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THE EFFECT OF FIRE ON NUTRIENTS IN A CHAPARRAL ECOSYSTEM[1]

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Abstract. The distribution of nutrients in plants, litter, and soil were studied before and after a prescribed burn in southern California chaparral. Total N, P, K, Na, Mg, and Ca were measured. The various nutrients were distributed differently in the plant parts and the litter before fire and this affected their redistribution by fire. Measurable losses of only 2 nutrients occurred—N (146 kg/ha) and K (49 kg/ha). Erosional losses of nutrients during the first rainy season after fire are also reported.

Key words: Brush; burning; California; chaparral; erosion; fire; plant nutrients.

INTRODUCTION

Quantitative data on the impact of chaparral fires on soil fertility and plant biomass are scant (Christensen and Muller 1975), although some information is available on the effects of fire on plant nutrients in other vegetation types (Daubenmire 1968, DeBell and Ralston 1970, Grier 1975). Most studies on fire-induced changes have been conceived and designed "after the fact," which means study areas are selected on burned areas and matched up with nearby unburned areas judged as being similar before the fire. Although this approach provides some insight into fire-related changes, uncertainty arises about the similarity of the burned and unburned sites. A better method for obtaining study sites is to select paired plots and sample the plant nutrients and biomass on 1 member of the pair before the fire. After a burn, the other member of the pair can be sampled for remaining plant biomass and nutrients. During wildfires, little opportunity exists for obtaining paired plots in this manner. In contrast, prescribed burning provides a possible way for pairing sites according to prefire conditions, thereby assuring better comparability between the burned and unburned condition.

This paper reports data on plant nutrient changes occurring during and after a prescribed fire in chaparral near Santa Maria, California, in summer 1973. Erosional losses of plant nutrients were reported in detail earlier (DeBano and Conrad 1976), and are only summarized here. Likewise, plant successional patterns after chaparral fires have been studied extensively and are not reported (Biswell 1974, Hanes 1971).

Fire affects vegetation, litter, and soils in several ways. It may directly consume part or all of the standing plant material and litter, as well as the organic matter in the upper layers of soil. Nutrients in the organic matter are either made more available or can be volatilized and lost from the site (e.g., gaseous loss of N). Although nutrient availability after forest and grassland fires has been studied most (Daubenmire 1968, Viro 1974, U. S. Forest Service 1971), some information is available on chaparral fires (Christensen 1973, Christensen and Muller 1975, Sampson 1944). Greater nutrient availability after fire usually makes fertilizers ineffective on freshly burned soils (DeBano and Conrad 1974, Vlamis and Gowans 1961). Some of the soluble nutrients deposited in the ash may be lost from the site by erosion if not immediately absorbed by plants (DeBano and Conrad 1976).

STUDY AREA

The area studied was on a 43-ha chaparral watershed in the Los Padres National Forest, northeast of Santa Maria, Santa Barbara County, California. Elevation ranges from 550 to 610 m. Slopes are mostly between 10 and 50%, although some approach 100%. The watershed and main channel are generally oriented in a north-south direction and most of the side slopes face east or west.

The vegetation biomass weight was composed of 38% red shank (*Adenostoma sparsifolium* Torr.), 22% chamise (*Adenostoma fasciculatum* H. & A.), 28% buckbrush (*Ceanothus cuneatus* Hook.), occasional manzanita (*Arctostaphylos* spp. Adans.), occasional scrub oak (*Quercus dumosa* Nutt.), and 28% black sage (*Salvia mellifera* Greene.). This stand was burned by a wildfire in 1948.

The underlying rock material is highly calcareous and is primarily Cretaceous sandstones and conglomerates and Quaternary age alluvium and landslide breccia (Bergwall 1973). Soils were gravelly loam Lithosols having *A*-horizon 0–10 cm thick. The surface layer was a loam texture (50% sand, 36% silt, 14% clay), weak to medium fine granular structure, and pH of 6.6. The *C*-horizon extended down to 46 cm or deeper and had a rocky loam texture, with medium to blocky structure and a soft friable sticky consistency. The *C*-horizon was 80% rock.

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The climate is Mediterranean. Summers are long and dry, and precipitation occurs during winter as rain. In the winter following the prescribed fire, 390 mm of rain were measured, which agreed with the average for the last 6 years at a nearby weather station.

