Water Repellency, Soil Moisture, Surface Runoff and Soil Erosion under Eucalyptus Canopy v. Oak Canopy in Coastal California

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Master of Arts
In
Geography: Resource Management and Environmental Planning

by

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San Francisco, CA

December, 2007

CERTIFICATION OF APPROVAL

I certify that I have read Water Repellency, Soil Moisture, Surface Runoff and Soil Erosion under Eucalyptus Canopy v. Oak Canopy in Coastal California by Arnold C. Thompson, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the requirements for the degree: Master of Arts In Geography: Resource Management and Environmental Planning at San Francisco State University.

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Water Repellency, Soil Moisture, Surface Runoff and Soil Erosion Under Eucalyptus Canopy v. Oak Canopy in Coastal California

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Blue gum eucalyptus (*Eucalyptus globulus*) has been associated in many studies worldwide with elevated soil water repellency due to its biochemical properties. Elevated water repellency has been associated with decreased soil moisture and increased surface runoff, a component of soil erosion. Soil water repellency, soil moisture, runoff and sediment yield were measured at eight sites for the 2006-2007 rainy season in the Bay Area of central California to analyze differences under the canopy covers of blue gum and coast live oak (*Quercus agrifolia*). Monthly soil water repellency was significantly higher ($p < .001$, $df = 14$) and monthly mean soil moisture was significantly lower ($p = 0.0179$, $df = 14$) under eucalyptus canopy than under oak canopy. There ware significant correlations between higher water repellency and reduced soil moisture ($r = .571$, $p < .01$, $N = 72$) and higher water repellency and increased runoff ($\rho = -0.189$, $p = .015$, $N = 132$). No significant differences in sediment yield were found, possibly due to unusually dry conditions in the 2006-2007 rainy season.

I certify that the Abstract is a correct representation of the content of this thesis.

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Chair, Thesis Committee Date

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Introduction

Ecologists suspect that eucalyptus trees in coastal California impact plants, animals and soil in significant ways by inhibiting growth of native plants, reducing forage area for insects, birds and animals, and clogging coastal aquatic habitat with increased sedimentation (WESCO, 1993). Eucalyptus in coastal California is currently under management for fire control (EBRPD, 2004) and habitat restoration (Chasse, 2007; Zebell, 2004). Several studies worldwide have looked at the hydrologic impacts of eucalyptus (e.g. Doerr et al., 2005; Ferreira et al., 2000; Keizer et al., 2002). Shakesby (2000) associated eucalyptus-induced elevated soil water repellency with reduced aggregate stability, reduced infiltration, increased rainsplash detachment, enhanced overland flow and increased soil erosion.

Our hypothesis is that the presence of introduced *Eucalyptus globulus* trees raises the level of water repellency in the soil when compared to the native species *Quercus agrifolia*. This effect may contribute to decreased soil moisture levels, and may increase surface runoff and erosion of fine soil particles. In this study, we assessed the influence of *E. globulus* on surface water repellency, soil moisture, surface runoff and sediment mobilization compared to a control species, *Q. agrifolia*. Previous studies have demonstrated hydrologic responses including changes in infiltration rates and erosion rates due to differences in vegetation on plot scales ranging from $0.24m^2$ to $500m^2$

(Keizer *et al.*, 2002; Wainwright *et al.*, 2000). Shakesby *et al.* (2000) 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.

As sedimentation in coastal creeks and streams presents resource management challenges, this project may help habitat restoration efforts by furthering our knowledge of soil moisture and runoff properties in areas of California dominated by eucalyptus trees. With finite restoration budgets, resource managers may consider results of this study in deciding where to focus eucalyptus control efforts such as near stream channels or in areas where native species are sensitive to decreased soil moisture.

Methods

We examined side-by-side (either contiguous or within 100 meters of each other) patches of an *E. globulus* and *Q. agrifolia* in 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 eucalyptus and oak pair was measured under similar physical conditions of slope (degree), aspect (compass direction), rainfall intensity and volume, and soil type. By using side-by-side patches, we tried to minimize confounding factors in hydrologic response. Eight suitable sites were identified, four in Tilden Park in the East Bay Regional Park District, one in the Presidio of San Francisco and three within the Marin Open Space District in Marin County (Figure 1).

