Fire and Terrain Controls on Soil Carbon in Chaparral Watersheds

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Summary

This project addressed the post-fire soil carbon distribution as a function of burn history and terrain characteristics in two chaparral watersheds in the uplands of the San Gabriel Mountains, Southern California. We hypothesized that (1) prescribed fire, because it does not burn as hot, leaves a greater amount of soil carbon on the landscape than a wildfire, and (2) soil carbon distribution is strongly linked to terrain characteristics that influence post-fire erosion. This relationship was assessed for two watersheds; one subjected to a prescribed fire, the other a wildfire. Terrain analysis using a 0.5-meter DEM defined terrain characteristics within each watershed. Soil samples were taken within a predetermined grid and analyzed for soil organic carbon (SOC). The mean SOC of the prescribed fire watershed, 4.44 kg m^{-2}, was significantly higher than that of the wildfire watershed, 3.47 kg m^{-2}, which indicates that fire severity is a major influence on the post-fire SOC. Terrain characteristics, such as elevation and curvature, were correlated to SOC only in their roles as defining elements of the broader landscape positions (shoulder, channel, sideslope). Slopes in this study were very steep, mostly near 60%, and the correlations between slope gradient and erosion found in studies of gentler landscapes do not occur here. The extreme steepness of these slopes may be such that substantial erosion occurs on all points of the landscape. This study provides values for SOC in the post-fire chaparral ecosystem and evidence of the differences that occur due to fire severity.

Objectives

Objective 1. Relate the spatial distribution and forms of soil carbon in small (1-2 ha) chaparral watersheds to terrain properties.

Objective 2. Determine the effect of prescribed burning on soil carbon storage in chaparral watersheds.

Approach and Procedures

Two watersheds were chosen for this study in the San Dimas Experimental Forest, a U.S. Forest Service research station in the uplands of the tectonically active San Gabriel Mountains of Southern California (*fig. 1*). The climate is Mediterranean with a mean annual precipitation of 678 mm that is mainly rain (Dunn et al. 1988). The bedrock is composed of gneisses and schists that are deeply weathered, poorly consolidated, and very unstable. The resulting topography has steep, complex slopes. The upland watersheds in which this study took place have first-order channels, narrow interfluves, and slope gradients mainly within the range of 25 to 100%. Soils mapped for this area are mostly Entisols (loamy, mixed, nonacid, thermic, shallow Typic

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Xerorthents) on the predominating steep slopes, with smaller areas of Alfisols and Mollisols on lower gradient slope positions (Ryan 1991). The vegetation of the area is chaparral. The mature chaparral was dominated by chamise (*Adenostoma fasciculatum*), hoaryleaf ceanothus (*Ceanothus crassifolia*), manzanita (*Arctostaphylos sp.*), and sugarbush (*Rhus ovata*). The first chaparral plants to resprout after fire in both watersheds were chamise and sugarbush. At the time of sampling, annuals, such as mustard (*Brassica* sp.), lotus (*Lotus* sp.), brome (*Bromus* sp.), manroot (*Marah macrocarpa*), and lupine (*Lupinus* sp.), dominated the vegetative cover, as is typical of post-fire succession in chaparral (DeBano et al. 1998).

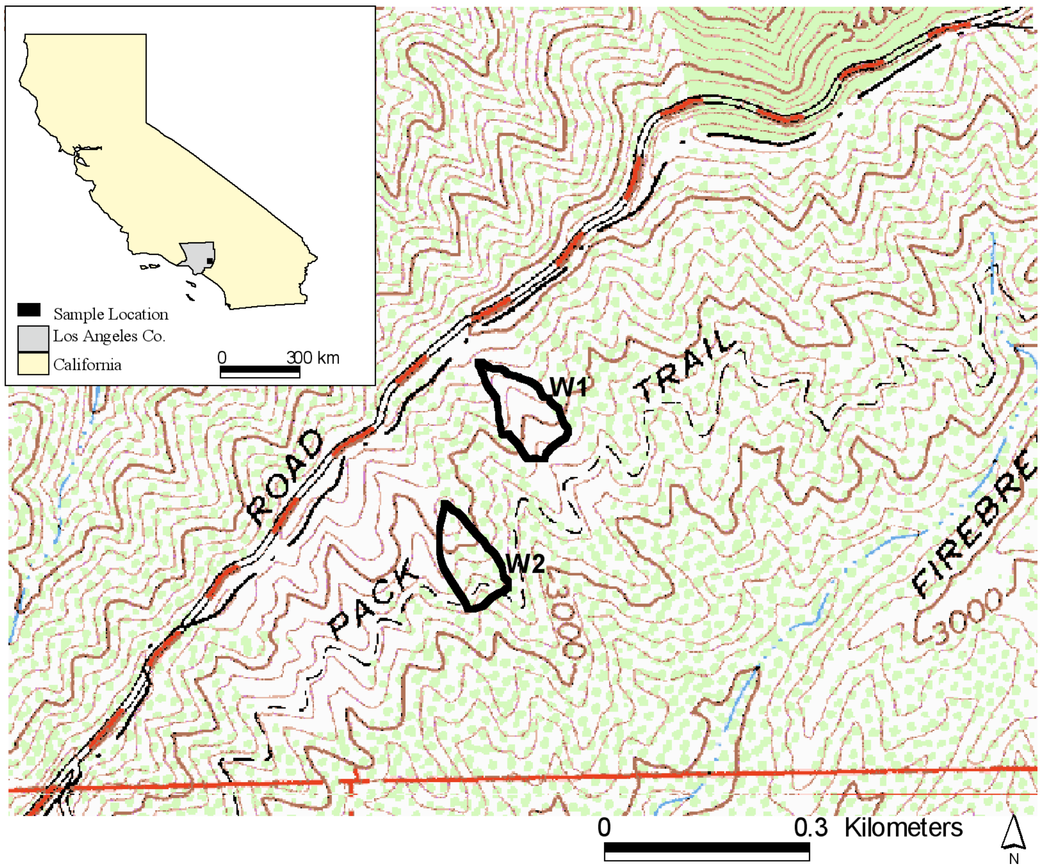

Figure 1. The locations of the two watersheds used in this study are outlined on the topographic map. Watershed 1 (W1) is 0.2 km northeast of watershed 2 (W2).