The fire was started at noon on 29 August 1973, and until about 1400 h it burned briskly, making several large runs from the canyon bottoms to the ridgetops. Relative humidities during the burn varied from 24–30%; air temperatures from 29–30°C; windspeed from 0–19 km/h; and the fuel stick was at 7 (the large dead fuel contained ≈7% H_2O). Although these were relatively intense burning conditions, the burning intensity varied widely over the plots studied.

Methods

Field sampling

The study site selected has a 50% slope. A set of 12-m² paired plots was chosen to sample plant yield and nutrients. One of the paired plots was clipped before burning and 1 after. Pairing of vegetation plots was done by selecting 2 areas which had similar species and cover characteristics. All vegetation on the plots was clipped at ground level and separated by species into 3 different classes: (a) live twigs, <0.64 cm in diameter; (b) live stems which are branches and trunks >0.64 cm in diameter; and (c) dead plant material made up of both twigs and stems. All foliar material was included in the <0.64 cm class. These 3 classes were picked because their flammability and nutrient content were expected to differ significantly. Live twigs and dead material were considered most flammable and would probably be completely consumed during the fire. Also, we expected larger amounts of nutrients to be present in the small live plant parts. Larger live stems were not expected to burn readily and probably contained smaller amounts of nutrients.

Litter was sampled on 6 randomly located paired plots up or down slope from the vegetation plots. Pairing of the litter plots was done by examining the relative thickness of the litter layer at a particular site and picking each member of the pair so the litter on the soil surface was similar. In all cases, members of each pair were within a metre of each other. One of each of the 6 pairs was randomly selected and sampled before burning and the other one after the fire. Litter was sampled on each plot by vacuuming all identifiable plant material from a 0.49-m² area. After the litter had been removed, soil was sampled at 1-cm intervals down to 49 cm and at 2-cm intervals down to 10 cm on 2 of the 6 litter sampling plots. On the remaining 4 litter sampling plots, soil samples were removed only from the 0–1 and 1–2 cm depths. Each soil sample was bagged individually and returned to the laboratory for processing and analysis. Bulk density and soil water samples were collected at each of the soil sampling sites before and after burning. The burned area was sampled the day after the fire.

During the fire, soil surface temperatures were measured by placing temperature-sensitive tablets (Tempils®) encased in an aluminum holder at several locations throughout the study area. These tablets melted at specified temperatures and provided estimates of maximum soil surface temperatures during the fire.

Laboratory analysis

Plant material collected in the field was subsampled for nutrient analysis by removing a representative subsample from each size class of each species. Each subsample was broken into smaller pieces and ground to pass through a 0.5-mm screen. About 100 g of the plant material were used for laboratory analysis. Litter samples were pulverized to pass through a 0.5-mm screen before chemical analysis. The same chemical procedures were used to determine N, P, Ca, K, Mg, and Na on litter and plant samples. Total N was determined by the micro-Kjeldahl technique modified to include nitrates (Bremner 1965, Chapman and Pratt 1961). Total P was measured by dry ashing after saturating with magnesium nitrate (Piper 1950). Phosphorus concentrations in the ashed material were analyzed colorimetrically by the vanadate–molybdate-yellow method (Chapman and Pratt 1961). An atomic absorption spectrophotometer using a hydrogen–air flame was used for determing Na and K and a nitrous oxide–acetylene flame, with either cesium or potassium chloride suppressant, for Ca and Mg. Organic carbon in the litter and soil was determined by the Walkley Black method and converted to organic matter content by multiplying by the Van Bemmelen factor of 1.724 (Allison 1965).

Soil samples were passed through a 2-mm sieve and the fractions greater and <2 mm were weighed. Particle size distribution on the <2-mm fraction was measured with a hydrometer (Day 1965). Total N was determined by micro-Kjeldahl as outlined by Bremner (1965) and total P by sodium carbonate fusion (Chapman and Pratt 1961). Total exchangeable and soluble cations of Ca, Mg, Na, and K were replaced with ammonium acetate and the concentrations of each ion in the leachate measured by atomic absorption. Cations fixed in the soil minerals were not determined. Wettability of the <2-mm soil fraction was evaluated by liquid–solid contact angle measurements according to Letey et al. (1962) and water drop penetration time (Savage et al. 1969). Soil pH was based on a 1:1 (wt:wt) soil to water suspension.