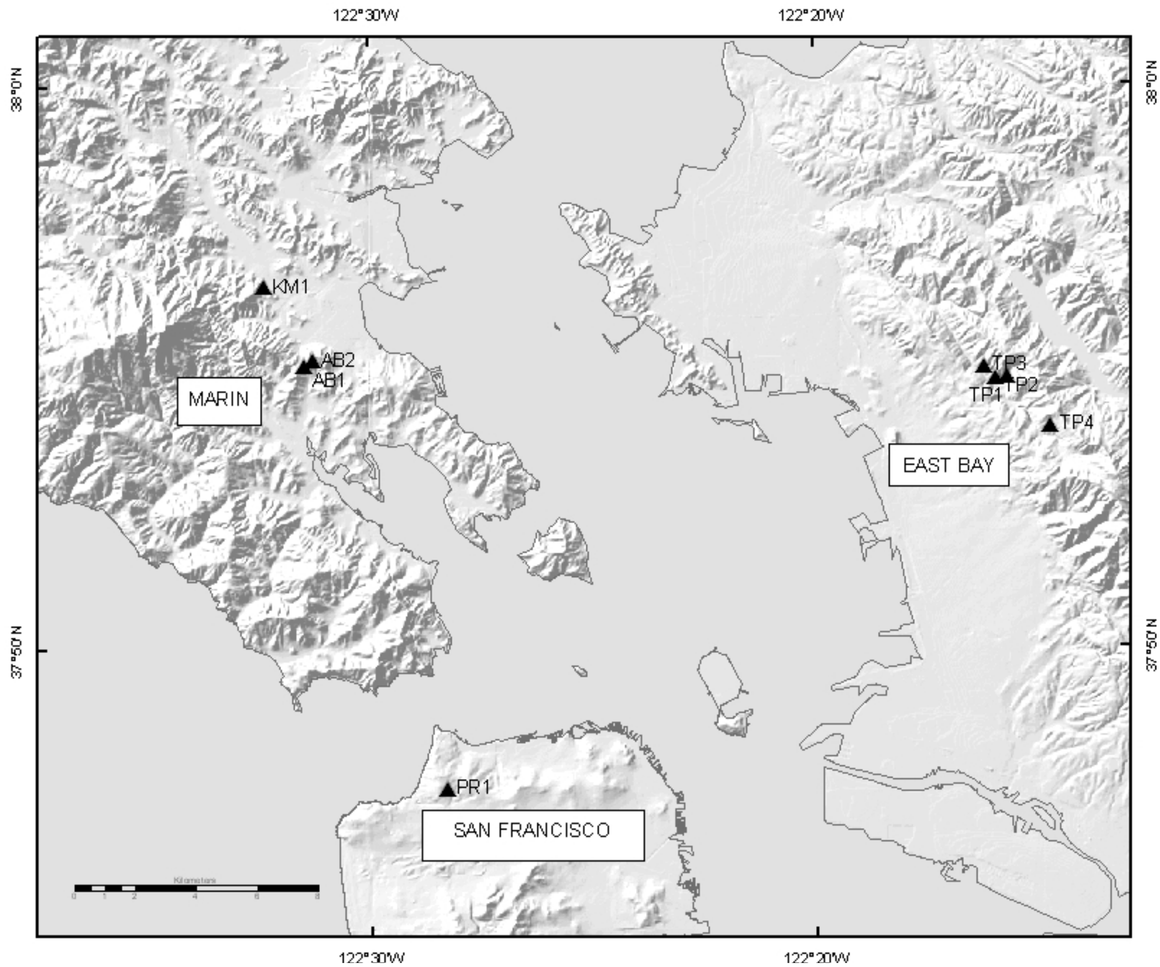

Figure 1. Locations of study sites in the SF Bay Area. TP sites are in Tilden Park, Berkeley located in the East Bay. The PR site is in the Presidio of San Francisco. AB and KM sites are in Marin County. (Source: U.S. Geological Survey 1997)

The San Francisco (SF) Bay Area has a Mediterranean climate with about 84% of the precipitation falling almost exclusively as rain between the months of November and March (Table 1). Rainfall averages for 1971-2000 varied considerably (NOAA, 2004) with Kentfield in Marin County receiving roughly double the rainfall of the San Francisco and East Bay sites, but the seasonal distribution remains quite similar.

Table 1. 1971-2000 precipitation and temperature averages near the study sites. Berkeley is near the Tilden Park sites, Kentfield is near the Marin sites and San Francisco is near the Presidio site. (Source: WRCC 2006)

City	Precipitation (mm)	Pct. falling Nov - Mar	Mean temp. °C
Berkeley (East Bay)	645	83%	18.3
Kentfield (Marin)	1206	85%	21.9
San Francisco	566	84%	15.6

The Mediterranean biome consists primarily of woodland, grassland and shrubland. Californian woodlands are dominated by oak varieties while Australian woodlands are dominated by eucalyptus varieties (MacDonald, 2003). Our study sites consist of woodland edges bounded primarily by grasslands, located in hilly areas upslope of the flatlands surrounding San Francisco Bay.