The watersheds were chosen for similar size (~1 ha), dominant aspect (south), steepness of slopes (generally 25-100%), and complexity of terrain. One watershed (W1) had a prescribed fire in the summer of 2001 and the other (W2) had a wildfire, the Williams Fire, in the fall of 2002. Before those fires, both were unburned since the Johnstone Fire in 1960 and had mature chaparral canopies before the most recent fires (Wohlgemuth 2003). Given their similarities in vegetation and terrain characteristics, it is reasonable to assume that pre-fire SOC contents and distributions were also similar. Table 1 lists the monthly and yearly precipitation totals following each fire. The average sedimentation rates in collectors with 30-cm wide upslope apertures at the W1 site changed from 6 g day^{-1} before the prescribed fire to 9 g day^{-1} immediately after the fire to 328 g day^{-1} during the following wet season (de Koff 2004).

Table 1. *Timing of fire events, sampling, and precipitation totals. Months that are not listed did not have an important event or precipitation.*

Hydrologic Year	Month	Event	Precipitation		
			Monthly	Hydrologic Year Total	Total Between Fire and Sampling Dates
			in		
	May, 2001	Prescribed Fire in W1			
2001-2002				9.29	
	November		2.51		
	December		1.77		
	January		0.26		
	February		2.99		
	March		1.36		
	April		0.00		
	May		0.57		
2002-2003				25.14	
	September	Wildfire throughout SDEF, including W2	0.00		
	October		0.00		
	November		4.84		
	December		0.38		
	January		3.56		
	February		6.56		
	March		4.70		
	April		2.46		
	May		2.14		
	June	Sampling begun in W1			
			0.50		
	July	Sampling completed in W1			34.60
2003-2004				17.62	
	November		1.12		
	December		5.76		
		Sampling begun in W2			
	January		0.62		
	February	Sampling completed in W2			32.64
			4.08		
	March		4.94		
	April		0.56		

Sample points within each watershed were selected using a predetermined grid system as shown in figure 2. The hillslope position of each point (i.e., shoulder, sideslope, or channel) was determined using the general location on the map and notes from field sampling. At each grid point, soil samples were taken from morphologic horizons exposed in a hand-dug pit down to the Cr horizon or 50-cm depth, whichever was shallower. Point A6 from W1 and point G4 from W2 were not sampled because they were located on manmade trails. Bulk density samples were collected from representative soil horizons on the different watershed positions using a metal core with a volume of 69 cm^3.

At each sample point, the curvature of the landscape was described for a 1-m and 5-m diameter area. By visual observation, the horizontal (along the contour) and vertical (perpendicular to the contour) curvature was determined to be convex (V), concave (C), or linear (L).

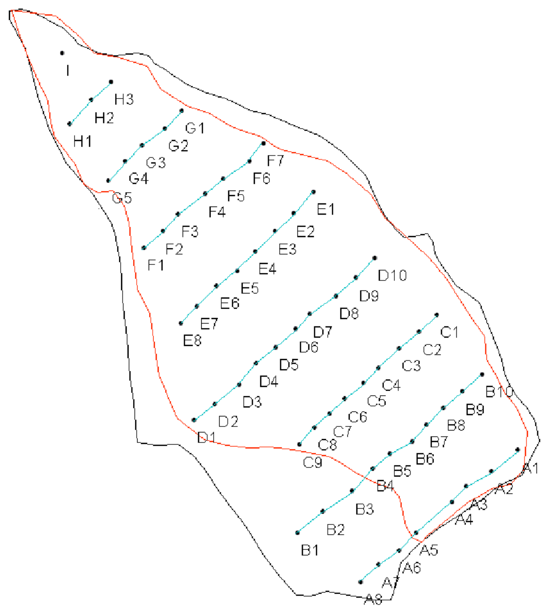

Fig. 2a

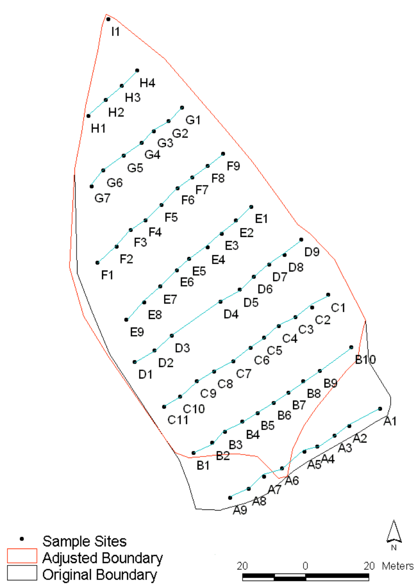

Fig. 2b

Figure 2. The sampling grid is shown here for Watershed 1 (a) and Watershed 2 (b). The boundary for each watershed was adjusted based on the interpolated upslope contributing, which removed some points in each watershed from consideration during data interpretation.