Data analysis

The effect of fire on plant nutrients was evaluated in 2 ways. First, the amounts of nutrients in the litter and upper 2 cm of soil before and after fire on the 6 paired plots were averaged and used to estimate

TABLE 1. Plant biomass and nutrients contained in live and dead plant material of different chaparral species

Size class	Total plant	N		P		K		Mg		Ca		Na	
	kg/ha	%	kg/ha	%	kg/ha	%	kg/ha	%	kg/ha	%	kg/ha	%	kg/ha
Red shank													
<0.64 cm	1,758	1.00	17.6	.126	2.2	0.86	15.1	.15	2.6	0.78	13.7	.058	1.0
>0.64 cm	4,677	0.16	7.5	.032	1.5	0.33	15.4	.050	2.3	0.35	16.4	.024	1.1
Dead	5,007	0.24	12.0	.012	0.6	0.055	2.8	.040	2.0	0.56	28.0	.023	1.2
Total	11,442		37.1		4.3		33.3		6.9		58.1		3.3
Chamise													
<0.64 cm	2,228	0.66	14.7	.085	1.9	0.54	11.9	.095	2.1	0.94	20.9	.025	0.6
>0.64 cm	1,907	0.20	3.8	.027	0.5	0.26	5.0	.039	0.7	0.72	13.7	.023	0.4
Dead	2,570	0.32	8.2	.005	0.1	0.11	2.8	.032	0.8	0.73	18.8	.027	0.7
Total	6,705		26.7		2.5		19.7		3.6		53.4		1.7
Ceanothus													
<0.64 cm	5,216	0.85	44.3	.046	2.4	0.55	28.7	.085	4.4	1.17	61.0	.024	1.3
>0.64 cm	2,988	0.34	10.2	.005	0.1	0.25	7.5	.036	1.1	0.82	24.5	.024	0.7
Dead	176	0.50	0.9	.005	.01	0.17	0.3	.055	0.1	0.93	1.6	.022	.04
Total	8,380		55.4		2.5		36.5		5.6		87.1		2.0
Black sage													
<0.64 cm	661	0.56	3.7	.122	0.8	1.63	10.8	.122	0.8	0.86	5.7	.066	0.4
>0.64 cm	680	0.26	1.8	.018	0.1	0.79	5.4	.064	0.4	0.42	2.9	.050	0.3
Dead	1,172	0.27	3.2	.036	0.4	0.54	6.3	.050	0.6	0.41	4.8	.033	0.4
Total	2,513		8.7		1.3		22.5		1.8		13.4		1.1
Unknown dead	1,354	0.47	6.4	.003	.04	0.10	1.3	.066	0.9	1.60	21.7	.029	0.4
Total (all plants)	30,394		134.3		10.6		113.3		18.8		233.7		8.5

changes in organic matter and plant nutrients during burning. Average changes in organic matter and plant nutrients in the litter and these 2 soil layers on the 6 paired plots were tested for differences by using a t-test. Combining the nutrients contained in these 3 layers only gave estimates of net change because an unknown quantity was added by ash falling from the burning overstory vegetation. Nutrients added to the soil surface from the burning overstory were estimated from the nutrient loss occurring in the paired vegetation plots clipped before and after fire.

Another method used related nutrient changes in the litter layer at each paired plot location to the amount of organic matter destroyed. Organic matter destruction at the soil surface was considered an index of fire intensity. This approach assumed that only small amounts of organic matter were added to the soil surface during the fire. Plant nutrients in the deeper soil layers (2–10 cm) were estimated by combining data of the 4 deep soil sampling sites. Two of these sites were sampled before fire and 2 after. These deeper depths were combined because fire probably did not affect plant nutrients below 2 cm downward in the soil.

RESULTS

Prefire biomass and plant nutrients

Total standing plant biomass on the site was 30,394 kg/ha (Table 1). The proportion of biomass made up by the different species (in percentage) was 38 for red shank, 22 for chamise, 27 for buckbrush, and 13 for unidentifiable plant material and black sage. About ⅓ of the aboveground biomass (10,279 kg/ha) was dead (Table 1). The percent dead, by species, was: 44—red shank, 38—chamise, 47—black sage, and 2—buckbrush. Live plant stems >0.64 cm and twigs <0.64 made up 32% and 34% of the total biomass, respectively. Small live twigs (<0.64 cm) contained the highest concentrations of N, and ≈60% of the N in the plants was in this smaller plant material. Dead plant material contained 23% of the N but the live plant stems >0.64 cm contained only 17%. The distribution of N among the different size classes is important because smaller live twigs and dead material are almost totally consumed during a fire. Nitrogen is particularly susceptible to volatilization by heating, and significant amounts of gaseous N can be lost above 300°C (DeBell and Ralston 1970, Knight 1966, White et al. 1973).