Finding subsite pairs with similar slopes was a primary design consideration as slope is a major component in runoff (Assouline and Ben-Hur, 2006). Difference in slopes at a site ranged from 1 to 7 degrees with a standard deviation of the difference of 2.89 degrees. In seven cases the slope of oak trees was equal to or greater than the slope of eucalyptus trees and in one case the slope of eucalyptus trees was one degree greater than the slope of oak trees (Table 2). Because our hypothesis is that runoff is greater under eucalyptus trees than under oak trees and because runoff increases with slope (Assouline and Ben-

Hur, 2006), we looked for oak slopes equal to or greater than eucalyptus slopes to avoid a false positive. Mean oak slope was 21.4 degrees while mean eucalyptus slope was 19.1 degrees with a standard deviation of 9.1 for oaks and 8.1 for eucalyptus. Aspect differences ranged from six to 67 degrees with a standard deviation of 26.6. As leaf litter acts as a mulch and reduces runoff and sediment yield (DFG, 2006), to further reduce the chances of a false positive we measured litter depths under oak and eucalyptus canopy. Mean oak litter depth was five cm while mean eucalyptus depth was 10cm, with a standard deviation of 2cm for oak and 4cm for eucalyptus.

Table 2. Characteristics of the sites: slope, aspect, distance between oak & eucalyptus plots, and average litter depth.

Site Name	Slope°			Aspect°			Spacing between oak & eucalyptus plots (m)	Litter Depth (cm)		
	Oak	Euc	Diff	Oak	Euc	Diff		Oak	Euc	Diff
AB1	32	31	1	220	227	7	41	8	6	-2
AB2	24	25	-1	100	106	6	24	7	13	7
KM1	30.5	25	5.5	189	196	7	87	5	7	2
TP1	9	9	0	229	296	67	41	1	8	7
TP2	12	10	2	143	197	54	81	7	14	7
TP3	25	18	7	264	215	49	62	2	8	6
TP4	12	12	0	187	175	12	32	4	8	5
PR1	27	23	4	121	115	6	25	3	17	14

Assessing soil water repellency

To assess the degree of soil water repellency (also referred to as soil hydrophobicity) of soil under the tree canopies, we applied a 'critical surface tension test' (CST), also referred to as the 'molarity of ethanol droplet' (MED) test (Doerr *et al.*, 2003). Rather than measuring the soil itself, we looked at the surface tension of a solution that was able to penetrate the soil *in situ* within three seconds. The result was a threshold, a critical surface tension value, required to penetrate the soil.

Ethanol has less than one-third the surface tension of water at 20^{o} C (Lange, 2002) and penetrates soil surfaces more easily than water under hydrophobic conditions (Doerr, 1998). Higher ethanol concentrations lower the surface tension of solution (Table 3). The higher the concentration of ethanol in water required to penetrate the ground within three seconds, the more water-repellent the soil (Doerr, 1998). We reduced the number of ethanol concentrations (hydrophobicity classes) from nine to six to allow us to test at all sites as soon as possible after rain events. Five repetitions of the test were performed at each subsite and averaged to obtain CST for each visit. In the case of doubt as to the penetration times, solutions were reapplied to confirm results.

Table 3. 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 critical surface tension expressed in milli-Newtons per meter. (reproduced after Keizer et al. 2002, Doerr et al. 2003)

Hydrophobicity Class	**0**	**I**	**II**	**III**	**IV**	**V**	**VI***
Ethanol Concentration (%)	**0**	**1**	**5**	**13**	**24**	**36**	**50***
Critical Surface Tension (10^{-3} N m^{-1})	**72.1**	**66.9**	**56.6**	**46.3**	**38.6**	**33.1**	**28.5***

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 (denoted by asterisk) and assumed it would take an ethanol concentration of 50% to penetrate the soil within three seconds.

Assessing soil moisture

We assessed soil moisture in terms of volumetric water content (VWC) by taking gravimetric soil core samples 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 200cm^3 in volume were weighed wet, dried in a drying oven at 60º C for 48 hours (Parker, 2006) or in a microwave oven (Foth *et al.*, 1982), then re-weighed to obtain the water content. With density of water assumed to be 1 g cm^{-3} , VWC was calculated using these formulae (Foth *et al.*, 1982):

$$\text{Bulk Density (BD)} = \frac{\text{dry soil weight (g)}}{\text{soil volume (cm}^3\text{)}} \quad (1)$$

$$\text{Percent soil water by weight } (\%_w) = \frac{\text{weight of water (g)}}{\text{dry soil weight (g)}} \quad (2)$$

$$\text{Percent water by volume (VWC)} = \frac{(\%_w) * \text{BD (g cm}^{-3}\text{)}}{\text{density of water (g cm}^{-3}\text{)}} \quad (3)$$

During the dry season and the early part of the rainy 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 soil moisture measurements by TDR to a depth of 10cm, corresponding to our 10cm core depth. Three TDR measurements were taken at random locations outside of but within 1m 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 = -0.0005x2 + 0.0506x - 0.6919 (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 (Figure 2). 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. These measurements were averaged to obtain a mean litter depth for each plot.

