soil moisture–runoff relationships for 2006 to 2007, and on sediment yield for 2007 to 2008, for the same paired eucalyptus/oak sites.

Precipitation, soil water repellency and soil moisture

Totals of rain events captured by the tipping bucket stations and each of the study subsite standard rain gauges were used to develop linear models predicting daily totals for each subsite. The regression results showed that all sites under-represented the tipping bucket rainfall totals consistently: the coefficient of determination for all subsites averaged 0.91 with a standard deviation of 0.1. The difference in regression slopes between oak and eucalyptus was not statistically significant at the 2% level ($p = 0.43$), although both were significantly different from their adjacent clearings ($p = 0.0018$) which recorded 16% more rainfall on average.

A high degree of soil water repellency (smaller CST values) at the end of the summer dry season was measured for both tree types. After about six weeks of periodic rain, soil water repellency under oak subsites generally decreased while remaining higher at eucalyptus subsites (Figure 5). One exception to this was during the wettest month, February 2007, when CST values do not significantly differ between tree cover types. No relationship was found between repellency results and the number of days since the last event, for either eucalyptus or oak sites. Table V provides summary statistics of the number of days from the last significant rainfall event (using either 5 or 10 mm as representing significant daily rainfall), ranging from one day to over a month.

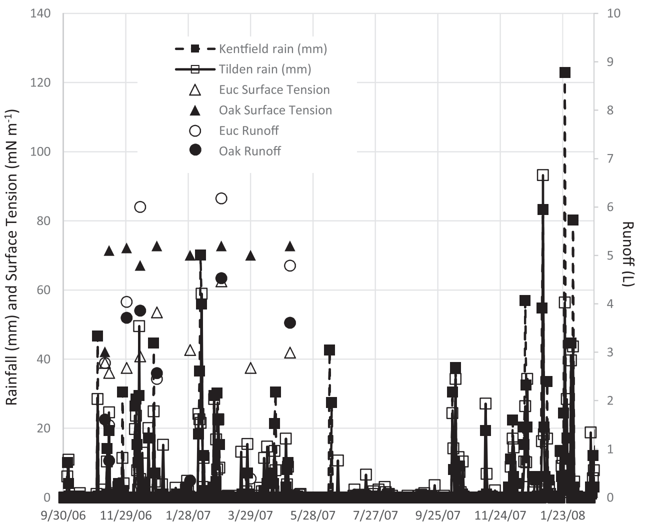

Figure 4. Daily rainfall from Kentfield (Marin) and Tilden (East Bay) stations from September 30, 2006 through March 31, 2008, including repellency as surface tension and runoff in the overflow buckets when measured during the 2006–2007 wet season. The overflow bucket capacity is 10 l, which had been exceeded when Gerlach troughs were emptied in February 2008.