The concentrations and amounts of P were also greatest in the <0.64-cm live twigs. About 71% (7.3 kg/ha) of the total P in the plants was contained in the small twigs (<0.64 cm) but the dead material accounted for only 11%.

Potassium was concentrated in the small live twigs of all plant species. Concentrations in the twigs of black sage (1.63%) were particularly high. About 59% (66.5 kg/ha) of the K in the aboveground plant material was in the live twigs. About 29% of the K was in the >0.64-cm live plant stems and 12% in the dead material.

The highest concentrations and largest amounts of Ca, Mg, and Na were also present in the <0.64 cm live twigs, except in red shank, which had larger quantities of Ca in the dead material than either of the 2 live plant classes.

The effect of fire on nutrient distribution in plants, litter, and soil

Biomass.—Before the fire, 41,072 kg/ha of organic matter was on the site in the plants, litter, or upper 2 cm of soil (Table 2). Most of the organic matter on the site was in the standing plants and less was present in the litter and soil. About 66% of the plant material was consumed during the fire. Before the fire, ≈30,400 kg/ha of plant material was present on the site; after the fire, only 10,300 kg/ha was present. Plant material remaining after the fire was composed mostly of large stems that were not highly flammable because of their size and H_2O content. Almost all dead material and live plant twigs <0.64 cm were consumed during the fire. Flame temperatures >1,000°C were measured in the canopy during the fire. The average amount of organic matter on the soil surface of the paired plots was reduced 46% during the fire. Although the amount lost varied from 0 to 70% among the 6 plots, this loss was statistically significant (at the .05% level in a paired plot comparison). The loss of organic matter at the soil surface probably represented the amount destroyed by fire because ash material settling from the burning plant canopy probably did not contain significant amounts of organic matter.

Organic matter was also lost from the upper soil layers and the amount destroyed decreased with depth (Table 2). Although the average loss of organic matter in the 0–1 cm soil layer was 120 kg/ha and in the 1–2 cm was 53 kg/ha, these losses were not statistically significant. However, the combined loss of organic matter from the litter and 2 upper soil layers was significant at the .10% level. Organic matter in the litter and upper 2 cm of soil was easily destroyed during the fire because of the dry soil. Prefire measurements showed the litter contained 9.37% H_2O. The H_2O content in soil layers was: 0–1 cm—1.84%; 1–2 cm—2.09%; 5–7 cm—2.34%; 10–12 cm—3.38%. These low moisture contents probably had little affect on the temperatures developing in the soil during the fire.

Maximum surface temperatures measured by Tempil® plates at 5 locations during the fire were 370°, 370°, 370°, 370°, 340°, and 200°C. Temperatures of 300°C are sufficient to ignite carbonaceous residues (Hosking 1938). Although temperatures below the soil surface were not measured, we estimated from soil data collected during other fires that the maximum temperatures at the 1-cm depths probably did not exceed 167°C and at the 2-cm depth, 65°C. Temperatures >100°C can nondestructively distill volatile organic substances (Hosking 1938). The distillation of organic substances was also suggested by a slight increase in the liquid–solid contact angle in the upper soil layers. Hydrophobic substances have been shown to move along temperature gradients (DeBano et al. 1976).

Nitrogen.—Living and dead aboveground biomass contained 134 kg/ha of total nitrogen—an amount comparable to that reported by other investigators studying chaparral vegetation. For example, Zinke (1969) found 109 kg/ha of N in the leaves and stems of chamise stands on areas in Los Angeles County receiving 61 cm of precipitation annually. Rainfall in this study area was ≈300 mm annually. Nitrogen in the aboveground plant parts of a 40-yr-old chamise and *Ceanothus* stand on the San Dimas Experimental Forest in southern California amounted to 140 kg/ha (Specht 1969). Lossaint (1973) reported 160 kg/ha of N in the aboveground biomass of a 17-yr-old stand of *Quercus coccifera* in France. The upper 2-cm soil layer in our study contained ≈337 kg/ha of N, and the 2–10 cm layer contained an additional 805 kg/ha of N. Nitrogen below 2 cm was contained mostly in the plant roots but nearer the soil surface it was in both small roots and partially decomposed litter material. Although the soil was analyzed to 10 cm, probably only the upper couple centimetres were affected by fire and erosion.