The post-fire vegetation distribution was taken into account as a possible control on the soil organic carbon (SOC) distribution. It was expected that a plant would act as a dam, inhibiting soil deposition at points downslope while increasing deposition immediately upslope, depending on the distance. Therefore, the distance to the nearest plant upslope and downslope of each sample point was measured, but only if the plant had evidence of being present during the fire. Measurements were made to the center of each plant base. The diameter of the base of the plants ranged from 10 cm to 25 cm.

A 0.5-m DEM (digital elevation model) was developed from GPS surveyed points (Trimble ProXRS) combined with data extracted from a 5-m Global Terrain DEM. For W1, 1158 points were surveyed, and 1,827 were mapped for W2. The elevation values of the unsampled areas between the GPS survey points were interpolated using ordinary kriging and a Gaussian model. The other topographic characteristics derived from the DEM were slope gradient, aspect, upslope contributing area, and topographic index. Percent slope is the tangent of the slope gradient in degrees multiplied by 100%. Upslope contributing area (UCA) is the sum of the terrain area that drains to a single point. Topographic index (TI) is derived from UCA and the slope and is used to describe the distribution of moisture in a watershed.

Soil samples were sieved through a 2-mm mesh sieve and weighed for gravel content. Subsamples of the <2mm fraction of soil were ground to pass a 0.150-mm mesh sieve, oven dried, and analyzed for total carbon content using a CNS analyzer. Total soil carbon was equivalent to soil organic carbon (SOC) in these soils because no carbonates were present. The carbon content was corrected for the volume of gravel in each sample and converted from percent to kg m^{-2} using an average bulk density value of 1.2 g cm^{-3} for the area. More details on the study site and methods are presented by Akers (2004).

Results

During the sampling process, it was observed that most soils had an A horizon that transitioned into the Cr horizon. The few soils that had weak structure development seemed to be limited to the shoulder position along the upper boundaries of the watersheds. Depth to Cr was below 50 cm in only 9% of the sample sites in W1 and only 3% in W2. Gravel content by mass ranged from 1 to 85 % for all samples in W1 and 0 to 88 % in W2.

The comparisons of terrain characteristics showed that W1 and W2 are only significantly different in terms of elevation (*table 2*). W1 has a higher mean altitude than W2. Such minor altitude differences have no direct influence on SOC distribution or sediment movement. The steepness of slopes of the watersheds is illustrated in figure 3, using W1 as an example. The interquartile range for W1 is 43 to 65% and for W2 is 53 to 68%.

The SOC concentrations in the <2-mm soil fraction ranged from 0.2 to 11.0% in W1 and 0.3 to 14.2% in W2. When gravel content and bulk density are taken into account, the SOC concentrations translate to 0.62 to 13.94 kg m^{-2} in W1 with a mean of 4.44 kg m^{-2}; and 0.22 to 17.80 kg m^{-2} in W2 with a mean of 3.47 kg m^{-2}. In a one-tailed t-test, testing whether W1 has greater SOC than W2, there was a significant difference at $p = 0.04$.

The correlation coefficients, r, for each comparison of a terrain characteristic to SOC are shown in table 3. In W1, SOC was not correlated to any of the terrain characteristics. In W2, SOC was correlated with relative elevation ($p < 0.05$) and aspect ($p < 0.001$). All correlations with SOC were negative, except for the W1 A horizon with slope, and the correlations with aspect, which cannot be negative because aspect involves circular data.

Table 2. *Statistical comparisons of elevation, slope, and aspect between W1 and W2.*

	W1	W2
df	54	59
Mean Elevation, m***	972.03	954.76
Mean Slope, %	55.85	61.26
Mean Aspect, degrees †	143.75	164.13

*** Significant at the 0.001 probability level.

† Mardia-Watson-Wheeler test for differences in the distribution of angles for circular data.