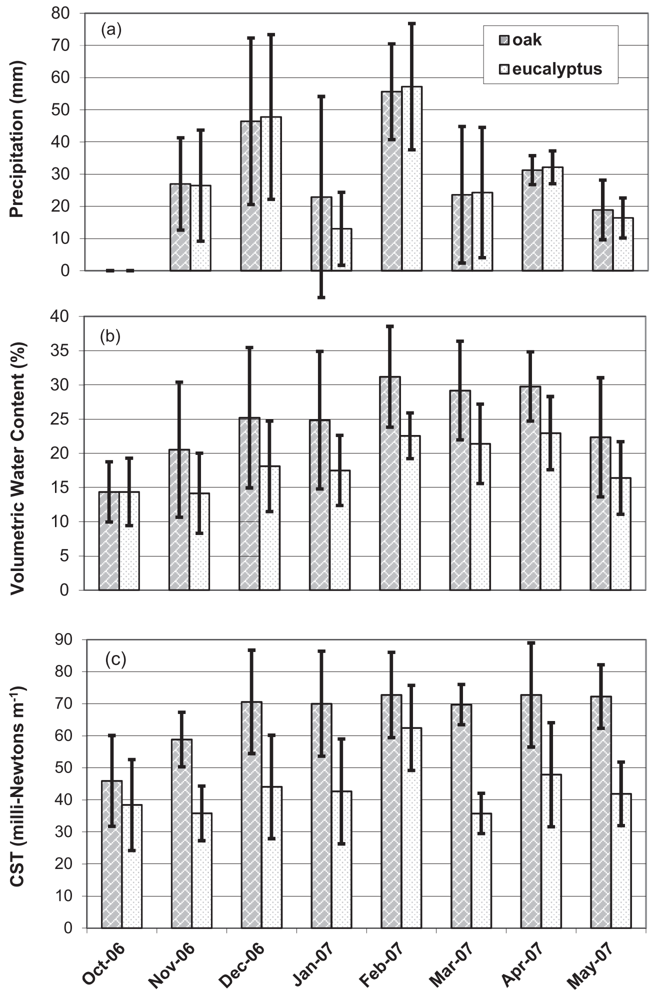

Figure 5. Precipitation, volumetric water content (VWC) of soil (0–10 cm) and critical surface tension (CST) at mineral soil surface by month. Monthly totals are used for precipitation and monthly average values used for VWC and CST measurements. Error bars represent ± one standard deviation among site values. Precipitation was not measured on site in October 2006 but conditions were dry regionally (GGWS, 2007). Lower CST numbers represent higher water repellency.

Soil moisture (VWC) started out fairly low for all subsites in the early part of the sampling season. VWC reached a peak in late February and tapered off into May as the rainy season came to an end. October represents the end of the dry season, with no appreciable precipitation for several months in 2006 (Golden Gate Weather Services [GGWS], 2007). VWC increased more for oak subsites than for eucalyptus subsites ($p = 0.0179$, df = 14). The February and April dips in water repellency at eucalyptus subsites can be explained by episodic rains followed by dry spells where repellency can break down then re-establish (Shakesby *et al.*, 2000). Oak subsites exhibited consistently low repellency following initial rains.

Noting that soil under eucalyptus trees exhibits higher soil water repellency (Wilcoxon rank sum test: $W = 4121.5$, p-value < 2.2e-16), and lower moisture levels than soil under oak trees we looked at the correlation between water repellency expressed as CST and VWC. An aggregate plot of moisture data shows that as CST decreased, soil moisture decreased (Figure 6). Results are significant per Spearman's rank correlation (rho = 0.596, $p = 3.241\text{e-}08$). Due to overall low soil moisture levels after the dry summer season, the chart reflects measurements from six weeks after the start of the rainy season.

Table V. Summary of the number of days since the last effective rainfall event, assuming either 5 or 10 mm as an arbitrary threshold defining effective rainfall

Location	Weather station	Threshold precipitation estimate (mm)	Mean (days)	Standard deviation	Minimum	Maximum
Marin	Kentfield	5	5.1	9.46	1	33
Marin	Kentfield	10	8.0	12.37	1	34
East Bay	Tilden	5	5.21	7.15	1	26
East Bay	Tilden	10	5.6	7.02	1	26

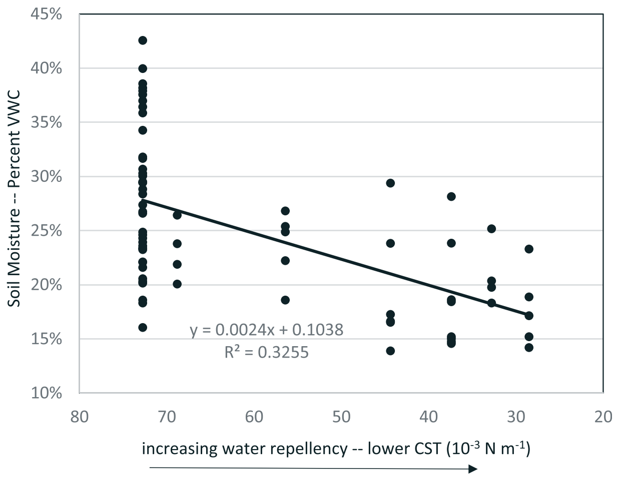

Figure 6. Water repellency and soil moisture starting six weeks into the rainy season. Light symbols represent eucalyptus, dark symbols represent oak. Data from sandy soil at PR1 (very low volumetric water content) not included.