Although 34% of the standing plant material remained after burning, the nutrients in it were not retained in the same proportion. Only about 25% of the nitrogen contained in the plants before burning remained in the charred plant material after the fire (Table 2). Most plant nutrients, except N, were enriched at the soil surface by ash material falling to the surface from the burning plant canopy. Less total N was present in the ash at the soil surface than was present in the litter before burning, although some N was probably added in the ash settling to the soil surface during the fire. Christensen and Muller (1975) estimated that 21 kg/ha of N may be added to the surface during a fire.

In this study, a net loss of nitrogen at the soil surface suggests very little N was added and N in the burning plants was probably volatilized and lost into the air during burning. Temperatures of 700°C or greater can easily volatilize substantial amounts of N (DeBell and Ralston 1970, White et al. 1973). About 110 kg/ha of N was apparently lost from the plants and litter during this fire (Table 2). This loss was most likely from the live twigs <0.64 cm. Before burning, the small twigs contained ≈80.3 kg/ha and the dead material ≈30.7 kg/ha (Table 1). An additional 21.7 kg/ha of N was lost from the 0–1 cm soil layer, and 14.7 kg/ha from the 1–2 cm layer. Below 2 cm, little N was probably lost because the soil temperatures were relatively cool. Therefore, a reasonable estimate of the N lost during this prescribed burn from the plants, litter, and soil amounts to 146 kg/ha.

Information on concentrations and amounts of nitrogen in the plants, soil, and litter before and after burning illustrates a mistake commonly made while evaluating the impact of fire on plant nutrients if data are only collected on the concentrations of nutrients contained in the litter layer before and after fire. For

TABLE 2. Plant nutrients and biomass contained in the plant, litter, and soil (in kilograms/hectare) before and after a prescribed burn in chaparral. Diff. = difference in content before and after burn

	N			P			K			Mg		
	before	after	diff.	before	after	diff.	before	after	diff.	before	after	diff.
Plants	134.3	33.0	−101.3	10.3	0.83	−9.5	113.3	23.7	−89.6	18.8	4.4	−14.4
Litter	146.7	138.3	−8.4	21.8	31.1	+9.3	173.7	217.4	+43.7	171.7	233.3	+61.6
Soil												
0–1 cm	181.7	160.0	−21.7	63.1	56.7	−6.4	35.1	34.7	−0.4	26.6	26.5	−0.1
1–2 cm	155.7	141.0	−14.7	57.0	51.7	−5.3	27.7	25.1	−2.6	24.9	29.4	+4.5
Total: Litter 0–1 cm 1–2 cm	484.1	439.3	(2.17)[b] −44.8	141.9	139.5	(0.33) −2.4	236.5	277.2	(0.70) +40.7	223.2	289.2	(1.31) +66.0
Soil 2–10 cm[a]		805.5 ± 135.0			416.2 ± 47.2			51.9 ± 21.6			136.7 ± 42.2	
TOTAL	1,423.9	1,277.8	−146.1	568.4	556.5	−11.9	401.7	352.8	−48.9	378.7	430.3	+51.6

	Ca			Na			Organic Matter		
	before	after	diff.	before	after	diff.	before	after	diff.
Plants	233.7	86.7	−147.0	8.5	3.2	−5.3	30,400	10,300	−20,100
Litter	465.4	601.4	+136.0	16.2	19.7	+3.5	9,550	5,200	(1.91) −4,350
Soil									
0–1 cm	676.8	654.3	−22.5	11.4	9.0	−2.4	637	517	−120
1–2 cm	702.0	700.6	−2.6	8.9	9.3	+0.4	485	432	−53
Total: Litter 0–1 cm 1–2 cm	1,844.2	1,956.3	(0.10) +112.1	36.5	38.0	(0.29) +1.5	10,672	6,149	(1.91) −4,523
Soil 2–10 cm		6,724.1 ± 1,725			21.6 ± 9.3			. . .	
TOTAL	8,802.0	8,767.1	−34.9	66.6	62.8	−3.8	41,072	16,449	−24,623

[a] Average of 4 sampling sites; 2 prefire and 2 postfire.
[b] Number in parenthesis indicates the calculated t-value for 6 paired plots.