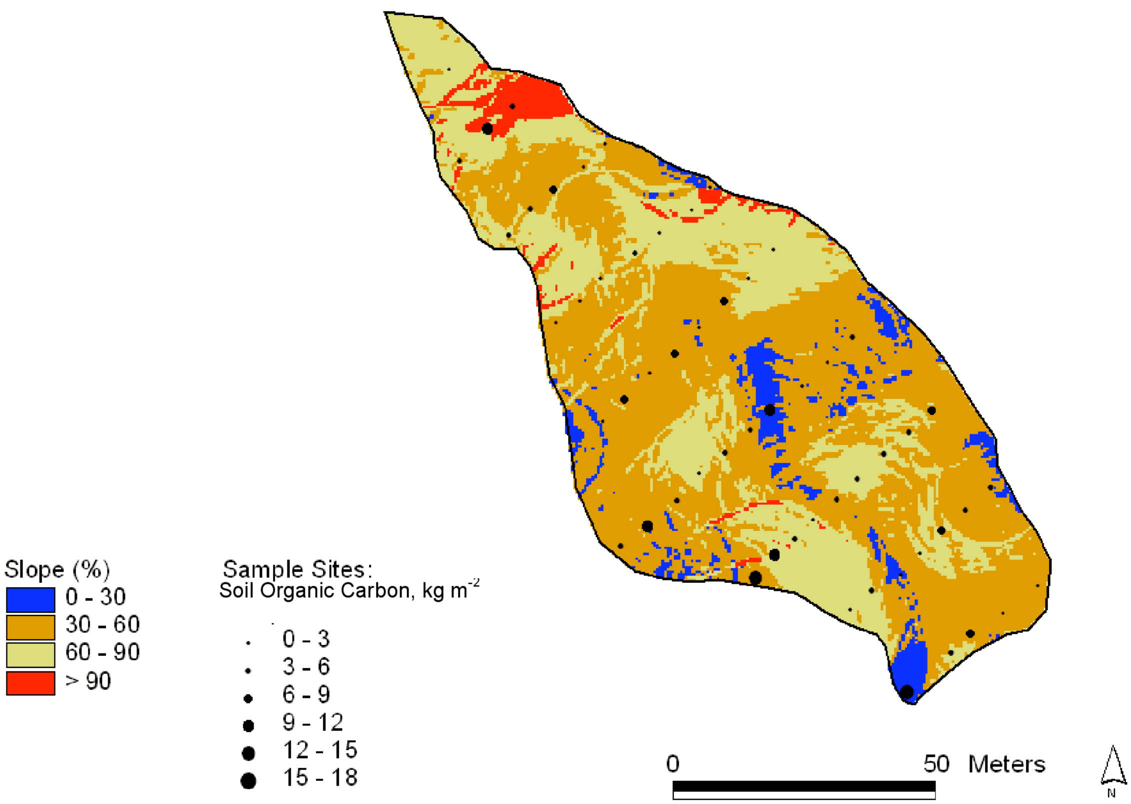

Figure 3. The slope gradient of the land area in W1 is mostly greater than 30%, as shown in the map. The histogram, at top left, represents the slope gradient frequencies of the sample points in W1. W2 has a similar range of slope gradients.

The distribution of aspect in W2 is bimodal between southwest and southeast (fig. 4). The modes are approximately divided at 155º. In a t test, SOC was significantly different between the southwest aspect and the southeast aspect at $p < 0.01$. In order to eliminate other possible influences, relative elevation and slope gradient were compared between the southwest and southeast sides of the watershed using t tests, but were not significantly different.

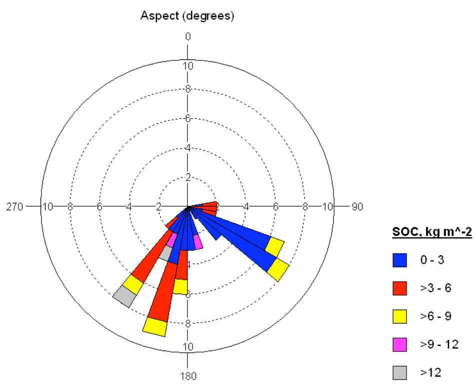

Figure 4. Rose compass histogram depicting the frequency of aspect and soil organic carbon (SOC) in Watershed 2. The width of each wedge in the rose compass covers a range of 10 degrees and the length represents the frequency of observation within each SOC category. The aspect distribution is bimodal, divided at approximately 155°.

The A horizon, the uppermost part of the soil profile, is most affected by post-fire erosion. Thus, to further explore the relationship between slope and SOC, slope was compared to the A horizon SOC (Table 3). Also, A horizon SOC and slope were compared for sample points with slope gradients less than 88%, as will be explained below. The correlation trend of SOC with slope in W1 went from positive to negative when only slopes with <88% gradient were used. There were no significant correlations between A horizon SOC and slope.

Upslope contributing area and topographic index both have weak, insignificant correlation to SOC. Their low r values, shown in table 3, are probably the result of being derived from the other terrain characteristics that are weakly correlated to SOC.

The statistical results of comparing the channel, sideslope, and shoulder positions are shown in table 4. There is a significant difference in mean SOC between the channel and sideslope positions in W1 ($p < 0.01$), but there is no significant difference when considering A horizon SOC. In W2, the situation is reversed in that the significant difference is seen only in the A horizon, not in the total SOC, and is between the sideslope and shoulder positions ($p < 0.01$).

The number of sample points placed into each of the fine-scale curvature (1-m and 5-m) categories are shown in table 5. There were no significant differences between watersheds in either the 1-m or 5-m fine-scale curvature categories.

The maximum distance from each sample point to a plant, upslope or downslope, was 4.6 m in W1 and 20 m in W2. The mean distance to the nearest plant from the sample points was significantly higher in W2 (4.46 m) than in W1(1.85 m) ($p < 0.001$). The correlation coefficients of the comparisons between SOC and the distance to upslope and downslope plants in either watershed were not significant. All coefficients are less than 0.2. The trend of the correlations (positive versus negative) varies in W1, in that the correlation of SOC to distance upslope is negative while the SOC versus distance downslope is positive, and vice versa for comparisons to A horizon SOC. However, in W2 the correlations are all negative.

Table 3. *Statistical analysis of the correlation between soil organic carbon (SOC) and the terrain characteristics in watersheds W1 and W2.*

Terrain Characteristic	n	df	r: Total SOC	r: A horizon SOC †
Elevation				
W1	55	53	-0.1493	
W2	60	58	-0.3161*	
Slope				
All				
W1	55	53	-0.2011	0.0834
W2	60	58	-0.0026	-0.0128
< 88% slope ‡				
W1	52	50		-0.0068
W2	57	55		-0.0654
Aspect §				
W1	55	53	0.1000	
W2	60	58	0.3980***	
UCA#				
W1	55	53	-0.0808	
W2	60	58	-0.0312	
TI††				
W1	55	53	-0.0920	
W2	60	58	-0.0499	

*,*** Significant at the 0.05 and 0.001 probability levels, respectively.

† A horizon SOC was analyzed to further explore the relationship between slope and SOC.

‡ Slopes less than 88% gradient were analyzed in response to a study that suggests erosional differences above and below a critical slope break of 88% (Liu et al., 2001)

§ Correlation coefficient for aspect cannot be negative because of the circular nature of the aspect data.