Runoff

While less extreme than in arid climates, significant precipitation in this region does tend to be concentrated in relatively few larger events, enhancing runoff during those times. This can be seen for our study period at the two weather stations, Kentfield in Marin and Tilden in the EBRPD, in Table VI and Figure 4. This record reflects the generally low precipitation totals throughout California during the 2006–2007 rainy season (California Department of Water Resources (DWR), 2007), e.g. 58% of normal at the San Francisco airport (Golden Gate Weather Services (GGWS), 2007), which reduced the frequency and quantity of runoff-producing rainfall events.

The difference of means test analyzes the dependent variable runoff against the independent variable tree type, adjusting for differences (covariates) in local slope and precipitation. When removing variances between sites as a factor (i.e. assuming all sites have similar properties other than slope and precipitation), results show elevated runoff (one-tailed $p = 0.029$) in eucalyptus subsites. Eucalyptus subsites averaged 3.048 l of runoff compared to 2.164 l for oak subsites.

Given the likelihood of autocorrelation, we attempted to account for other variables using an analysis of covariance (ANCOVA), adding factors such as site and leaf litter to our analysis. Tree type no longer appeared as a significant factor ($p = 0.204$), with site (partial eta squared = 0.285) as the largest contributor to runoff after rainfall (partial eta squared = 0.341). While in general runoff under eucalyptus exceeded that under oaks (Figure 7), the three Marin oak sites had more runoff than Marin eucalyptus sites, while eucalyptus runoff exceeded oak runoff at the other five sites (Figure 8). Slopes at Marin sites averaged 27.9° while slopes at the other sites averaged 15.7°, so there may be a threshold effect not taken into account.

Returning to the hypothesis that elevated soil water repellency increases runoff, we tested for all cases of elevated soil water repellency including oak subsites with elevated water repellency after prolonged dry spells. Results show that runoff

Table VI. Monthly precipitation including maximum daily and number of days with more than 10 mm precipitation, at the two weather stations nearest field sites

	Kentfield			Tilden		
	Total precipitation (mm)	Number of days > 10 mm	Maximum daily (mm)	Total precipitation (mm)	Number of days > 10 mm	Maximum daily (mm)
October 2006	14	1	10	19	2	11
November 2006	119	4	47	88	4	28
December 2006	184	7	45	175	7	25
January 2007	9	0	3	31	1	15
February 2007	307	9	70	228	8	59
March 2007	9	0	7	33	2	15
April 2007	69	2	30	57	3	15
May 2007	21	1	10	33	1	17
June 2007	70	2	43	11	1	11
July 2007	0	0	0	17	0	2
August 2007	0	0	0	8	0	3
September 2007	1	0	1	7	0	4
October 2007	87	2	38	105	5	34
November 2007	20	1	19	37	1	27
December 2007	209	7	57	140	6	26
January 2008	458	10	123	456	10	123
February 2008	135	4	80	135	4	80
March 2008	6	0	4	6	0	4