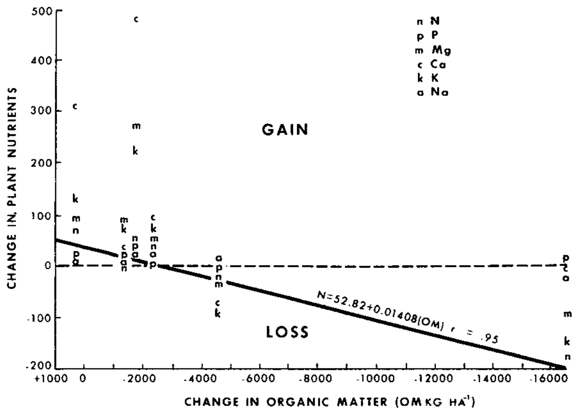

FIG. 1. Change in plant nutrients associated with varying losses of organic matter. Larger losses in organic matter were taken to indicate more severe burning conditions.

example, in this prescribed burn, the litter layer contained 0.30% N before the fire and the ash layer after fire had 0.24%. It is easy to conclude that fire had little effect on N at this site. However, if these concentrations are placed on a weight per unit area basis before and after fire, a loss of 146 kg/ha is obvious. This mistake has also been illustrated by Knight (1966) with data taken during a laboratory burning experiment.

Phosphorus.—The amount of this nutrient in the standing plants was low (Table 2). Twice as much phosphorus was present in the litter as in the plants. Only about 1.8% of the total P in the plants, litter, and soil was found in the plants before burning. Low quantities of P are typical for chaparral and Specht (1969) reported only 10–20 kg/ha in a 40-yr-old stand of chamise in southern California. Phosphorus in the soil was fairly evenly distributed with depth. After the fire ≈8% (0.83 kg/ha) of the P in the plants before burning remained in the charred plants. The reason only a small percent remained in the burned plant material was because the smaller twigs had a large proportion of this nutrient which was released during burning (Table 2). Practically all the P in the plant material was deposited on the soil surface as ash by the fire. All P in the plants and litter before fire (32.1 kg/ha) could be found in the charred plant remains and ash on the soil surface after burning (Table 2). The increase in P of the ash layer was statistically significant (Table 2). Phosphorus in the upper 2 cm of soil was lower after the fire for some unknown reason. Phosphorus is not generally considered susceptible to loss by volatilization (Wells 1971).

Potassium.—This nutrient was distributed differently in the chaparral ecosystem than N and P because a large proportion (71%) was in the plants and litter. This distribution pattern made potassium easily cycled by fire. The soil surface was enriched with K during the fire, and ≈217.7 kg/ha were found on the soil surface after burning as contrasted to only 173.7 kg/ha before fire (Table 2). This increase was not statistically significant because of the variation between paired plots. Only 23.7 kg/ha of K remained in the charred plant stems after burning; in contrast, 33.3 kg/ha of K was present in the live plant twigs (>0.64 cm) before burning (Table 1). The difference suggests that some of the larger live stems were consumed by the fire. The K balance for the site suggests some K was lost during the fire—possibly by volatilization. Before the fire, 287 kg/ha of K were recorded in the plants and litter but after burning, only 241.1 kg/ha were found in the charred plant stems and ash, showing a loss of ≈46 kg/ha. Although K is not as easily volatilized as N, significant amounts can be lost above 550°C (Jackson 1958). The 66.5 kg/ha of K in the live stems <0.64 cm (Table 1) were the most likely source of this loss because the stems were small, extremely flammable, and almost entirely consumed by the fire. Temperatures of these small stems undoubtedly exceeded 550°C during the fire.

Magnesium, calcium, and sodium.—Magnesium was distributed similarly to K, except smaller amounts were in the plants. Magnesium was generally uniformly distributed throughout the upper soil layers. Calcium was abundant in the plants, litter, and soil although the soil contained large amounts. High concentrations of Ca were expected because the parent rock was highly calcareous (Bergwall 1973). About 37% of the sodium was located in the litter and plants.