UCA = upslope contributing area.

†† TI = topographic index.

The effect of aspect on plant density was explored in W2 where aspect is significantly correlated to SOC. By using an east/west aspect division (east: 0 - 180 degrees, west: 180 – 360 degrees), the west-facing slopes have a significantly higher mean distance to the nearest plant than the east-facing slopes ($p < 0.05$). Differences in the plant distribution by east/west aspect division did not exist in W1.

Table 4. *Results of the statistical comparisons of channel (CH), shoulder (SH), and sideslope (SS) in each watershed.*

	Total SOC				A horizon SOC			
			ANOVA				ANOVA	
	n	Mean SOC	df	F	n	Mean SOC	df	F
		kg m^{-2}				kg m^{-2}		
Total SOC								
W1								
All positions	55		54	3.32*	55		54	1.59
between groups			2				2	
within groups			52				52	
CH	8	6.89a†			8	2.23a		
SH	15	4.32ab			15	1.81a		
SS	32	3.89b			32	1.02a		
W2								
All positions	60		59	0.51	60		59	3.46*
between groups			2				2	
within groups			57				57	
CH	6	3.61a			6	1.24ab		
SH	13	4.28a			13	2.15a		
SS	41	3.2a			41	0.73b		

* Significant at the 0.05 probability level.

† T tests were only performed if results of ANOVA were significant. Within columns for each watershed, means followed by the same letter are not significantly different. All tests were one-tailed.

Discussion

Because the prescribed fire watershed (W1) was burned less severely, it was hypothesized that it would retain a greater amount of SOC than the wildfire watershed (W2). The mean SOC of W1 was significantly higher than that of W2, as predicted. A higher severity fire not only combusts a greater amount of ground cover, but also typically results in more erosion than a low severity fire (Cannon and Reneau 2000). The greater severity of the wildfire, therefore, caused a greater loss of carbon either through more complete combustion or by increasing sediment movement out of the watershed where loss of vegetative cover was more complete.

The mean soil carbon storage was 4.44 kg m^{-2} for W1 and 3.67 kg m^{-2} for W2. Table 6 presents SOC measurements from other studies. Values obtained by Feng et al. (1999) under mature ceanothus and mature chamise were higher than the post-fire values of this study. The lower values in this study are to be expected because of the volatilization of carbon during fire and the loss of soil due to post-fire erosion on steep slopes. The range of SOC values under