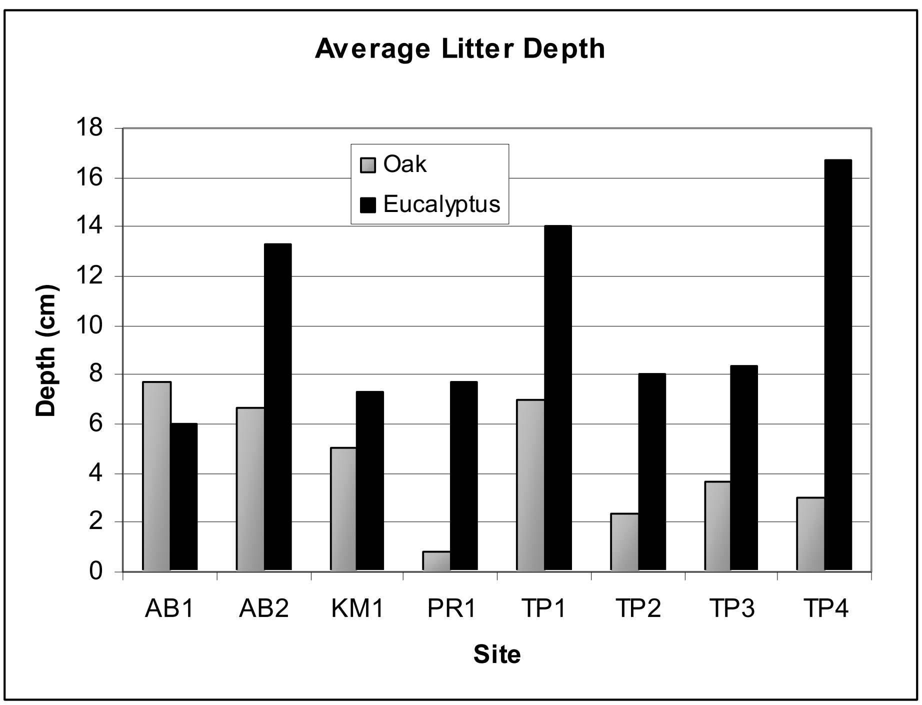

Figure 2. Leaf litter depth by site. Eucalyptus litter was deeper at all sites except Alto Bowl 1 (AB1).

Runoff & sediment collection using Gerlach troughs

Gerlach troughs were installed to collect runoff and sediment moving downslope during rainfall events. These were designed after Larsen *et al.* (1999) and Utomo *et al.* (1999), and consisted of 50cm lengths of plastic raingutter 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 3). The lid kept out direct rainfall interception and prevented sediment kicked up by rainsplash from entering the trough.

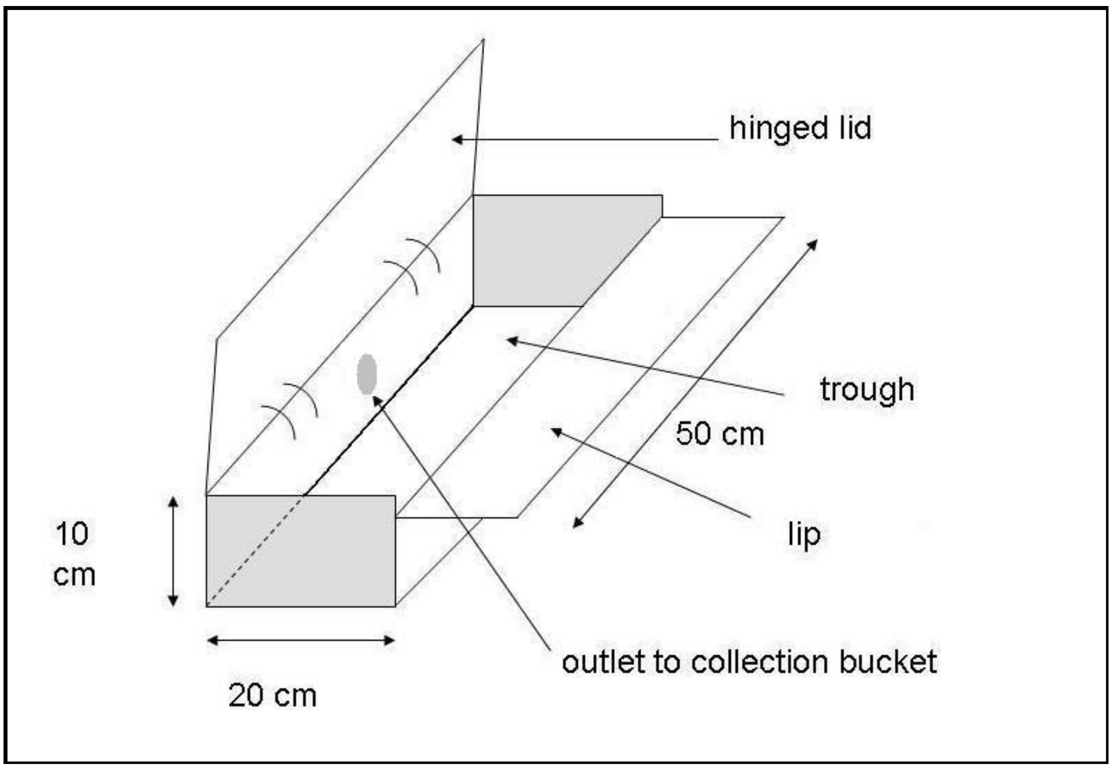

Figure 3. Illustration of a Gerlach trough (reproduced after Utomo *et al.*, 1999)

The downslope side was fitted with a runoff tube leading to a collection bucket with a minimum volume of 10 L (Figure 4). We used various types of overflow containers including laundry detergent buckets, industrial cleaner buckets and plastic jugs with volume markings on the sides.