About 76% of the Mg and 62% of the Na in the plants before burning were released during the fire and probably deposited in the ash on the soil surface. Although a large amount of Ca was also deposited on the soil surface after fire, ≈86.7 kg/ha of this element was retained in the larger diameter plant stems remaining after burning.

Susceptibility of plant nutrients to burning

The changes in plant nutrients on the 6 paired plots seemed related to burning intensity and the change in organic matter on the plots ranged from +8% to −70% during the fire. This change in organic matter suggested a difference in burning intensity among the paired plots, although temperature data were not available for the individual plots. The greatest loss in organic matter (70%) undoubtedly occurred on the most severely burned plot. One plot gained ≈400 kg/ha of organic matter, indicating either a sampling error or a less intense burn where organic matter was added from the burning canopy. Ash material from burned chamise plants has been reported to contain up to 38% organic matter, although the amount contained in ash will depend partly on the burning intensity (Christensen and Muller 1975).

When the change in organic matter on each plot was related to the change in plant nutrients on the same plot, some differences in nutrient response to burning intensity emerged (Fig. 1). For example, N loss ap-

TABLE 3. Soil properties before and after a prescribed fire

Location	CEC (meq/ 100 g)	Sand (%)	Silt (%)	Clay (%)	Wetting angle (°)	pH
0–1 cm:						
Before	21.7	46.6	38.6	14.8	69.1	7.01
After	21.9	51.6	35.5	13.0	71.6	6.83
1–2 cm:						
Before	21.8	51.5	35.1	13.5	69.6	7.19
After	22.2	52.1	32.7	15.2	69.9	7.02

peared linearly related to the amount of organic matter destroyed. Small amounts of N were added at the lighter burning intensities (until 4,000 kg/ha of organic matter was destroyed). As intensity increased, N loss increased, until finally on the most severely burned plot (which lost 16,500 kg/ha of organic matter) about 177 kg/ha of N was lost from the soil surface. The linear relationship between N loss and organic matter destruction was highly significant and had a correlation coefficient of about .95. Other nutrients also accumulated at the soil surface until ≈4,000 kg/ha of organic matter were destroyed, although their change was not linearly related to the amount of organic matter lost. Generally when 4,000 kg/ha or more of organic matter were destroyed, nutrients no longer accumulated at the soil surface but instead were present in the same quantity as before burning or showed a loss. In theory, nutrients should accumulate at the soil surface during a fire regardless of burning intensity, if plant nutrients are not affected by fire intensity, because ash material contains the nutrients formerly present in the standing plants before burning. This did not seem to occur when 4,000 kg/ha or more of organic matter were lost because the nutrients either showed no appreciable change (P, Ca, Na) or showed a pronounced loss (Mg, K, N). The average change in plant nutrients contained in the litter layer on the 6 plots during the fire (Table 2) does not show these nutrient changes related to burning intensity. If only average changes are considered, then all nutrients except N increased on the soil surface during fire. Therefore, it seems necessary to relate nutrient changes to fire intensity before meaningful estimates of nutrient changes can be made during both wildfires and prescribed burns.

Changes in other soil properties

Prescribed fire had little effect on soil properties of the upper 2 cm of soil not discussed previously. Neither cation exchange capacity (CEC) nor percent sand, silt, or clay changed appreciably during the fire (Table 3). Liquid–solid contact angle, which is a measure of soil wettability, increased only slightly in the 0–1-cm layer after burning. Increasing the liquid–solid contact angle decreases wettability because the soil has a weaker affinity for water. The small increase in contact angle probably did not affect water movement in the soil although it did suggest hydrophobic substances had moved into this soil layer during burning. The contact angle can increase appreciably during a fire in coarse textured soil (DeBano et al. 1970). The clay content of this soil was >13% and is probably partly responsible for the slight increases in contact angle. No appreciable change in soil pH occurred during the fire.

Discussion and Conclusions

The distribution of nutrients in plants and litter must be considered in any study of the effects of fire. For example, nutrients in small live twigs (<0.64 cm) or dead plant material are probably either released in a highly soluble form and deposited on the soil surface or are lost by volatilization during fire. These highly soluble plant nutrients on the soil surface may be used for plant growth or are easily lost by erosion. Increased solubility of nutrients on burned chaparral areas after fire leads to a lack of fertilizer response on burned areas (DeBano and Conrad 1974, Vlamis and Gowans 1961).