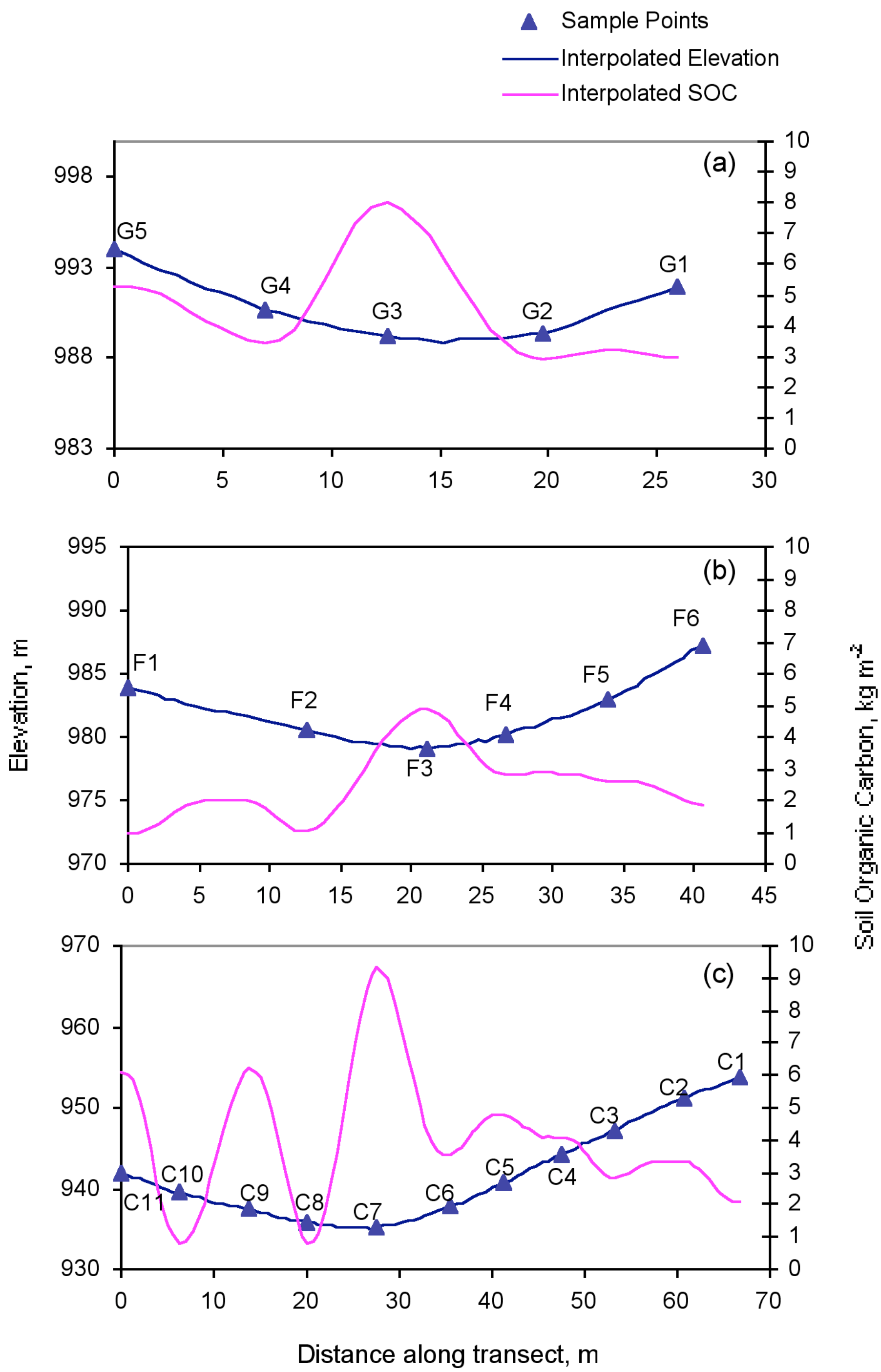

Figure 5. Elevation and soil organic carbon (SOC) are graphed along transects G (a) and F (b) of Watershed 1 and transect C (c) of Watershed 2. The lines are created from interpolated data with a resolution of 0.5-m, based on sampling and mapping data. Each transect runs west to east.

mature manzanita, ceanothus, chamise, and scrub oak calculated from data presented by Haydu (2000) were not as high as those from the current study. Unlike the sample plots of Haydu

(2000), the W1 and W2 watersheds included sample sites at the base of very steep slopes where carbon was concentrated by post-fire erosional redistribution of charred plant remains.

Table 5. *A list of the number of sample points within each curvature category.*

	W1		W2	
Curvature Category †	1-m‡	5-m	1-m	5-m
CC	6	9	11	9
CL	7	7	4	5
CV	1	2	0	0
LC	5	5	4	11
LL	21	10	22	14
LV	3	7	5	8
VC	2	0	1	0
VL	4	4	5	2
VV	6	11	8	11

†The curvature categories are based on the following notation: C=concave, L=linear, and V=convex. The first letter represents the vertical curvature and the second represents the horizontal curvature.

‡Diameter of curvature description.

SOC storage in the post-fire chaparral ecosystem is similar to that in other California ecosystems, being slightly higher than in the San Joaquin Valley agricultural land (*table 6*). Compared more generally to other agricultural and natural lands, the post-fire chaparral SOC values are low, but still within a similar range.

It was expected that SOC would be strongly linked to terrain characteristics, especially slope and curvature. Previous studies showed that organic matter and slope were negatively correlated due to the increased plant biomass, and thus increased plant detritus, in lower landscape positions where moisture accumulates (Moore et al. 1993; Johnson et al. 2000). The surface SOC, in particular, should have a negative relationship with slope since it has been removed from steeper slopes and deposited onto lower, more stable slopes. Furthermore, charred plant material on the soil surface is especially easily moved by erosion. Fox and Bryan (1999) demonstrated that erosion increased significantly as slope gradient increased within the range of 2.5 to 40%. The relationship between slope and SOC in both W1 and W2 is negative, as predicted, although small and not significant (*table 3*).

In order to more closely consider the effect of post-fire erosion on SOC, the SOC of the A horizon in both W1 and W2 was compared to slope (*table 3*). The A horizon was used because it is at the surface of soil profile and therefore most likely affected by erosion. Also, it has been shown that in chaparral soils the A horizon holds the most SOC within the soil profile and that carbon at the soil surface increases post-fire due to wood-ash depositions (Quideau et al. 1998; Feng et al. 1999; Haydu 2000; de Koff 2004). For these two reasons, the A horizon has the potential for being the greatest source of SOC variation in the soil profile. However, the correlation was not strong in either watershed.

It has been shown in simulation studies, using large boxes or by creating models from existing field data, that erosion is proportional to the slope gradient below a critical slope gradient, θ_c, but above it erosion falls as the gradient rises (Renner 1936; Horton 1945; Chen 1985; Liu et al. 2001). It follows that the relationship of slope to SOC under the influence of erosion would be affected similarly by θ_c, except it would change from a negative relationship to a positive one. According to Liu et al. (2001), θ_c is unique for each soil, depending on factors such as grain size, soil bulk density, surface roughness, runoff length, net rain excess, and the friction coefficient of the soil. However, they estimated that most soils have a θ_c within the range of 41.5 - 50° (88 – 119%). The high amount of sand in the soils of this study would indicate a lower θ_c, so the SOC of the A horizon was again compared to slope using only data with slopes below 88%. The correlations for both watersheds were negative, as was predicted for slopes below θ_c (*table 3*).

Table 6. *Soil organic carbon (SOC) values taken from the literature for different environments.*

	SOC†		
Study Site Location	Mean	Range	Literature Source
	----------------kg m^{-2}--------------		
Chaparral watershed - wildfire	3.67	0.22 - 17.80	Current Study
Chaparral watershed - prescribed fire	4.44	0.62 - 13.94	Current Study
Mature chaparral canopy	n.d. ‡	0.21 - 6.12	Haydu, 2000
Mature ceanothus and chamise	6.1 and 5.8	n.d. ‡	Feng et al., 1999
San Joaquin Valley cultivated land	3.08	n.d. ‡	L.Wu, personal communication, 2004
U.S. agricultural land	2.5 - 12.8	n.d. ‡	Ogle et al., 2003
California coastal sage and oak	n.d. ‡	2.25 - 20.1	Gessler, et al., 2000
Deciduous forests	17.4	n.d. ‡	Paustian, 2002
Evergreen forests	14.5	n.d. ‡	Paustian, 2002
Grasslands	11.7	n.d. ‡	Paustian, 2002
Deserts	6.2	n.d. ‡	Paustian, 2002

†Not all sources included both mean and range values for SOC.