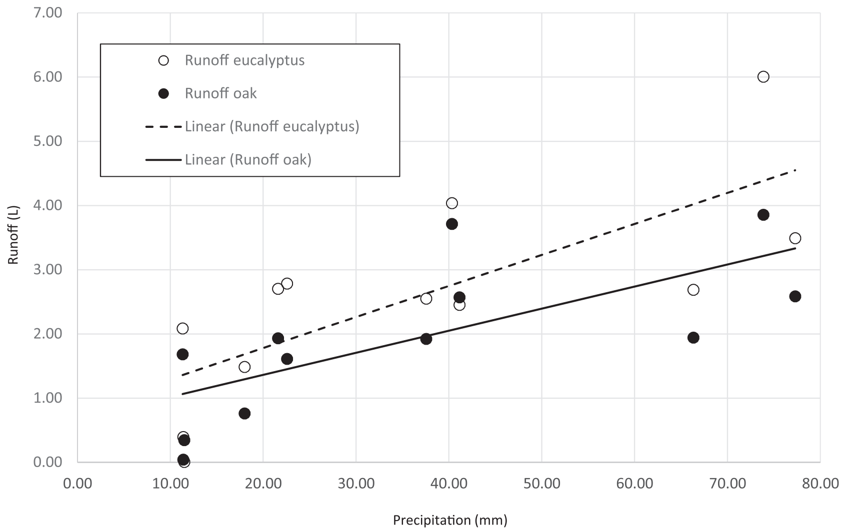

Figure 7. Runoff (in liters) in overflow buckets under eucalyptus and oak sites related to precipitation (in millimeters) since the last collection, typically a one month period, during the 2006–2007 wet season.

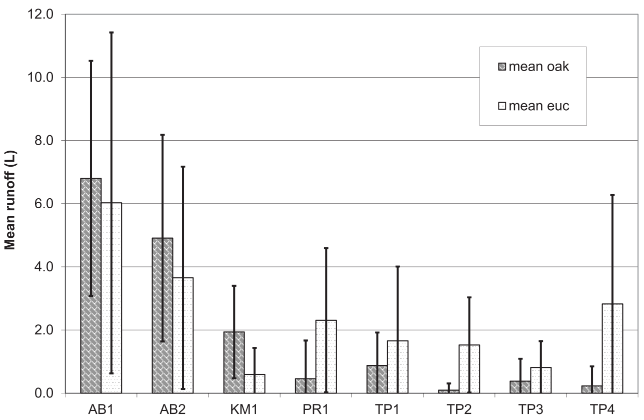

Figure 8. Oak and eucalyptus runoff for all sites. Alto Bowl (AB1 and AB2) slopes are 10° steeper than the other slopes on average, partially accounting for the increased runoff.

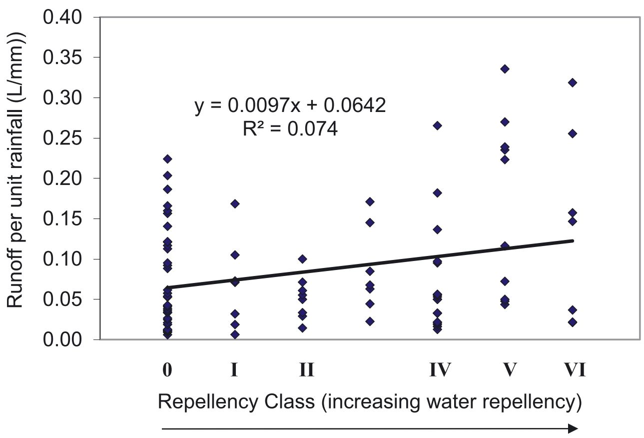

Figure 9. Runoff (in liters) per unit of rainfall (in millimeters) compared to water repellency class. As soil water repellency increases, runoff per unit rainfall increases. Covariates such as site, slope and leaf litter depth are ignored.

increased ($p = 0.001$, partial eta squared = 0.252) with increased soil water repellency (Figure 9). Water repellency was the biggest contributor to runoff after rainfall ($p < 0.001$, partial eta squared = 0.318). These results should be used with caution however because error variances are not equal across all groups (Levene's Test $p < 0.001$), however Spearman's non-parametric test shows a significant one-tailed correlation (rho = −0.189, $p = 0.015$, $N = 132$) between CST and runoff per unit of rainfall (in l mm^{-1}). Leaf litter depth and soil bulk density were not significant contributors to runoff.