Figure 4. Gerlach trough and runoff bucket.

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

Measurements were taken after 12 rainfall events from November 2006 through May 2007. Runoff was quantified by measuring the water depth in unmarked buckets and converted to volume. Rainfall was quantified under each type of tree canopy and out in the open at a location near the trees with inexpensive plastic rain gauges with a maximum capacity of 100 mm of precipitation. Following each runoff and rainfall reading, we emptied the buckets and rain gauges.

To quantify sediment we took grab samples from the runoff buckets by agitating the runoff water to resuspend settled sediment and taking 60mL samples (Larsen, 2006). The sediment was filtered in the lab 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.

Results and Discussion

Precipitation, Soil Water Repellency and Soil Moisture

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 broke down while remaining higher at eucalyptus subsites (Figure 5).

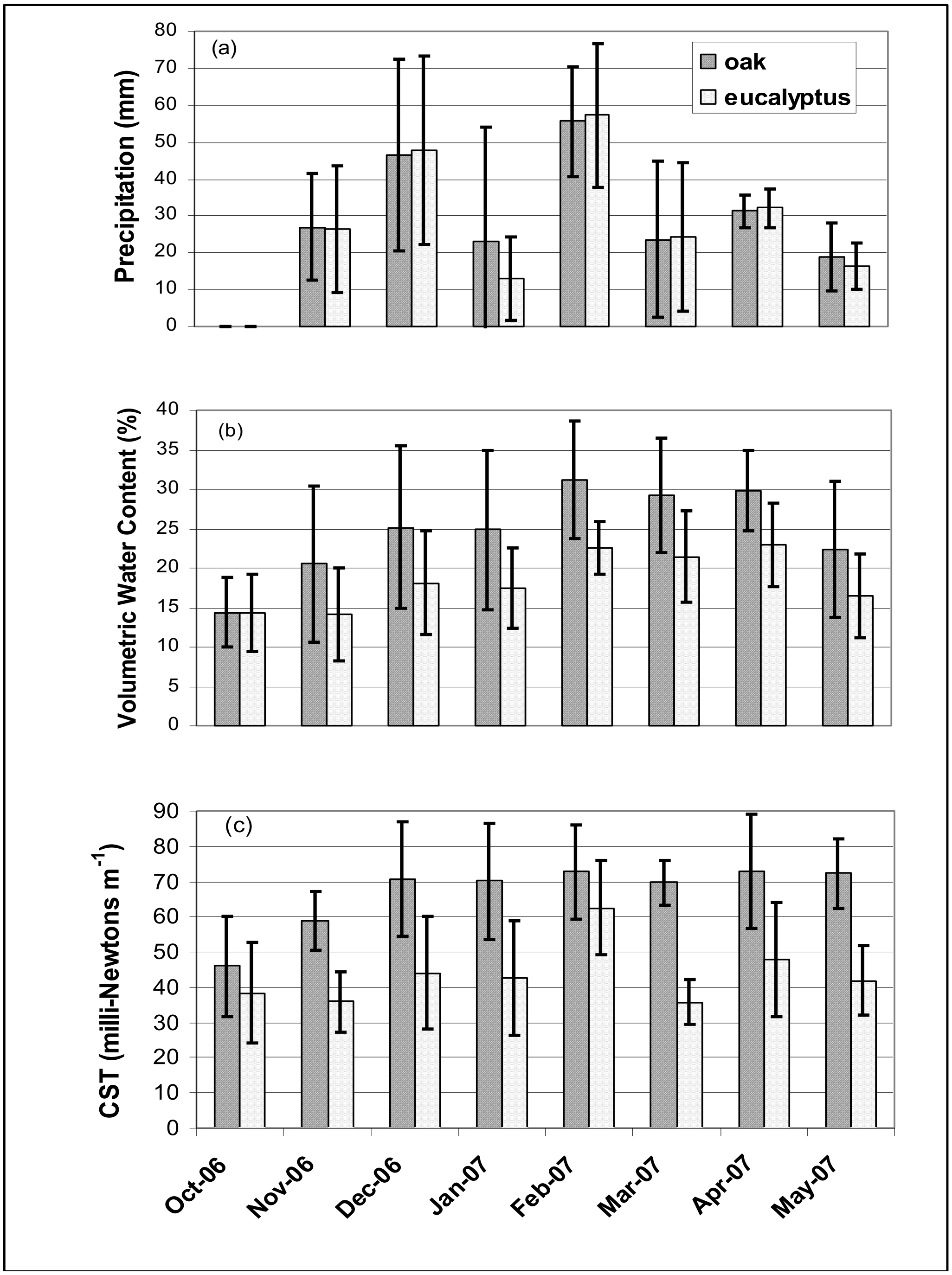

Figure 5. Precipitation, volumetric water content (VWC) of soil and critical surface tension (CST) by month. Error bars represent ± one standard deviation. Precipitation was not measured on site in October 2006 but conditions were dry regionally (GGWS 2007). Lower CST numbers represent higher water repellency.