‡ n.d. = not determined.

None of the correlations considered above are statistically significant, which indicates that the variability of SOC is high, independent of the effects of slope gradient. Notably, the slopes addressed in this study were much steeper than the range for which erosion has been traditionally studied – generally 5 to 30% (McCool et al. 1987; Liu et al. 1994; Fox and Bryan 1999; Sheridan et al. 2003; Ben-Hur and Wakindiki 2004). In this study, 96% of the slopes were >30% gradient. The steepness of slopes in watersheds W1 and W2 may have led to such extensive erosion that most surface SOC was removed from the watershed rather than redistributed within it.

Curvature of landscape has been shown to influence water flow, which in turn affects soil development. Soils are likely to have less water infiltration in a convex area of landscape because the shape causes overland flow to diverge, as opposed to concave areas where water converges (Birkeland 1999). Also, a convex area generally experiences erosion by overland flow, while a concave position accumulates sediment (Birkeland 1999; Huang et al. 2001).

The curvature of the landscape of the study sites was considered in two ways. First, the hillslope positions (shoulder, sideslope, and channel) were considered. The three positions were compared to determine if their SOC was different (*table 4*). It was hypothesized that SOC distribution would be influenced by post-fire erosion such that the convex areas (shoulder) would be depleted of SOC while concave positions (channel) would have a higher SOC concentration from sediment deposition. The sideslopes were expected to have an intermediate SOC content since they are mainly areas of sediment transport between the shoulder and channel, as described for the mid-slope in the nine-unit landsurface model of Dalrymple et al. (1968).

In W1, the mean profile SOC of the channel position is significantly higher than that of the shoulder position (p=0.005) (*table 4*). There are no significant differences when using A horizon SOC, so the difference originates in the subsoil. The channel soils formed form both residuum and colluvium. Thus, the channel subsoils may have a higher SOC than the shoulder subsoils due to either the collection of organic-rich debris from upslope positions, or due to greater water infiltration at the concave position, leading to an increase in biomass production. Most likely, both scenarios have contributed to pedogenesis and SOC accumulation over a time period that is greater than the single fire cycle considered in this study.

In W2 no significant differences occur between channel, shoulder, and sideslope positions when comparing the mean profile SOC (*table 4*). However, when comparing the mean A horizon SOC, the shoulder and sideslope positions are significantly different (p=0.006). The shoulder has a higher SOC than the sideslope, which is reverse of what was predicted based on the erosional susceptibility of the shoulder position. The slope gradients of the sites sampled within the shoulder positions and the sideslope positions are not significantly different (p = 0.08). As will be shown below, the fine-scale curvature is not the reason for the difference either. The shoulder soils tend to have a weak B horizon, which is more soil development than the channel or sideslope positions have. The weak B horizon is evidence that the shoulder area has been more stable than the other positions, despite its convex curvature, which may be the reason for the higher SOC in W2. If it is the most stable position, the shoulder has been accumulating SOC through plant and microbial activity and has not been losing SOC through erosion as drastically as first predicted based on previous studies of landscape positions and curvature (Daniels et al. 1985; Huang et al. 2001). The complex local variation provided by features such as rocks and plants that act as sediment dams may also contribute to the observed differences.

The channel position in W2, using either profile SOC or A horizon SOC, has a mean that is intermediate between shoulder and sideslope positions, as opposed to W1 where it had the highest mean (*table 4*). The channel position is prone to flushing of accumulated sediment during heavy rains and W2 may have experienced this more than W1. The soils in the channel positions of the prescribed-burned W1 may be better stabilized against flushing since more plants remained after the fire than in the wildfire-burned W2.

The terrain within each watershed is very complex, so that it may be possible for curvature on a fine scale to affect SOC distribution. At each sample point, the curvature within a 1-m and 5-m diameter was described (*table 5*). The two diameters were chosen in order to take into account different amounts of landscape detail surrounding the sample point. For example, the 1-m diameter relates to the scale of a local depression or small rock outcrop, while the 5-m diameter takes into account a rill or small ridge within the sideslope area. Again, it was predicted that convex positions would have less SOC due to the effects of erosion, compared to concave positions that accumulate SOC from upslope sediment. However, no significant differences were found when sample points were separated into the nine combinations of vertical and horizontal curvature. In fact, very little variation was seen between the groups whether they were compared using total SOC or A horizon SOC. Again, the post-fire erosion in both watersheds may have been sufficiently severe to have removed a substantial amount of SOC from all points within each watershed, thus eliminating any differences among them. The lack of variation among the finer-scale curvature observations, as opposed to the differences that appeared between the shoulder, sideslope, and channel positions, suggests that the wider-scale features have a stronger effect on the SOC distribution.

The broad-scale landscape positions of shoulder, sideslope, and channel are defined based on curvature and position relative to each other. Therefore, it is reasonable that the relative elevation of the channel and shoulder positions is significantly different in W2 ($p < 0.05$). The link between elevation and landscape position is the source of the correlation between SOC and relative elevation in W2 (*table 3*). In W1 there was not a significant correlation between elevation and SOC because the landscape positions did not have significantly different relative elevations.