Complex relationships among soil properties influenced by tree type, such as transpiration and litter decomposition processes, may contribute to contrasts in soil moisture and, runoff and erosion. For example, while increased runoff under eucalypts may suggest a cause for associated low soil moisture levels observed in this study, high transpiration from eucalypts (Bell and Williams, 1997; Pryor, 1976) is another possible cause.

Sediment yield

Notably, no mineral sediment was captured by the Gerlach troughs during the entire 2006–2007 wet season; only minor leaf litter remained in the troughs, thus the primary story for the first year is on runoff and its relationship with repellency. All mineral sediment captured by the Gerlach troughs followed large storms in January 2008, which produced approximately 450 mm of rainfall at both weather stations, with up to 123 mm on a single day (see Table VI and Figure 4), compared with a 70 mm maximum daily rainfall at the sites in 2006–2007. Trap installations were removed in early February 2008, after all of these major precipitation events. Given the high runoff rates, the total water runoff exceeded the capacity of the collection system, so our results from these periods are based only on sediment yield captured in the Gerlach troughs. Sediments were dried and weighed separately as fines (<2 mm) and litter (≥2 mm, dominated by litter); results are given in Table VII.

Field observations during the installation removal suggested that erosion was greater under oaks than eucalyptus. At two oak sites (AB2-O and TP3-O), removal of all soil litter cover was visible below the upslope barrier (Figure 10). Laboratory results support this observation. Sediments collected at oak sites were significantly greater (ANOVA F test: $p = 0.019$). This result is also supported by non-parametric Wilcoxon signed-rank tests, where sediment yield was significantly greater under oaks than eucalyptus ($p = 0.0325$). Considering slope at the paired sites did not change this result (Figure 11); ANCOVA tests did not support adding slope as a covarate in the linear

Table VII. Sediment runoff May 5, 2007 through February 10, 2008

Site name	Slope (deg)	Bulk density (g cm^{-3})	Litter depth (mm)	Fines (g)	Litter (g)	Total (g)
AB1-E	31	1.29	47	16.2	44.3	60.5
AB1-O	32	0.96	92	45.0	57.5	102.4
AB2-E	25	1.06	25	18.1	16.9	35.0
AB2-O	24	1.14	45	56.8	69.1	125.9
KM1-E	25	1.3	64	11.4	18.8	30.3
KM1-O	30.5	1.2	97	26.9	21.9	48.9
TP1-E	9	1.06	81	NA	NA	NA
TP1-O	9	1.05	135	47.0	40.4	87.4
TP2-E	10	1.26	82	13.3	14.0	27.4
TP2-O	12	1.19	111	25.8	69.6	95.5
TP3-E	18	1.49	73	17.1	97.8	114.9
TP3-O	25	1.11	109	202.2[a]	67.6[a]	269.8[a]
TP4-E	12	0.99	39	9.2	14.3	23.5
TP4-O	18	1.09	73	7.5	50.3	57.8

[a]TP3-O results were not used in statistical analysis due to possibility of disturbance.

Figure 10. Downslope movement of leaf litter and soil. Note the exposed ground below the barrier.