During this study, 66% of the total standing plant material and 46% of the litter were destroyed by fire. The nutrients in the plants and litter made available by fire were not in the same proportion as the amount of litter and plant material destroyed. For example, 66% of the plant material consumed during the fire contained 9.5 kg/ha of P and 89.6 kg/ha of K. These values represent 92% and 79%, respectively, of the nutrients in the unburned plant material. These elements, as with N, were concentrated in smaller stems which were almost entirely consumed during the fire.

Measurements taken the winter following burning showed 785,900 l/ha of runoff water removed 7,340 kg/ha of debris (DeBano and Conrad 1976). The debris contained (in kilograms per hectare): 15.08 N, 3.37 P, 19.34 K, 28.02 Mg, 47.39 Ca, and 2.57 of Na. The runoff water contained an additional 7.67 kg/ha K, 3.63 kg/ha Mg, 20.04 kg/ha Ca, and 2.00 kg/ha of Na. Only trace amounts of N and P were lost in the runoff water. The debris and runoff water from the unburned sites contained only trace amounts of plant nutrients.

The effect of fire on nitrogen was particulary noteworthy because 146 kg/ha of this element were lost by volatilization, and an additional 15 kg/ha by erosion after the fire (Table 4). This N loss represented ≈11% of the N in the plants, litter, and upper 10 cm of soil before burning. If this quantity of N was lost from the stie during each fire over the many millennia chaparral vegetation has been evolving, and no mechanisms existed for replenishing this N, then the site would be completely devoid of N. Although chaparral sites are typically low in N (DeBano 1974, Hellmers et al.

TABLE 4. Summary of nutrient changes during and after a prescribed fire in chaparral

	N	P	K	Mg	Ca	Na
Total, before fire (kg/ha)[a]	1,424	568	402	379	8,802	67
Total, after fire (kg/ha)	1,278	557	354	430	8,767	63
Loss/Gain kg/ha (fire)	−146	−11	−48	+51.0	−35	
% before	10.3	1.9	11.9	13.5	0.4	
Loss by erosion						
debris kg/ha	15	3	19	28	47	3
water kg/ha	trace	trace	8	4	20	2
Inputs						
precipitation kg/ha	2					
symbiotic fixation kg/ha	60					

[a] Amount contained in plants, litter, and upper 10 cm of soil.

1955), some mechanisms for replenishing N during the years between fires must be present. Rain undoubtedly contains some N, although this input probably is not more than a couple kilograms per hectare annually. A more important mechanism seems to be nitrogen-fixing organisms. Studies show that some shrubs, such as deerbrush (*Ceanothus integerrimus*), develop root nodules (Vlamis et al. 1958) capable of fixing up to 60 kg/ha of N annually under optimum conditions (Delwiche et al. 1965). Other postfire leguminous herbs, such as *Lotus*, undoubtedly also fix N. Nitrogen fixation by nonsymbiotic organisms may also replenish N after a fire, although this source has not been studied.

Potassium also seems to have a special role in nutrient recycling during a fire because a large proportion of this element is contained in the plants and litter. About 287 kg/ha, or 73%, of the K on the site was in the litter and plants. During the fire, ≈43.7 kg/ha of the K in the plants were deposited as ash on the soil surface and another 48 kg/ha were lost—possibly by volatilization (Table 4). An additional 27 kg/ha of K were also lost by erosion and runoff after the fire.

Only ≈5.4% (32.1 kg/ha) of the phosphorus in the system studied was contained in the plants and litter. Almost all P in the plants was returned to the soil surface as ash during the fire because it was concentrated in the smaller plant stems that were consumed by the fire. Volatilization of P was not evident, although 3.37 kg/ha of this element were lost by erosion during the first winter season after burning (Table 4).

Although 45 kg/ha of calcium, 14.4 kg/ha of magnesium, and 5.3 kg/ha of sodium were translocated to the soil surface during the fire, their importance in nutrient cycling in this chaparral ecosystem during fire is not yet ascertained. About 67 kg/ha of calcium, 32 kg/ha of magnesium, and 4.6 kg/ha of Na were lost by erosion and runoff. This condition suggests that not only soluble cations deposited in the ash were lost but that also some of these elements in the burned and unburned litter material also eroded.

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