As discussed above, we did not find a significant pattern to the soil carbon distribution in either watershed by comparing the SOC to slope or fine-scale curvature. The SOC and elevation were plotted for each of the transects in both watersheds to look for more localized trends in the SOC distribution. The representative transects in figure 5 were created using interpolated elevation and SOC data based on the sampling and mapping. As shown in figure 5a and b, the highest levels of SOC were found at the points closest to the channel, G3 and F4. Figure 5c is an example of a transect with multiple peaks of SOC that each have unique explanations. Point C7 is the closest point to the channel, C9 is in a concave position, and C11 is both in a concave position and also is surrounded by large rocks that may act as sediment dams. Multiple peaks occur in most of the transects and some are not easily explained. High values that occur on shoulder positions may be due to these being stable positions that do not experience erosion to the same extent as the sideslopes. Some transects have channel positions that have low SOC values because they have been flushed of sediment during a storm.

The most significant correlation among the terrain characteristics exists between aspect and SOC in W2 (*table 3*). The distribution of aspect in W2 is bimodal between southwest and southeast and the SOC is significantly different between the southwest and southeast sides, using an aspect division of 155 degrees (fig. 4). Aspect has been shown in previous studies to affect moisture, depth, and organic matter concentration of soils, but the differences are most often found between south- and north-facing slopes with the south-facing having drier summer conditions and the least amount of soil development (Finney et al. 1962, Birkeland 1999). It was expected that there would be no correlation between aspect and SOC in these watersheds due to their dominant south-facing slopes. However, in a study of a 10.5-ha watershed in Illinois, a southeast-facing slope had higher organic C content than a southwest-facing slope (Kreznor et al. 1989). According to Rosenberg (1974), the time of day that a slope is exposed to sun (i.e., morning versus afternoon) can cause a difference in soil moisture. Slopes exposed to the afternoon sun are drier because they have warmed considerably throughout the morning and then receive direct solar radiation in the afternoon. As a result, evapotranspiration is greater on those slopes. In contrast, the W2 watershed had higher SOC concentrations on the southwest-facing slope that receives the harsh, afternoon solar radiation.

The vegetation density by aspect for each watershed was estimated by comparing the mean distance to the nearest plant from sample sites on the east- and west-facing slopes. In W2, the mean distance from a sample site to the nearest plant was significantly less on the east-facing slope than on the slope facing west ($p < 0.05$), but in W1 there was no significant difference. Aspect has affected the two watersheds differently, which is suggestive that the differences in fire-history have also played a role. The influence of sun exposure is most important during the summer when the sun is highest in the sky (Rosenberg 1974). The less severe prescribed fire of W1 occurred in a moister season than that of the late summer wildfire in W2. At the time of the wildfire in W2, aspect-influenced sun exposure would have caused the chaparral canopy to be drier on the west-facing slope than the east-facing slope. Thus, the canopy was likely consumed unevenly between the east- and west-facing slopes, based on the difference in fuel moisture, as described by Birkeland (1999). Therefore, the higher SOC on the west-facing slope may derive from the greater deposition of charred plant debris during the fire.

Both watersheds had mature chaparral canopies before the fires, but the post-fire vegetation distribution appeared very different. Qualitatively, the resprouted shrubs are much less dense in W2 than in W1. The vegetation density can be estimated using the distance to the nearest plant from the sample points, the mean of which was significantly larger in W2 than in W1 ($p < 0.001$). The higher severity fire in W2 completely combusted some shrubs, including all branches and root crown, thereby significantly lowering the number of post-fire shrubs compared to the prescribed-fire watershed. This difference is consistent with findings of previous studies (DeBano and Conrad 1978; Minnich and Chou 1997).

The distance from each sample point to the nearest plant upslope and downslope was compared to the SOC to identify the effect that a plant in near proximity to a point might have. As mentioned before, it was expected that a plant would act as a dam, inhibiting soil deposition at points downslope while increasing deposition immediately upslope, depending on the distance. A previous study by Campbell (1985) found that rocks and fallen trees act as local sediment dams in the channel areas of chaparral watersheds. If sediment dams on watershed slopes were an important factor, SOC would show a positive relationship to distance to plants upslope and a negative relationship to distance to plants downslope. However, that trend does not appear in the correlation coefficients; instead the correlations were not significant and their trends were unpredictably variable. Apparently, plants do not create sediment dams that affect the post-fire SOC distribution on the watershed slopes.

An important contribution of this study is that it provides values for SOC in the post-fire chaparral ecosystem, allowing a more accurate accounting of chaparral ecosystems as part of local and global carbon budgets. Mean SOC values after a prescribed-fire are significantly higher than after a wildfire, implying that the lower severity of prescribed fires results in retention of more SOC. The post-fire chaparral ecosystem has 6 to 60% less carbon than the pre-fire ecosystem, based on a range of pre-fire values reported in the literature. Still, the range of post-fire values are higher than a mean SOC reported for San Joaquin Valley agricultural land. The post-fire chaparral SOC in this study is slightly lower than the SOC values for a California coastal sage and oak ecosystem and all U.S. agricultural land. The post-fire chaparral SOC values are also low when compared to mean SOC values for deciduous forests, evergreen forests, deserts, and grasslands throughout the world.

The results of this study will be useful in the further investigation and management of the Southern California chaparral ecosystem. The near proximity and encroachment of residential communities relative to chaparral lands creates the need to manage the occurrence of fires, possibly through the use of prescribed fire to prevent large wildfires. A benefit of a prescribed fire is the lower severity, which leaves more ground cover and soil carbon than a wildfire. Also, the fire cycle of this ecosystem is not simply a local phenomenon of Southern California, but plays an active part in the global carbon cycle. The post-fire SOC values derived from this study will assist in the estimation of the full range of soil carbon storage in the chaparral ecosystem as part of the global carbon budget.

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