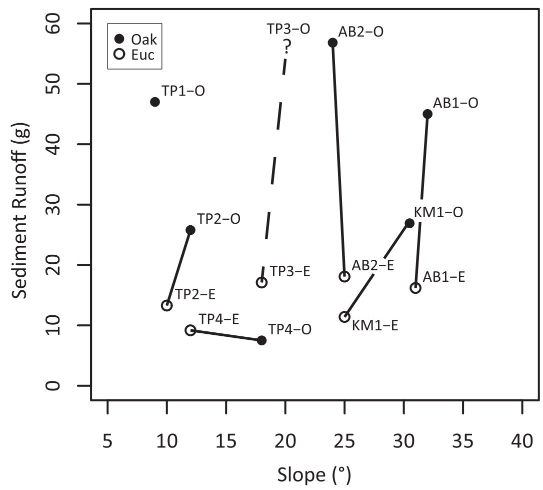

Figure 11. Sediment runoff due to storms in January 2008, in relationship to plot slopes at paired sites. Two sites are not shown, TP1-E and TP3-O, due to the possibility of disturbance, most likely by deer: TP3-E (slope 18°) was substantially damaged, however TP3-O (slope 25°) was only slightly damaged and we were able to collect 202 g of sediment captured by the trough.

model. A likely factor at these sites is a significant contrast in litter cover: oaks had a mean litter depth of 4.63 cm while eucalyptus had a mean depth of 10.13 cm, a difference of 5.5 cm ($p < 0.01$, df =14, $t = 3.2874$). All tests were conducted in R 2.71 (R Core Team, 2013).

Discussion and Conclusions

This study found increased sediment yield under oaks as compared to eucalyptus during the intense rainfall events of January 2008. We suspect this was related to increased litter depth under eucalyptus, which may have decreased splash detachment and intercepted more rainfall. While we also found soil water repellency and runoff greater under eucalyptus cover during the relatively limited 2006–2007 wet season, the effect of repellency appears to be a poor predictor of runoff and especially sediment yield when litter cover remains intact. During the wettest months water repellency is low under both oaks and eucalyptus, however the 2006–2007 winter season did not produce significant mineral sediment runoff at either eucalyptus or oak sites. The much more intense rains of January 2008 exceeded erosion thresholds that led to significant sediment yield from all sites, and soils under oaks experienced the greater erosion effects and sediment yield.

Management recommendations deriving from this study must reflect the importance of soil litter cover, which for eucalypts must include not only the chemical effects that lead to soil water repellency but more importantly the physical effects that limit sediment yield. In our study, sediment yield was shown to be greater under oak canopies, and the likely cause of this contrast is the markedly greater cover of litter under the eucalyptus sites when compared to oaks on topographically similar paired sites. Use of our findings however should be limited to undisturbed sites with intact litter cover that have not experienced recent wildfires. Other management considerations may point to the need to control the spread of eucalyptus: the same eucalyptus litter that may protect the soil from eroding creates an allelopathic suppression of other species (del Moral and Muller, 1970), many of which may be native species important to avian species of concern. While this allelopathic property is often given as an advantage for monoculture timber operations (e.g. May and Ash, 1990), for areas managed for natural habitat this creates an invasion with negative effects on local ecosystems.

In part, our study demonstrates that what may be apparent under conditions of relatively limited rainfall intensity – a connection between soil water repellency and runoff and soil moisture – does not necessarily translate to greater sediment yield. As has been well established in the geomorphic literature (e.g. Schumm, 1979), being on either side of a geomorphic threshold can dictate contrasting results; in our case, surface soil erosion threshold exceedances appear to have been much more controlled by litter cover than any water repellency effects, which were in turn likely inconsequential after a series of early rainfall events during the 2007–2008 wet season that eliminated any effect of initially contrasting water repellency.

Also well-established is the significance of fire disturbance of ground cover in increasing the potential for sediment soil erosion (Arend, 1941; Wells *et al.,* 1979; Shahlaee *et al.,* 1991; Kutiel *et al.,* 1995). Prosser and Williams (1998) observed much greater erosion under eucalypts after intense fires disturbed ground cover. As our study was limited to sites with intact litter cover and no recent fire disturbances, we would expect that other results might unfold after such a disturbance. Eucalyptus forest are well known to be highly fire-prone with a tendency for crown fires (Cohen and Butler, 1996), and these fires would lead to much greater soil erosion and potential for sediment yield connectivity to stream channels than that observed in this study.

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