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 (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 ($p = .0002$, $df = 14$), and lower moisture levels than soil under oak trees we looked at the correlation between water repellency expressed as critical surface tension and VWC. An aggregate plot of moisture data shows that as critical surface tension decreased, soil moisture decreased (Figure 6). Results are significant per Pearson's correlation ($r = 0.571$, $p < .001$, $N = 72$). 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.

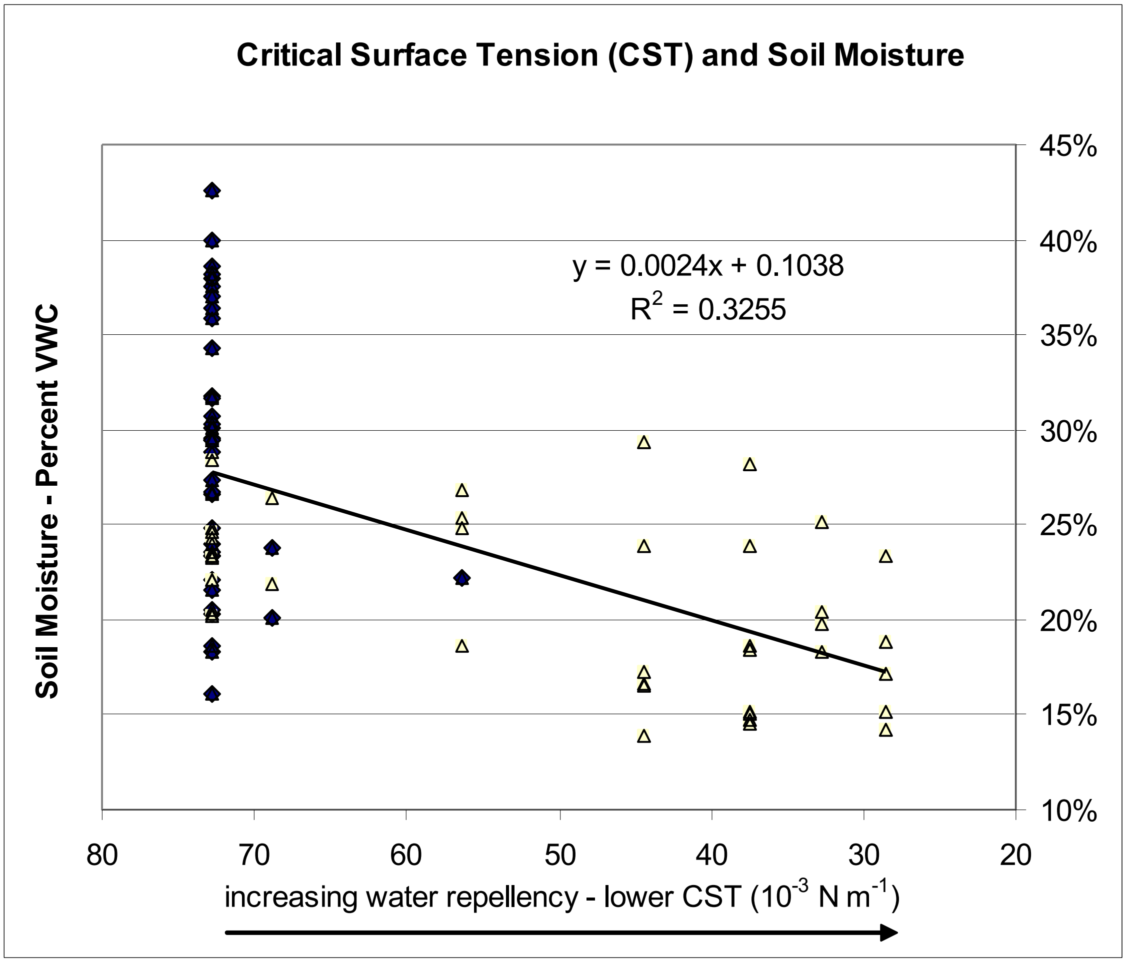

Figure 6. Water repellency and soil moisture starting six weeks into the rainy season. Light symbols represent eucalyptus, dark symbols represent oak. Data from sandy soil at PR1 (very low VWC) not included.

Runoff

Precipitation throughout California was quite low during the 2006-2007 rainy season (DWR, 2007), eg. 58% of normal at the San Francisco airport (GGWS, 2007), which reduced the frequency and quantity of runoff-producing rainfall events. Measurements were not always available at each site following rainfall due to trap damage, an overturned overflow bucket or other disturbance.

Runoff events with no measurable runoff at either the oak subsite or eucalyptus subsite were removed from the analysis. In analyzing runoff it is informative to note that while the difference in slope is not statistically different ($p = .054$, $df = 7$, $t = 2.2632$), the mean slope of oak tree sites in this study (21.4 degrees) is almost statistically greater than the slope of eucalyptus trees (19.1 degrees). This indicates a possible bias toward greater observed runoff at oak subsites.

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. It assumes that all measurements are independent, which we believe may not be a valid assumption due to autocorrelation. 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 $p = .029$) 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 ($p = .204$), with site (partial eta squared = .285) as the largest contributor to runoff after rainfall (partial eta squared = .341). The three Marin oak sites had more runoff than Marin eucalyptus sites, while eucalyptus runoff exceeded oak runoff at the other five sites (Figure 7). Slopes at Marin sites averaged 27.9 degrees while slopes at the other sites averages 15.7 degrees, so there may be a threshold effect not taken into account.

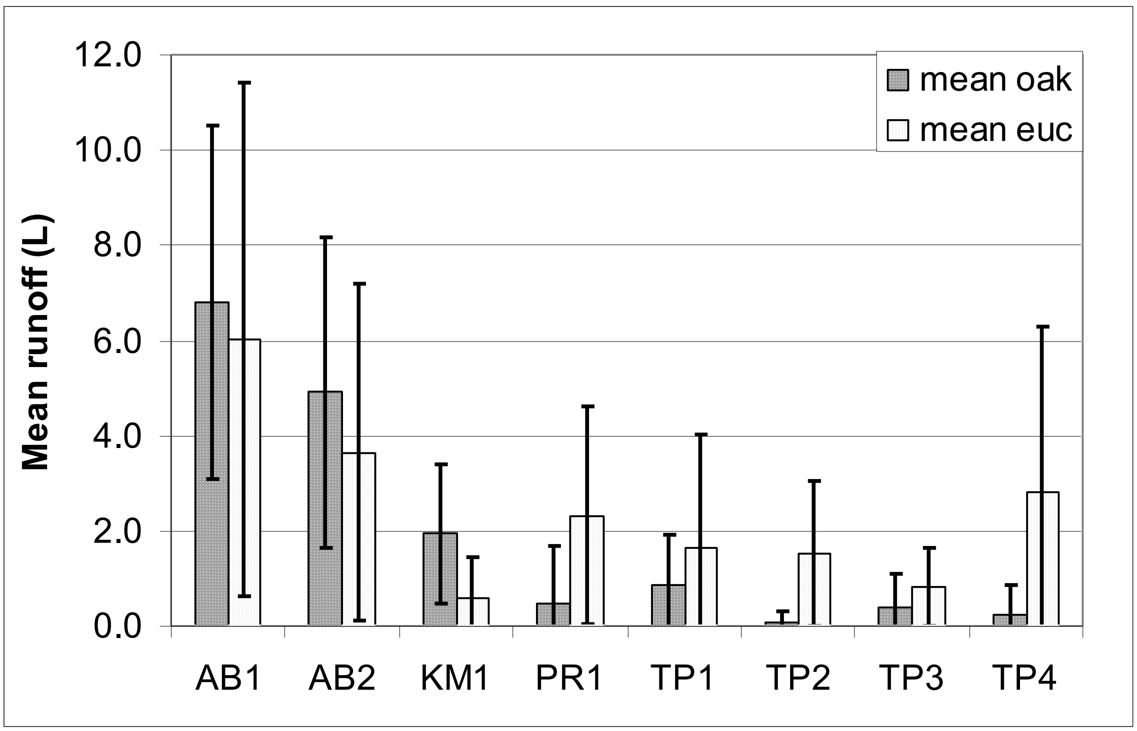

Figure 7. Oak and eucalyptus runoff for all sites. Alto Bowl (AB1 & AB2) slopes are 10 degrees steeper than the other slopes on average, partially accounting for the increased runoff.

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 increased (p = .001, partial eta squared = .252) with increased soil water repellency (Figure 8). Water repellency was the biggest contributor to runoff after rainfall ($p < .001$, partial eta squared = .318). These results should be used with caution however because error variances are not equal across all groups (Levene's Test $p < .001$), however Spearman's non-parametric test shows a significant one-tailed correlation ($\rho = -0.189$, $p = .015$, $N = 132$) between CST and runoff per unit of rainfall (L mm^{-1}). Leaf litter depth and soil bulk density were not significant contributors to runoff.

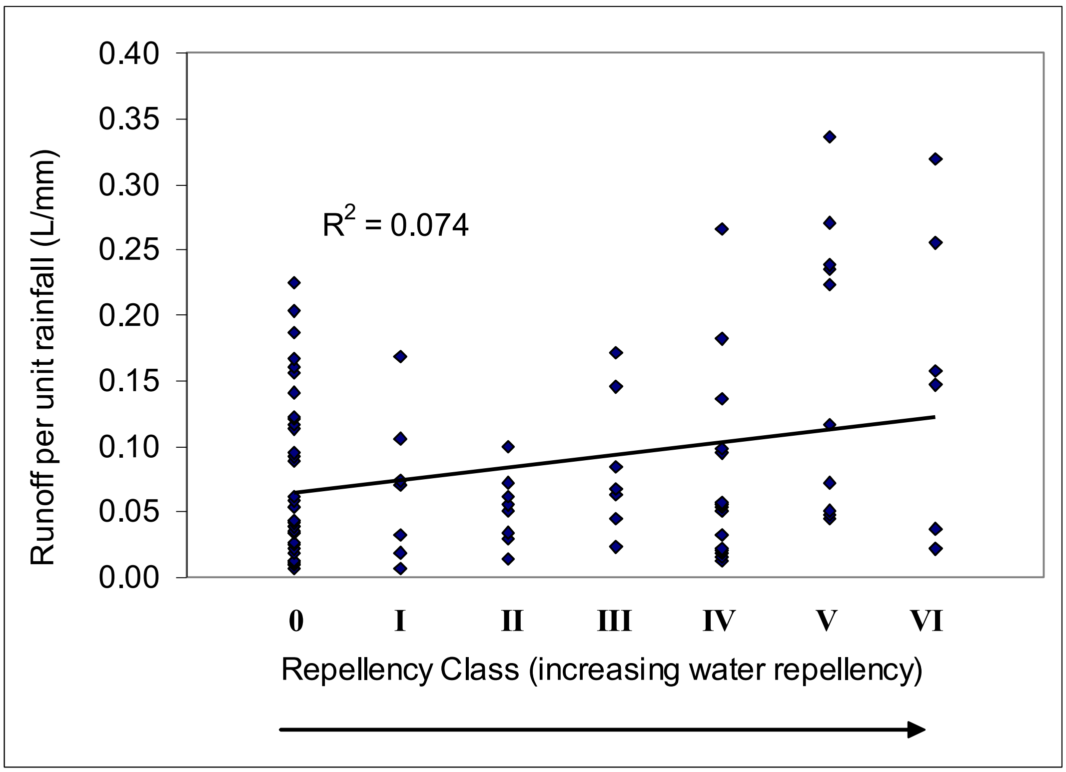

Figure 8. Runoff (L) per unit of rainfall (mm) compared to water repellency class. As soil water repellency increases, runoff per unit rainfall increases. Covariates such as site, slope and leaf litter depth are ignored.

Sediment Yield

Water samples taken from overflow buckets had sediment yields lower than our ability to reliably quantify it, on the order of .01 gram or less, so the results were not statistically analyzed. Future analysis might be improved by taking larger water samples such as 250 mL instead of 60 mL, which would have a greater likelihood of yielding a measurable amount of sediment.

It is also quite possible that the presence of leaf litter acting as mulch prevents mobilization of fine sediments. 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 ($p < .01$, $df = 14$, $t = 3.2874$). Leaf mulch has strong erosion prevention properties (DFG, 2006). Areas with a greater percentage of bare soil, such as could be found on steeper slopes, might yield more sediment.

Conclusions

There is a clear difference in the degree of soil water repellency between oak and eucalyptus and a clear difference in levels of soil moisture between the two. We cannot say with certainty that water repellency is the cause of the observed drop in soil moisture because eucalyptus is known to extract and transpire large quantities of groundwater (Bell and Williams, 1997; Pryor, 1976), but we did find a significant correlation between water repellency and reduced soil moisture at a depth range of 0 - 10 cm.

The runoff trend is interesting but inconclusive. There appeared to be a weak but significant positive correlation between increased water repellency and increased runoff per unit rainfall, but this result was not directly linked to tree type. Given the variances and relatively small differences observed, a larger sample size would be needed to obtain a significant result between oak and eucalyptus. Obtaining a larger sample size could be obtained through the use of more sites or taking more samples per site, but a primary limitation was the limited number of runoff-generating events during this abnormally dry year.

The presence of considerable amounts of leaf litter could have had significant and unanticipated effects on the outcome. Litter may have absorbed water that otherwise would have produced runoff and trapped sediment that otherwise would have accumulated in the overflow buckets. Oak leaf litter was deeper than eucalyptus leaf litter at one site, AB1, which was also the steepest of the eight sites. There may be a threshold gradient above which runoff and sediment yield is more pronounced.
It was not possible using our methods to quantify the amount of water or sediment trapped by litter, but we would expect that with greater rainfall the litter would have become saturated and yielded more runoff.

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